AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100

Silver Spring, Maryland 20910

301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

1 of 3

Title:

Progress at LAMPF — 1992–1993

Author(s):

C. M. Hoffman (editor and compiler)

Submitted to:

For Internal and External Distribution
July 25, 1994

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory, an affirmative action/equal opportunity employer, is operated by the University of California for the U.S. Department of Energy under contract W-7405-ENG-36. By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Form No. 836 R5
ST 2629 10/91

MASTER

Progress at LAMPF

1992–1993

***Clinton P. Anderson
Meson Physics Facility
Los Alamos National Laboratory***

FOREWORD

This Progress Report describes the operation of the Los Alamos Meson Physics Facility (LAMPF) and the research programs carried out there for the years 1992 and 1993. The accelerator operated for over 100 days in 1992, providing beams of H^+ , H^- , and polarized H^- for a rich and varied research program in nuclear physics. The accelerator had only fair beam availability in 1992 (for example, the average H^+ beam availability was 72%), caused largely by problems in the 201-MHz rf system. A major effort was expended to address these problems before the 1993 run. These efforts were rewarded by good beam availability in 1993 and few problems with the 201-MHz system.

LAMPF operated remarkably smoothly during 1993, in the midst of a period of great uncertainty in the future of the facility and the downsizing of MP Division, which led to the loss of a large number of key people to positions elsewhere in the Laboratory. The H^+ intensity had to be held to no more than $\sim 800 \mu A$ because of a vacuum leak in the A2 target. Nevertheless, the accelerator operated very reliably and the summer run in 1993 proved to be extremely productive.

1993 marked the first time that three major new detectors, LSND, MEGA, and NMS, acquired data. Construction of the LSND neutrino detector was completed in August and data were acquired during September and October. These data have yielded the first measurement of the cross section for ν_μ -C scattering near threshold; the cross section appears to be about a factor of 2 smaller than predictions based on the Fermi-gas model. Other measurements made by LSND include a determination of the cross section for $\nu_e C \rightarrow e N$, a study of $\bar{\nu}_e$ and νp elastic scattering, and a sensitive search for $\bar{\nu}_\mu$ - $\bar{\nu}_e$ oscillations. The detector performance was in excellent agreement with expectations. Considerably more data will be acquired in 1994.

The MEGA detector took 50 days of production data searching for the forbidden decay $\mu \rightarrow e\gamma$. These data will allow the reconstruction algorithms to be tuned and should yield a 15-fold improvement in the sensitivity to the $\mu \rightarrow e\gamma$ branching ratio. The positron spectrometer in the MEGA apparatus was also used to take data on ordinary muon decay to determine the ρ Michel parameter with a statistical precision of 0.00044. The low-mass chambers and the intrinsic symmetry of the apparatus should result in small systematic errors. A determination of ρ to this precision will probe left-right symmetric weak interactions.

The construction of the Neutral Meson Spectrometer (NMS) was nearing completion in the fall of 1992 when an unfortunate rigging accident destroyed a major part of one detector arm. A determined effort resulted in the spectrometer being repaired in time for the beam in July 1993. The first experiment with the NMS was the precision measurement of the differential cross section for π^-p charge exchange at incident energies from 140 to 260 MeV. These data will provide important constraints on phase-shift analyses of the π -nucleon system. Additional data were taken with the NMS on several pion-induced single-charge-exchange processes.

The experiment at LANSCE studying parity violation in the scattering of epithermal neutrons from heavy nuclei ran well throughout the production beam periods. This process exhibits large enhancements allowing many parity-violating asymmetries to be measured in a single nucleus. Improvements in the experimental apparatus resulted in a given experimental precision being achieved 400 times faster than that previously achieved! The anomalous results in ^{232}Th , where all seven of the measured parity-violating asymmetries had the same sign, was verified with new data. However, measurements on uranium and other nuclei did not exhibit this sign anomaly. Thus, it appears that there is some property of thorium that is responsible for the sign anomaly. The determination of the average parity-violating matrix element provided new constraints on the meson couplings in the NN weak interaction.

1993 marked the final run of the experimental nuclear physics program in Line X. This program utilized the polarized H^- beam from the high-intensity Optically Pumped Polarized Ion Source (OPPIS). A program of precision measurements of the analyzing power in np elastic scattering was completed. Measurements of the longitudinal and transverse nuclear response in (p,n) scattering were extended to test models that aimed at explaining the surprising suppression of the longitudinal response. Other measurements in Line X included a study of coherent pion production in the $(p,n\pi^+)$ reaction, a measurement of the analyzing power in np inelastic scattering, and a study of the production of H^0 ions in the interaction of H^- ions with thin foils. The latter measurement is of importance for understanding first-turn beam losses in storage rings.

An experiment to perform a precision measurement of the hyperfine splitting in muonium took data to demonstrate the experimental technique. They achieved the first detection of the "old muonium" line-narrowing technique in a strong magnetic field. The measurements are in accord with expectations and indicate that a precision of 10 ppb can be achieved for the hyperfine interval over the next two years. A group studying muon capture on polarized ^3He demonstrated that their detector is capable of detecting recoil tritons and measuring their direction. This experiment

should yield a precision measurement of the pseudoscalar coupling constant, g_p , in the next year.

An active pion scattering program included a number of experiments studying pion-double-charge exchange (DCX) reactions. These studies yielded information on two-nucleon correlations in nuclei, the role of sequential single-charge exchange in DCX, the energy dependence of the formation of double-giant resonances, and the study of the mass dependence in the production of the double isobaric-analog state. An ambitious experiment studied π^+ elastic scattering from a polarized ^3He target to separate the dependence of the cross section on nuclear structure from the reaction mechanism.

A He-jet target was installed at the beam stop and operated reliably even at high beam currents. The yield of various radioisotopes was measured as a function of the proton beam current. This measurement demonstrated that this technique can be used to provide radioisotopes for a radioactive beam facility and for a planned experiment to measure the level of atomic parity violation for a range of cesium isotopes.

The CYGNUS extensive air shower array continued to operate during this period searching for astrophysical sources of gamma rays above 50 TeV. New limits were set on the emission of high-energy gamma rays from a variety of point sources including active galactic nuclei, primordial black holes, and gamma-ray bursts. This group, augmented by an expanded collaboration, is preparing a new detector, Milagro, to be built in the Jemez Mountains west of Los Alamos. Milagro will be the world's first large-aperture, full duty-cycle detector of 1-TeV astrophysical photons.

LAMPF continues to perform world-class research in an extraordinarily broad program serving a strong, diverse User community. The next year should see exciting new results in neutrino physics, pion single and double charge-exchange scattering, muonium studies, rare muon decays, and muon capture. Even though the nuclear physics research at LAMPF will diminish in scope over the next several years, we anticipate that the first-class facilities here will continue to serve the national nuclear physics program in the years ahead.

CONTENTS

	Foreword.....	v
	<u>Nuclear and Particle Physics Research</u>	1
969	MEGA: Search for the Rare Decay $\mu^+ \rightarrow e^+ \gamma$	3
978	Two-Nucleon Processes in Pion-Induced Double Charge Exchange In ^4He : A Coincidence Measurement of the $^4\text{He}(\pi^+, \pi^-)3p$ Reaction.....	9
1054	A New High Precision Experiment to Measure the Hyperfine Structure Interval and Zeeman Effect of Muonium in its Ground State.....	14
1100	Mass Measurement of Neutron-Rich Isotopes from ^{51}Ca To ^{72}Ni	17
1109	Pion-Induced Fission.....	26
1173	Liquid Scintillator Neutrino Detector	29
1179	The $\pi^+ p \rightarrow \pi^+ \pi^0 p$ Reaction near Threshold: A Study of Chiral Symmetry Breaking	35
1188	Parity Violation in the Compound Nucleus and its Interpretation.....	42
1207	The Nature of $T_{\frac{1}{2}}$ States Observed in DCX on Medium Mass Nuclei.....	46
1209	Energy Dependence Of Double Resonances In Pion DCX.....	49
1216	π^+/π^- Cross Section Ratios in the $(\pi, \pi'p)$ Reaction on ^2H , ^3He , and ^4He	54
1217	Accurate Determination of the $T_{\frac{1}{2}}$ GDR in Light $T = 1/2$ Nuclei	58
1231	Laser Polarized Muonic Atoms and Spin Dependence of Nuclear Muon Capture	63

1240	Measurement of the Michel Parameter ρ with the MEGA Positron Spectrometer.....	71
1245	Pion DCX on Odd Z Nuclei: An Experiment to Clarify Apparent Shell Effects in Dias Cross Sections.....	79
1267	Elastic Scattering of π^+ from Polarized ^3He	82
1268	Measurements of Pion-Nucleon Charge Exchange near the Δ Resonance using the NMS.....	88
1272	Pion Induced Single Charge Exchange in Deuterium.....	93
1286	Study of the Neutron-Neutron Scattering Length using the $^2\text{H}(\pi^-,nn)\gamma$ Reaction	98
1289	The Spin-Flip Electric Dipole in Pion Single Charge Exchange	105
1293	np Elastic Analyzing Power.....	108
1294	Spin Decomposition Of The Giant Resonance Region for the $\text{Ca}(p,n)$ and $\text{Pb}(p,n)$ Reactions at 795 MeV	112
1296	High-Resolution Coincidence Study of $^{12}\text{C}(p,n\pi^+)^{12}\text{C}$	115
1303	A High-Intensity He-Jet Production Source for Radioactive Beams and the Cs-PNC Experiment	121
1309	Analyzing Power for the np Inelastic Channels At 790 MeV: $np \rightarrow NN\pi$	129
<u>Atomic Physics Research</u>		133
1307	Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions	135
<u>Radiation Effects Research</u>		141
1139	Testing of Radiation Resistance of Read-Out Chips and Silicon Detectors for Use in High-Rate Nuclear and Particle Physics Applications.....	143
<u>Materials Science Research</u>		145
1235	Muon Level-Crossing Resonance in Heavily-Doped GaAs:Si..	147

<u>Astrophysics Research</u>	153
High-Energy Gamma-Ray Astronomy: CYGNUS/Milagro Experiments.....	155
<u>Theoretical Physics Research</u>	161
T-5 Theory Group Research Highlights.....	163
<u>LAMPF Publications</u>	187
<u>Operations and Facilities Development</u>	219
Accelerator Operations	221
Linac Beam Energy Measurements.....	226
<u>Appendices</u>	229
Appendix A: Experiments Run in 1992–1993	231
Appendix B: New Proposals in 1992–1993.....	235
Appendix C: LAMPF Committees.....	240

Nuclear and Particle Physics Research

Experiment 969 — SMC

MEGA: SEARCH FOR THE RARE DECAY $\mu^+ \rightarrow e^+ \gamma$

Participants

S. C. Wright, P. S. Cooper, L. Tang, Y. Chen, M. Dziedzic, J. Flick, E. V. Hungerford III, K. Lan, B. W. Mayes II, L. Pinsky, W. von Witsch, J. Knott, K. Stantz, J. Szymanski, J. F. Amann, R. D. Bolton, M. Brooks, S. Carius, M. D. Cooper (Spokesman), W. Foreman, R. Harrison, G. Hart, G. E. Hogan, T. Kozlowski, M. A. Kroupa, D. M. Lee, R. E. Mischke, F. J. Naivar, J. Novak, M. A. Oothoudt, C. Pillai, S. Schilling, J. Sturrock, D. Whitehouse, C. Gagliardi, G. Kim, F. Liu, R. E. Tribble, X. Tu, L. Van Ausdeln, X. Zhou, D. D. Koetke, R. Manweiler, S. Stanislaus, W. Stephens, B. Wright, K. O. H. Ziock, D. Haim, L. E. Piilonen, Y. Zhang, and W. Zhou

Institutions

University of Chicago, Fermilab, Hampton University, University of Houston, Indiana University, Los Alamos National Laboratory, Texas A&M University, Valparaiso University, University of Virginia, and Virginia Polytechnic Institute

The failure to observe processes such as $\mu^+ \rightarrow e^+ \gamma$ has led to the postulation that muon number is conserved. The Standard Model of electroweak interactions builds in this phenomenology. However, there is no physics reason for such a conservation law, and the discovery of this decay would indicate the need for new physics. The MEGA experiment at LAMPF searches for $\mu^+ \rightarrow e^+ \gamma$ with a branching-ratio sensitivity of roughly 5×10^{-13} .

The first data with a partial detector were acquired in 1992. The detector construction was completed in 1993. The year 1993 also marked the first of three years of data-taking needed to reach the expected sensitivity. The data are currently in analysis.

The experimental signature for $\mu^+ \rightarrow e^+ \gamma$ from decays at rest is a positron and photon, each of 52.8 MeV, that are back-to-back, in time coincidence, and originate from a common spatial point. The detector consists of two spectrometers designed to measure the kinematic characteristics of positrons and photons with the hope of matching the above signature. The MEGA apparatus is shown in Fig. 1. The apparatus is contained in a large solenoidal magnet with a 1.5-T field, a clear bore of 1.85 m, and a length of 2.9 m. All of the charged particles arising from muon decay are confined

Fig. 1. A simplified cutaway view of the MEGA apparatus. The detector is mounted inside a superconducting solenoid with a 1.5-T field. The muons enter along magnetic field and stop in the target. Positrons from muon decays are detected in the eight cylindrical wire chambers and the cylindrical arrays of scintillators surrounding the beam pipes. The three large cylinders are pair spectrometers for photon detection.

by the magnetic field to the positron elements, leaving the photon counters in a relatively quiet environment.

The positron arm consists of two parts, scintillators for timing and a set of multi-wire proportional chambers (MWPC) for momentum determination. The 174 scintillators determine the time associated with the positron. The positron spectrometer consists of a cylindrical chamber, one with 11.25-cm radius that surrounds the beam, and seven of 6-cm radius that are colinear and evenly spaced outside the large one. The component of momentum perpendicular to the field is measured by the wire hits, and the parallel component is measured from the induced pulses on the cathodes that contain stripes that spiral relative to the wires.

These chambers, which have a very stringent set of specifications, performed well in the beam. They have a normal thickness of $3 \times 10^{-4} X_0$ because they consist only of inflated foils and wires; their shape is maintained by differential gas pressure. They have operated at 250-MHz instantaneous stop-rate, drawing up to 300 μA of beam-induced current for the better part of a LAMPF running year, without degradation of performance.

The photon arm has three concentric pair-spectrometers of similar construction. Each pair spectrometer is made of lead converters, MWPCs, drift chambers, and scintillators. The inner two have three drift chambers for tracking pairs, and the third one has a bigger turning region for the particles and an extra row of drift chamber wires added to increase the acceptance for high energy gamma rays. The increased capability of the third layer is extremely useful in determining the energy response function from the decay $\pi^0 \rightarrow \gamma\gamma$. If the π^0 is made from stopping pions via $\pi^- p \rightarrow \pi^0 n$, the energies of the two gamma rays range from 55–83 MeV.

The measurement of track coordinates parallel to the axis of the cylinders is made by 1-cm by 180-cm long delay-line strips with a factor of 40 time expansion. The resolution of these delay lines is around 8 mm FWHM and is expected to improve slightly as the analysis techniques improve.

The complete data processing system is assembled. Both first- and second-level trigger modules, utilizing PALs programmed according to Monte Carlo simulations, work well for all three pair spectrometers. The active multiplexing of FASTBUS channels that depends on the geometrical output of the first stage triggers has successfully reduced the accidental backgrounds from low-energy photons to acceptable levels. The full FASTBUS system of ADCs, TDCs, and latches is in use. The routing of both data and busy signals in a trigger dependent way is reliable. The third-level trigger is performing up to requirements and depends on the compute power of an eight-node farm of DECstation 5240s and their 200 MIPS.

The first data to search for $\mu^+ \rightarrow e^+ \gamma$ were taken in 1992 with a partially completed detector and an average muon-stop rate of $5 \times 10^6 \mu/\text{s}$. Most of the beam time was used to shake down the detector, but enough data were taken to roughly match the sensitivity of the current limit for the process. These data are of good quality and will eventually be combined with the larger set from subsequent years.

The fully assembled MEGA apparatus took about 50 days of beam in 1993, split roughly equally between working out problems and collecting data. The average beam intensity for production data was 1.8×10^7 muon-stops per second (average), about 60% of the design. The limiting factors were primary beam intensity and noise in the electron-chamber electronics. The

primary beam will return to full intensity in 1994 with the repairs to the A2-production target. The electron-chamber electronics has been upgraded to reduce the noise that interferes with pattern recognition, but an increase in beam intensity of 20% is the most that is likely to be tolerable. There are about 20% spare CPU cycles in the farm. Software improvements in the third-level trigger are also expected for 1994. The combined effect of all the improvements should yield more efficient running in the future.

An essential feature of the on-line filter (third-level trigger) is that the two spectrometers must be in time with one another. The only direct evidence of this timing is the observation of the allowed process $\mu^+ \rightarrow e^+ \gamma \nu \bar{\nu}$. The clear peak observed in Fig. 2 at a time difference of zero demonstrates that the timing was correctly prepared. The observation of the peak demonstrates that the apparatus can observe a real coincidence process.

During the 25 days of production data taking, MEGA collected about 100 million triggers on tape. These data are currently under analysis. If the analysis efficiency can be kept high, the statistical power of these data

Fig. 2. The timing spectrum that indicates the presence of coincidences of positrons and photons from the expected process $\mu^+ \rightarrow e^+ \gamma \nu \bar{\nu}$.

should allow a factor of 15 improvement in the sensitivity to $\mu^+ \rightarrow e^+ \gamma$. The search with 90% confidence would be improved from 5×10^{-11} to 3.3×10^{-12} .

The primary difficulty in the analysis of these data is the development of reconstruction algorithms that both give high efficiency and good resolution. Many calibrations and detailed corrections are needed to get the design resolutions, and this work is in progress. At our current level of sophistication, the positron and photon spectra are presented in Figs. 3 and 4, respectively. The positron spectrum shows the characteristic normal muon-decay shape (modified by our acceptance) and a 10-90 resolution of around 600 keV. The design anticipated 350 keV, but non-uniformities in the magnetic field have not yet been taken into account. The photon spectrum reproduces a characteristic bremsstrahlung shape with an end point at 52.8 MeV. Refinements in the pattern recognition and quality of fit are expected to improve this spectrum. The photon resolution will be extracted from the above mentioned pion data once the best pattern-

Fig. 3. The Michel spectrum of normal muon decay as measured with the MEGA apparatus.

Fig. 4. The measured photon spectrum from the muon beam. The dominant contribution is from $\mu^+ \rightarrow e^+ \gamma \nu \bar{\nu}$, where only the photon is detected.

recognition program has been found. A substantial part of the full analysis should be complete during the summer of 1994.

The run during the summer of 1994, with the improvements mentioned, is expected to more than double our existing data set. If the beam time is available in 1995, the MEGA apparatus should reach a sensitivity of 7×10^{-13} .

**TWO-NUCLEON PROCESSES IN PION-INDUCED DOUBLE CHARGE
EXCHANGE IN ${}^4\text{He}$: A COINCIDENCE MEASUREMENT OF THE
 ${}^4\text{He}(\pi^+, \pi^-)3p$ REACTION**

Participants

S. F. Pate, W. Fong, M. T. Harvey, J. L. Matthews, H. T. Park,
L. L. Vidos, V. V. Zelevinsky, A. Saunders, M. D. Holcomb, E. R. Kinney,
B. J. Kriss, P. A. M. Gram, and D. A. Roberts

Institutions

Massachusetts Institute of Technology, University of Colorado,
Los Alamos National Laboratory, and University of Michigan

ABSTRACT

Inclusive measurements of pion double charge exchange in ${}^3\text{He}$ [1] and ${}^4\text{He}$ [2] in the $\Delta(1232)$ resonance region suggest the dominance of a two-step sequential single-charge-exchange mechanism involving quasi-free nucleons. To investigate this reaction mechanism, we have observed protons in coincidence with the outgoing pion in $\pi^+ + {}^4\text{He} \rightarrow \pi^- + 4p$ at $T_\pi = 240$ MeV. Pions were detected in a magnetic spectrometer at $\theta_\pi = 32^\circ$, while protons were detected in a close-packed array of plastic scintillator telescopes covering $\theta_p = 67.5^\circ\text{--}157.5^\circ$ on the same side of the beam as the spectrometer, and $\theta_p = 22.5^\circ\text{--}157.5^\circ$ on the opposite side. We will present preliminary results for the distributions in energy and angle of the coincident protons.

Two-nucleon correlations have long been a subject of study in nuclear physics, from the point of view of medium modifications to the NN interaction as well as nuclear structure issues. Two-nucleon processes play a large role in the absorption of photons [3] and pions [4–6] by nuclei. The contributions of these multi-nucleon mechanisms are in many cases difficult to study directly, since these mechanisms are by nature second order and may be obscured by first order processes. Pion-induced double charge exchange (DCX), however, must proceed via interactions with at least two nucleons (since two nucleons must change charge during the reaction) and thus affords the study of two nucleon processes directly.

Over the last decade, the cross section for inclusive DCX has been systematically studied over a range of target mass and beam energy, with emphasis on the energy region near the $\Delta(1232)$ resonance [1,2,7–9]. Several distinct features of these data are worthy of mention. The total cross section for DCX as a function of A obeys a scaling law (a function only

of A and Z) based on competition between DCX and other channels [9]. Only the helium isotopes differ significantly from this scaling behavior. Despite this apparent universality in the total cross section, there is a distinct change in the appearance of differential quantities as a function of A . Figure 1 shows doubly differential cross sections for DCX on ^4He and ^{16}O . Whereas the ^{16}O cross section has a shape consistent with a final state described by four-body phase space (i.e., $\pi^+ + ^{16}\text{O} \rightarrow \pi^- + p + p + ^{14}\text{O}$), the ^4He data are not consistent with any of several phase space descriptions. The behavior of the ^{16}O data are typical of targets heavier than carbon [8], and one sees, with decreasing A , a gradual change to the double-peaked structure of ^4He [7].

Fig. 1. Doubly differential cross sections for the reactions (a) $^4\text{He}(\pi^+, \pi^-)4p$ [2,10] and (b) $^{16}\text{O}(\pi^+, \pi^-)X$ [8] at incident energy 240 MeV and laboratory angle 25° . The dashed and dot-dashed curves in (a) correspond to the distribution of events in five-body and three-body phase space, respectively, while the solid curves in (a) and (b) correspond to four-body phase space.

The double-peaked structure, seen in both helium isotopes [1,2], qualitatively suggests the dominance of a simple two-step mechanism, consisting of sequential single-charge-exchange (SCX) reactions. In the vicinity of the $\Delta(1232)$ resonance, the SCX cross section will resemble the p -wave $1+3\cos^2\theta$ dependence. At forward angles, DCX events resulting from two large-angle, or two small-angle, SCX events will be favored, resulting in the double-peaked energy spectra observed. To investigate this mechanism in more detail is the purpose of the present investigation. We have chosen to detect recoiling protons resulting from ${}^4\text{He}(\pi^+, \pi^-)4p$ in a large solid-angle scintillator array, in coincidence with the outgoing pion. This will enable us to identify the contribution of such sequential SCX processes by observing the kinematic signature of each event in more detail.

The experiment was performed at the Clinton P. Anderson Meson Physics Facility (LAMPF) on the "P³W" pion beam channel. The beam from the channel was directed onto a 25.4-mm-diameter cylindrical liquid helium cell. Outgoing negative pions were detected at $\theta_{\pi^-} = 32^\circ$ in a magnetic spectrometer. The focal plane readout of this spectrometer [1,2,7,8] consisted of wire chambers for tracking, along with a scintillator and Čerenkov detectors for particle identification. Coincident protons were detected in an array of 15 scintillator telescopes (see Fig. 2). The thicknesses of the scintillators in a telescope were, successively, 1, 25, 75, 75, and 75 mm. Only the telescopes at the forward angles had five elements. Those telescopes with four (five) elements could stop protons of 150 (200) MeV, while the lowest detectable proton energy was about 20 MeV (due largely to energy losses in the helium target). The solid angle of each proton telescope was 100 msr.

The solid angle of the spectrometer was measured by observing pions elastically scattered from hydrogen nuclei in a 25.4-mm-diameter cylinder of CH positioned below the helium cell—this CH target was accessed by raising the cryogenic target arm within the scattering chamber. An angular distribution of such data also served to calibrate the in-beam ion chamber which measured the flux of beam particles.

Figure 3 shows some preliminary results. In addition to the coincidence data of interest, we also collected an inclusive sample at $\theta_{\pi^-} = 32^\circ$ for T_{π^-} from 30 to 190 MeV [Fig. 3(a)]. We selected two points in this distribution at which to take coincidence data, near the peaks of the low- and high-energy structures, $T_{\pi^-} = 45$ and 135 MeV. One result of those data is shown in Fig. 3(b), an angular distribution of coincident protons, for $T_{\pi^-} = 45$ MeV. The analysis of the coincidence data is well under way.

Fig. 2. Scale rendering of the experimental setup.

Fig. 3. Preliminary results: (a) Inclusive yield for $^4\text{He}(\pi^+, \pi^-)$ at $T_{\pi^+} = 240$ MeV and $\theta_{\pi^-} = 32^\circ$. The arrows indicate the energies at which the coincidence data were taken. (b) Angular distribution of coincident protons for $T_{\pi^-} = 45$ MeV. Positive proton angles are on the same side of the beam as the pion spectrometer.

References

1. M. E. Yuly, Los Alamos National Laboratory report LA-12559-T, 1993.
2. E. R. Kinney, Los Alamos National Laboratory report LA-11417-T, 1988.
3. J. L. Matthews, in *Nuclear Physics with Electromagnetic Interactions*, H. Arenhövel and D. Drechsel, eds. (Springer-Verlag, Berlin, 1979), p. 339.
4. P. Weber, G. Backenstoss, M. Izycki, R. J. Powers, P. Salvisberg, M. Steinacher et al., *Nucl. Phys. A* **501**, 765 (1989).
5. L. C. Smith, R. C. Minehart, D. Ashery, E. Piasetzky, M. Moinester, I. Navon et al., *Phys. Rev. C* **40**, 1347 (1989).
6. G. Backenstoss, D. Brodbeck, M. Izycki, P. Salvisberg, M. Steinacher, P. Weber et al., *Phys. Rev. Lett.* **61**, 923 (1988).
7. W. Fong, Ph.D. Thesis, MIT, 1993.
8. S. A. Wood, J. L. Matthews, E. R. Kinney, P. A. M. Gram, G. A. Rebka, Jr., and D. A. Roberts, *Phys. Rev. C* **46**, 1903 (1992).
9. P. A. M. Gram, S. A. Wood, E. R. Kinney, S. Høibråten, P. Mansky, J. L. Matthews et al., *Phys. Rev. Lett.* **62**, 1837 (1989).
10. E. R. Kinney, J. L. Matthews, P. A. M. Gram, D. W. MacArthur, E. Piasetzky, G. A. Rebka, Jr., and D. A. Roberts, *Phys. Rev. Lett.* **57**, 3152 (1986).

Experiment 1054 — SMC

A NEW HIGH PRECISION EXPERIMENT TO MEASURE THE HYPERFINE STRUCTURE INTERVAL AND ZEEMAN EFFECT OF MUONIUM IN ITS GROUND STATE

Participants

M. G. Boshier, D. E. Ciskowski, S. Dhawan, X. Fei, V. W. Hughes,
M. Janousch, K. Jungmann, W. Liu, C. Pillai, R. Prigl, G. zu Putlitz,
W. Schwarz, P. A. Souder, O. van Dyck, X. Wang, K. A. Woodle, and Q. Xu

Institutions

Yale University, Universität Heidelberg, Syracuse University,
Los Alamos National Laboratory, and Brookhaven National Laboratory

Muonium [1] (μ^+e^-), consisting of two leptons, is an ideal atom for testing the quantum electrodynamic theory of the two-body bound state and also the behavior of the muon as a heavy electron. In addition, values for the muon mass and magnetic moment are determined from precise measurements of $\Delta\nu$ and the Zeeman effect of muonium in its ground $1^2S_{1/2}$ state.

The present experimental values for $\Delta\nu$ and for μ_μ/μ_p , the ratio of muon and proton magnetic moments, were measured in a microwave magnetic resonance experiment at the Los Alamos Meson Physics Facility (LAMPF) [2].

$$\Delta\nu_{\text{exp}} = 4\,463\,302.88\,(16)\,\text{kHz}\,(36\,\text{ppb}) \quad (1)$$

$$\mu_\mu/\mu_p = 3.183\,346\,1\,(11)\,(360\,\text{ppb}) \quad (2)$$

Recent calculations [3] of additional higher-order contributions to $\Delta\nu$ provide the current theoretical value:

$$\begin{aligned} \Delta\nu_{\text{th}} &= \Delta\nu_F(1 + \epsilon_{\text{QED}}) + \Delta\nu_{\text{weak}} \\ &= 4\,463\,303.41(1.33)(0.06)(0.17)\,\text{kHz}\,(0.3\,\text{ppm}), \end{aligned} \quad (3)$$

in which the error of 1.33 kHz arises from uncertainty in μ_μ/μ_p , the 0.06 kHz arises from uncertainty in α , and the 0.17 kHz is an estimate of uncalculated QED terms. The small weak interaction contribution $\Delta\nu_{\text{weak}} = 0.07\,\text{kHz}$ is included in Eq. (3). Experimental and theoretical values of $\Delta\nu$ agree well within the relatively larger uncertainty in ν_{th} .

$$(\Delta v_{th} - \Delta v_{exp})/\Delta v_{exp} = (0.12 \pm 0.3) \quad (4)$$

The goals of the new experiment in progress at LAMPF are to measure Δn to 10 ppb and μ_μ/μ_p to 60 ppb, thus reducing the present experimental uncertainties by a factor of about 5. The experimental method is basically the same as the previous experiment. Figure 1 shows our present experimental setup.

Fig. 1. (a) Overall experimental setup. (b) Detail of muonium target.

The increased precision should be achievable due to the following features of the present experiment:

1. Narrower resonance lines due to the use of the old muonium technique, made possible with a chopped muon beam.
2. A muon beam of greater intensity and higher purity, the latter obtained by the use of an $\vec{E} \times \vec{B}$ separator.
3. A magnetic field of 17 kG with improved homogeneity and stability provided by a superconducting MRI magnet.

Experimental checkout and some initial data taking occurred in a short run in the Fall 1993. Resonance lines showing the line narrowing associated with old muonium are shown in Fig. 2. The status of analysis of our initial run will be presented.

Fig. 2. Resonance lines by conventional and old muonium techniques for two Zeeman transitions.

References

1. V. W. Hughes and G. zu Putlitz, *Quantum Electrodynamics*, T. Kinoshita, Ed. (World Scientific, 1990), p. 822.
2. F. G. Mariani et al., *Phys. Rev. Lett.* **49**, 993 (1982).
3. T. Kinoshita, in *Proc. of the International Workshop on Low Energy Muon Science—LEMS'93*, April 1993, Los Alamos National Laboratory report LA-12698-C, p. 168.

**MASS MEASUREMENT OF NEUTRON-RICH ISOTOPES
FROM ^{51}Ca TO ^{72}Ni**

Participants

H. L. Seifert, J. M. Wouters, D. J. Vieira, H. Wollnik, X. G. Zhou,
X. L. Tu, Z. Y. Zhou, and G. W. Butler

Institutions

Justus-Liebig-Universität (FRG), Los Alamos National Laboratory,
and Utah State University

Introduction

Nuclear masses are important in the understanding of nuclei because they embody in a single number the combined effect of nuclear and electrostatic forces. Of special interest are mass comparisons between many isotopes that can highlight subtle changes in nuclear structure that occur from nucleus to nucleus and in testing and improving nuclear mass models where correct mass predictions are of critical importance to nuclear astrophysics. In this article we report on measurements of thirty-nine neutron-rich isotopes from calcium through nickel that include the masses of the most neutron-rich isotopes for these elements determined to date. We also look at a variety of mass difference calculations to study the local nuclear structure of these nuclei, to examine pairing energy systematics, and to ascertain the accuracy of selected mass predictions far from stability. The experiment was performed using the Time-of-Flight Isochronous (TOFI) spectrometer at the Los Alamos Meson Physics Facility (LAMPF), which is described in more detail elsewhere [1].

Results

The results of our mass measurements together with the experimental errors are presented in Ref. [2]. Two observations were noted from these data. First, though this data set agreed well with the previous results of Tu et al. [1], there were significant deviations for the most neutron-rich nuclei of the elements V through Fe with the masses from this work being always more bound. Second a significant discrepancy was observed between these data and several previous mass measurements of ^{68}Ni .

To evaluate the discrepancy between this data set and that of Tu et al. [1], both data sets were analyzed using a series of identical procedures. The key

finding from the analysis is that the present data set is insensitive to the choice of mass-to-charge calibration function while that of Tu et al. is very sensitive. This finding points to a fundamental difference in the data from the two experiments. Figure 1 compares the plots of the differences between the masses as compiled by Audi-Wapstra [3] and the fitted masses. For the present data set, the overall trend of the distribution is smooth; especially noteworthy is the absence of oscillations in the region where most of the unknowns are located ($m/Q = 3.6$ to $m/Q = 4.0$) as opposed to those present in Tu's data. Moreover, the spread of the data within one mass-to-charge line is smaller in the present data set.

Fig. 1. The difference between the measured masses and masses from the Audi-Wapstra mass table [3] for this work (a,c) and for the experiment by Tu et al. [1] (b,d). On the left-hand side (a,b) are the differences for the uncorrected data and on the right-hand side (c,d) are the differences after the nonlinearity corrections and all fits (quadratic for this data set and linear plus the terms Z^2/v^2 and Z^2/N^2 for the data set of Tu et al. [1]) have been applied.

We conclude from the above discussion that the present data set is the superior one because of its intrinsically smaller spread in the critical mass-to-charge region and in single mass-to-charge lines. The consequences of the smaller systematic trends are that the present data are less sensitive to analysis techniques and ultimately, as will be mentioned later, show better agreement with known masses and with mass predictions.

In the case of ^{68}Ni , we find our results are ~ 1.6 MeV less bound than all the previous measurements [4–8] that agree among themselves to within 100 keV. We have carefully examined our ^{68}Ni result, which is comprised of a weighted average measurement of four charge states totaling over 50,000 events, but no inconsistencies are evident. Given the large disagreement with the previous measurements and the unrealistically sharp dip in the S_{2n} trend which our measurement of ^{68}Ni would cause, we conclude that we did not measure the ground state of ^{68}Ni but rather a high-lying, long-lived isomeric state.

There has been considerable interest expressed in ^{68}Ni given its proximity to the $N = 40$ subshell closure. Potential energy surface calculations using both Hartree-Fock-Bogoliubov [4] and folded-Yukawa, single-particle [9] methods strongly suggest the existence of a shape isomer. Measurements of the first excited state of ^{68}Ni ($J^\pi = 0^+$, $E_x = 1.77 \pm 0.03$ MeV) have yielded a lifetime of $211 (+60/-40)$ ns [10]. However, given a transport time through our system of ~ 2 ms, we estimate that less than 0.2% of ^{68}Ni recoils would survive in this isomeric state to be measured. Thus, our data suggest either an erroneous lifetime determination of this isomeric state or the existence of a second, longer-lived (>1 ms) isomeric state with a similar excitation energy. Further isomeric state work in ^{68}Ni appears warranted given this finding.

Discussion

The two-neutron separation energies (S_{2n}) in Fig. 2 show a smooth trend for most of the masses reported here. The region of enhanced binding (~ 1.2 MeV) centered around ^{53}Sc as first reported by Tu et al. [1] is confirmed by this work. In analogy to the enhanced binding energy region observed around ^{31}Na [11], Tu et al. suggest that around ^{53}Sc the binding energy enhancement could arise from the promotion of neutrons out of the normal spherical $1p_{3/2}$ level into the deformed $0g_{9/2} - 1/2[440]$ level. However, unlike the sodium case where the proton $d_{5/2}$ shell was half full so that n - p interactions could exert their maximal effect in promoting this deformation-driven rearrangement, the binding energy enhancement effect seen in neutron-rich scandium isotopes occurs at the beginning of the proton $f_{7/2}$ shell rather than at mid shell. We are intrigued by this idea and encourage theoretical exploration of the enhanced binding noted for ^{51}Ca ,

Fig. 2. The two-neutron separation energy versus the neutron number. The (J) represent previously measured masses [3], (A) are mass values obtained from a weighted average of masses between this work and previous work (see Table 2, Ref. [2]), and (O) are masses from this work only. Mass values that disagreed by more than 2σ from our values were excluded from the averaging with the exception of ^{68}Ni where we excluded our result for ^{68}Ni due to the possibility of a mixed ground state—*isomeric state* mass determination.

$^{52,53}\text{Sc}$, and additional mass, shape, and decay measurements of these nuclei.

A reinvestigation of the neutron-excess dependence of the proton and neutron pairing energies (Δ_n and Δ_p) using the same formalism used in our previous work [1] showed no significant changes, even though the most neutron-rich nuclei have masses that differ by as much as 2 MeV. Additional refits showed that for Δ_n , the neutron-excess dependence

decreases from that of Jensen et al. [12] by using a local Z region without our data and further decreases when either our masses or those of Tu et al. are included (see Table I). For Δ_n , use of the local Z region dramatically reduces the neutron-excess dependence while adding our results slightly increases it. We thus attribute the insensitivity of the results to which set of mass measurements is used to the large error bars of the most deviant measurements. These observations confirm our previous assertion [14] that the natural correlation seen earlier between increasing Z and isospin for isotopes along the valley of β -stability may be due to how the study is done (global versus local) and not to any intrinsic neutron-excess dependence in the pairing energies.

Mass measurements of neutron-rich nuclei starting with isotopes of iron and extending to higher atomic numbers are of special significance to r -process abundance calculations because the single neutron separation energies determine the r -process path. Although our measurements do not extend out to the r -process path, they provide an important constraint for validating mass models used in r -process calculations. Masses are also important in predicting β -decay rates, which are crucial for calculating the relative elemental abundances. In particular, there exists a discrepancy between observed and calculated abundances that might depend on the predicted half-life values being too long [15,16]. We conclude this section with a comparison of our masses to four mass models and with an examination of how β -decay energies calculated from our masses could improve the agreement between predicted and measured half-lives.

The four mass models we consider for evaluation of their predictive ability in this critical mass region are the macroscopic models of Möller-Nix [17] and Tachibana [18], the Jänecke-Masson recalculation of the Garvey-

Table I. Comparison of pairing energy calculations. The fitted functional form, $-\Delta A^{1/3} = a - b I^2$ (where the neutron excess $I = (N - Z)/A$), is taken from Vogel et al. [13]. Z values in brackets refer to $\Delta_p A^{1/3}$ values only. Errors are given in parentheses.

Data	$\Delta_n A^{1/3}$		$\Delta_p A^{1/3}$	
	a	b	a	b
Jensen et al. [12]	7.36	60	7.55	46
Vogel et al. [13]	7.2	44	7.2	44
Known data and this work for $Z = 21(22)-27$:				
w/o Tu et al. and this work	6.35 (0.13)	11 (13)	5.86 (0.17)	33 (12)
Tu et al. [1]	5.94 (0.15)	37 (8)	6.58 (0.12)	11 (9)
This work	5.76 (0.16)	26 (8)	6.54 (0.14)	17 (9)

Kelson mass relations [19], and the extended Thomas-Fermi approach of Aboussir et al. [20]. For the mass measurements, the general agreement between theory and experiment is good, but two regions exist with small systematic deviations (see Fig. 3). The model by Aboussir et al. [20] overpredicts the binding for the neutron-rich isotopes between scandium and vanadium, whereas Jänecke-Masson [19] calculate a less bound nucleus for all but one (^{43}Ti) of the last few neutron rich isotopes between calcium and manganese. All models systematically predict more bound masses for $^{63-68}\text{Co}$ than our measurements indicate. Finally, the growing systematic discrepancies with increasing neutron number are no longer evident, as observed in the work by Tu et al. [1] for the vanadium through iron region.

For the half-lives, we use the predictions of Tachibana [21] and Staudt [22] and the measurements of Bosch [15] and Bernas [30]. The Q_β -values from our masses agree well (within 1 MeV) with those calculated by Tachibana [21] for his half-life predictions. In the case of Staudt [22], who uses three different mass models (Hilf [23], von Groote [24], and Möller-Nix [25]), the Q_β -values are too small in the Hilf and von Groote mass predictions. Even so, use of the newly measured masses does not significantly improve the agreement between the calculated and measured half-lives. Bosch et al. [15] found in their r -process network calculations that even the shorter experimental half-lives cannot resolve the observed discrepancy between calculated and measured abundances. One possible suggestion they make to resolve this discrepancy is that in addition to the explosive helium burning site in a type II supernova, a site with significantly higher neutron density is required to reproduce the observed r -process abundance peak at $A \approx 80$. A different suggestion made by Möller and Nix [26] is that the knowledge of the nuclear ground state decay may not be enough to calculate r -process abundances because the β -decay half-life in a high-temperature environment can be drastically different for nuclei with low-lying isomeric states.

Summary

We have measured the masses of 39 neutron-rich nuclei. The comparison with theoretical mass calculations showed good agreement between experiment and theory, increasing our confidence in the use of these models for r -process calculations. However, using our masses for improved half-life predictions does not significantly alter the existing half-life predictions and thus is not sufficient to resolve discrepancies in relative abundances noted between theory and experiment. A few local deviations between our masses and theory are found, the most notable being in the neutron-rich scandium region. These deviations further support the S_{2n} trend, which suggests a region of enhanced binding centered around ^{51}Ca and $^{52,53}\text{Sc}$. The low binding energy of ^{68}Ni from our measurement suggests the presence of a high-lying, long-lived isomeric state in this

Fig. 3. Comparison of experimental masses and mass predictions from the mass models of Möller-Nix [17], Tachibana et al. [18], Jänecke-Masson [19], and Aboussir et al. [20].

nucleus. Finally, some systematic discrepancies with the previous work by Tu et al. [1] are observed with the remeasurements generally giving more bound masses. We have higher confidence with the present measurements because of the independence of the masses to the particular analysis techniques used and the lack of significant systematic dependencies.

This research was funded by the Department of Energy. The authors would like to thank P. Möller for his comments and suggestions.

References

1. X. L. Tu et al., *Z. Phys. A—Atomic Nuclei* **337**, 361 (1990).
2. H. L. Seifert et al., *Z. Phys. A—Atomic Nuclei*, in press (1994).
3. G. Audi and A. H. Wapstra, Interim atomic mass adjustment, June 1989, private communication.
4. M. Girod et al., *Phys. Rev. C* **37**, 2600 (1988).
5. T. S. Bhatia et al., *Z. Phys. A—Atoms and Nuclei* **281**, 65 (1977).
6. M. Bernas et al., *Phys. Rev. C* **24**, 756 (1981).
7. M. Bernas et al., *Phys. Lett. B* **113**, 279 (1982).
8. R. Haupt et al., *Z. Phys. A—Atoms and Nuclei* **317**, 193 (1984).
9. P. Möller, May 1993, private communication.
10. M. Bernas et al., *J. Phys. Lett.* **45**, L-851 (1984).
11. X. G. Zhou et al., *Phys. Lett. B* **260**, 285 (1991).
12. A. S. Jensen, P. G. Hansen, and B. Jonson, *Nucl. Phys. A* **431**, 393 (1984).
13. P. Vogel, B. Jonson, and P. G. Hansen, *Phys. Lett. B* **139**, 227 (1984).
14. J. M. Wouters et al., *Proc. of the Sixth International Conference on Nuclei Far From Stability and the Ninth International Conference on Atomic Masses and Fundamental Constants*, Bernkastel-Kues, R. Neugart and A. Wöhr, Eds. *Institute of Physics Conference Series Number 132*, 25 (1993).
15. U. Bosch et al., *Phys. Lett. B* **164**, 22 (1985).
16. M. Bernas et al., *Z. Phys. A—Atomic Nuclei* **336**, 41 (1990).
17. P. Möller, R. J. Nix, W. D. Myers, and W. J. Swiatecki, *At. Data Nucl. Data Tables*, 1994, to be published.
18. T. Tachibana, M. Uno, M. Yamada, and S. Yamada, *At. Data Nucl. Data Tables* **39**, 251 (1988).
19. J. Jänecke, and P. J. Masson, *At. Data Nucl. Data Tables* **39**, 265 (1988).
20. Y. Aboussir, J. M. Pearson, A. K. Dutta, and F. Tondeur, F., *Nucl. Phys. A* **549**, 155 (1992); Y. Aboussir, J. M. Pearson, A. K. Dutta, and F. Tondeur, *At. Data Nucl. Data Tables*, 1994, to be published.
21. T. Tachibana, M. Yamada, and Y. Yoshida, *Prog. Theor. Phys.* **84**, 641 (1990).
22. A. Staudt, E. Bender, K. Muto, and H. V. Klapdor-Kleingrothaus, *At. Data Nucl. Data Tables* **44**, 79 (1990).

23. E. R. Hilf, v. H. Groote, and K. Takahashi, CERN Report 76-13, 142 (1976).
24. v. H. Groote E. R. Hilf, and K. Takahashi, *At. Data Nucl. Data Tables* 17, 418 (1976).
25. P. Möller and J. R. Nix, *At. Data Nucl. Data Tables* 26, 165 (1981).
26. P. Möller et al., in *Proc. of the First Symposium on Nuclear Physics of the Universe*, Oak Ridge, Tennessee, 1992, M. R. Strayer, Ed. (IOP Publishing, 1993), p. 433.

Experiment 1109 — P3

PION-INDUCED FISSION

Participants

R. J. Peterson (Spokesman), S. deBarros (Spokesman), I. deSouza, M. Gaspar, H. A. Khan (Spokesman), N. A. Khan, and S. Mansoor

Institutions

University of Colorado, Federal University of Rio de Janeiro,
and Pakistan Institute for Nuclear Science and Technology

Cross sections for pion-induced fission have been obtained with solid state nuclear track detectors (SSNTD) to register the fragments. Their high sensitivity to fission events allows the study of small cross sections for light targets, while their low sensitivity to lightly ionizing events allows detectors and targets to be placed directly together in the LAMPF pion beams. Simultaneous exposures of several targets in a stack make relative cross sections particularly reliable. Some of these data have been presented for positive beams at 80 and 100 MeV [1-4] and with both signs at 131 and 138 MeV [5]. Here, further results from the exposures of Refs. [1-5] are presented, taken with the pion beams from LEP. We also report data at higher π^- beam energies from P³, using the methods of Ref. [5] and at several π^- energies with EPICS, exactly as carried out for Ref. [5].

The SSNTD material was in direct contact on both sides of the target for the 80- and 100-MeV exposures, analyzed in Pakistan. Measurements of the positions of the tracks on both sides allowed determination of binary and ternary events. Since the angular distributions were found to be nearly isotropic and tracks were nearly back-to-back [1,6], measurements of tracks in only one SSNTD sheet can be used to give reliable cross sections as in Ref. [5], analyzed in Brazil.

Data for heavy targets at 80 and 100 MeV mostly used mica SSNTD material, with development to register events with $Z > 16$ and $Z/\beta > 400$ to define 'fission' events [1,2]. The fragment mass data of Ref. [1] show these criteria to encompass the events fully. Data with CR39 and CN85 are added to the present work for lighter targets; these materials are sensitive to a lighter range of fragments but gave consistent yields. For Fe and Cu, CR39 with the lowest threshold was able to register fragments with Z/β no less than 60.

At all other beam energies the SSNTD material was makrofol. Comparison to tracks from spontaneous fission in the same material led us to define

'fission' events to be those above $5\ \mu$ in length for thick targets of Bi and Sn, and $7\ \mu$ for thin actinide samples [5].

Beam normalization was accomplished by the counts in an ion chamber in the beam just before or just after the samples. Absolute beam fluences (π/cm^2) were determined by comparing ion chamber readings to absolute production rates of ^{11}C in plastic scintillator disks approximately the same size as the targets, and much smaller than the beam spots, using the cross sections of Ref. [7] and absolute counting of the decays with the INC facilities.

These cross sections have been converted to fission probabilities P_f by dividing them by reaction cross sections computed by a standard DWIA code [8]. Results for pion beam energies from 80 to 138 MeV with both beam signs are collected in Fig. 1. These are far above the fission probabilities observed for stopped π^- for the lighter nuclei [9]. The target-dependent axis is taken to be the fissility for the initial target plus the pion beam charge, that is $f = (Z \pm 1)^2/A$. In the region near lead where the probabilities are dropping steeply, this plot indicates that the fissioning system retains the effect of the initial pion charge.

Fig. 1. Fission probabilities for both signs are collected for 80, 100, 131, and 138 MeV for a wide range of nuclear targets, using the fissility of the target plus the pion beam sign. Some of these data have been published in [1-5]. The curve is a fit to the parameterization given in the text to characterize all energetic pion fission probabilities below resonance energy.

We parameterize this mass dependence for both signs of energetic pions below resonance and for fissilities f above 15 by the form:

$$P_f = A + B[1 + \exp((f_0 - f)/d)]^{-1},$$

with the fissility midpoint $f_0 = 35.12$ and the transition region $d = 0.9215$. The binary fission probability saturates with $B = 0.999$ and does not fall below a value determined by $A = 0.00133$. The parameterized fit shown is a convenient summary of a very wide range of energetic pion-induced binary fission probabilities.

Data are still being analyzed for both pion signs at 150 MeV for a detailed array of isotopically enriched targets near doubly-magic ^{208}Pb , to see if the local maximum in the fission barriers has any influence on the fission rates. Data for π^- at 350 and 500 MeV for a wide range of target masses are also being analyzed, to see if the higher energy will increase the trend seen in the figure for pions below resonance. A few preliminary data points at 500 MeV indicate that P_f for Sn is only slightly above the trend found at lower energies, as evidence of a saturation in the nuclear excitation provided by energetic pions.

References

1. H. A. Khan, N. A. Khan, and R. J. Peterson, *Phys. Rev. C* **35**, 645 (1987).
2. H. A. Khan, N. A. Khan, and R. J. Peterson, *Nucl. Instrum. Methods B* **51**, 421 (1990).
3. H. A. Khan, N. A. Khan, and R. J. Peterson, *Phys. Rev. C* **43**, (1991) 250.
4. H. A. Khan and R. J. Peterson, in *Proc. of the 14th International Conference on SSNTD*, unpublished (Lahore, Pakistan) 1988.
5. S. deBarros, I. O. deSouza, M. Gaspar, and R. J. Peterson, *Nucl. Phys. A* **543**, 511 (1992).
6. K. H. Hicks et al., *Phys. Rev. C* **31**, 1323 (1985).
7. B. J. Dropesky, G. W. Butler, C. J. Orth, R. A. Williams, M. A. Yates-Williams, G. Friedlander, and S. B. Kaufman, *Phys. Rev. C* **20**, 1844 (1979).
8. DWPI, a coordinate space optical model for pions, R. A. Eisenstein and G. A. Miller, *Comput. Phys. Commun.* **11**, 95 (1976).
9. Y. A. Batusov, Z. Ganzorg, O. Otgonsuren, and D. Chulten, *Yad. Fiz.* **23**, 1169 (1976) [*Sov. J. Nucl. Phys.* **23**, 621 (1977)].

LIQUID SCINTILLATOR NEUTRINO DETECTOR

Participants

K. McIlhany, I. Stancu, W. Strossman, G. J. VanDalen, D. Evans, W. Vernon, D. Bauer, D. Borden, D. Caldwell, A. Lu, S. Yellin, B. Homann, R. Knoesel, D. Smith, A. Eisner, M. Sullivan, Y. Wang, G. Anderson, I. Cohen, D. Schnitzler, C. Starr, R. D. Bolton, R. Burman, J. Donahue, F. Federspiel, G. T. Garvey, T. Kozlowski, W. C. Louis, V. Sandberg, M. Schillaci, L. S. Weaver, D. H. White, D. Whitehouse, D. Wilkinson, R. Imlay, W. Metcalf, R. M. Gunasingha, C. Ausbrooks, B. Bisbee, B. Boyd, K. Johnston, M. Strickland, B. B. Dieterle, G. George, R. Reeder, M. Albert, J. Hill, A. K. Mann, A. Fazely, T. Phan, C. Athanassopoulos, L. B. Auerbach, V. Highland, J. Margulies, D. Works, and Y. Xiao

Institutions

UC Riverside, UC San Diego, UC Santa Barbara, Embry-Riddle Aeronautical University, University of California IIRPA, Linfield College, Los Alamos National Laboratory, Louisiana State University, Louisiana Tech University, University of New Mexico, University of Pennsylvania, Southern University, and Temple University

The LSND experiment has been designed and built to search concurrently for $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations with high sensitivity at LAMPF. The observation of neutrino oscillations would have a profound impact on nuclear, particle, and astrophysics, as it would imply that lepton number is not conserved and that neutrinos have mass and contribute substantially to the mass of the universe. In addition, the experiment will measure neutrino-proton elastic scattering and thereby determine $G_1^s = \Delta s$, the strange quark contribution to the proton spin. At low Q^2 the neutrino-proton elastic scattering cross section is approximately proportional to $G_1^2 = (-0.63 + G_1^s/2)^2$, so that a cross section measurement directly determines G_1^s unambiguously without additional assumptions. Other physics goals include measurements of νC charged-current scattering, $\nu C \rightarrow \nu C^*$ (15.11-MeV γ) inelastic scattering and $\nu e \rightarrow \nu e$ elastic scattering.

The detector is shown in Fig. 1 and consists of a cylindrical tank approximately 8.5 m long by 5.5 m in diameter. On the inside surface of the tank are mounted 1220 8-inch Hamamatsu phototubes, 25% of the surface area is covered by photocathode, and the tank is filled with 51,000 gallons (180 tons) of liquid scintillator consisting of mineral oil and 0.031 g/l of b-PBD. The

Fig. 1. A schematic drawing of the Liquid Scintillator Neutrino Detector, which consists of a cylindrical tank approximately 8.5 m long by 5.5 m in diameter. On the inside surface of the tank are mounted 1220 8-inch Hamamatsu phototubes, and the tank is filled with 51,000 gallons (180 tons) of liquid scintillator consisting of mineral oil and 0.031 g/l of b-PBD.

low scintillator concentration allows the detection of both Čerenkov light and scintillation light and yields a relatively long light attenuation length of more than 20 m for wavelengths greater than 400 nm. Surrounding the detector tank is a liquid scintillator veto shield that tags cosmic muons that pass through the detector. A typical 45-MeV electron created in the tank produces about 370 Čerenkov photoelectrons and 1115 scintillation photoelectrons (~ 33 photoelectrons per MeV) and can be reconstructed with a position resolution of ~ 25 cm, an angular resolution of $\sim 15^\circ$, and an energy resolution of $\sim 6\%$. A typical 45-MeV proton created in the tank produces about 500 scintillation photoelectrons and can be reconstructed with a position resolution of ~ 25 cm and an energy resolution of $< 10\%$ [1]. In addition, excellent particle identification is obtained for particles above and below Čerenkov threshold through the fit to the Čerenkov cone and from the time distribution of the scintillation light, which is relatively slower for particles below Čerenkov threshold [1]. The probability that a neutron or proton satisfies the electron particle identification criteria is about 10^{-3} . Figure 2(a) shows the energy distribution for a sample of Michel electrons from cosmic muon decays in the tank, from which is obtained the energy calibration. The end-point energy resolution is 6.0%.

The detector is located at a mean distance of 29 m from the A6 LAMPF beam stop and at an average angle of 12° relative to the incident proton direction. The beam stop consists of a 20-cm water target positioned 1 m upstream of a water-cooled Cu beam dump. Approximately 20% of the protons in the LAMPF beam interact in the upstream targets A1 and A2, located 120 m and 100 m from the detector, allowing 80% of the LAMPF beam to interact at A6. The neutrinos arise from pion and muon decay and

Fig. 2. (a) The energy distribution for a sample of Michel electrons from cosmic muon decays in the tank, from which is obtained the energy resolution and calibration. The end-point energy resolution is about 6%. (b) The electron energy distribution from muon decay, where the muons are produced by $\nu_\mu C \rightarrow \mu^- X$ scattering. Approximately 250 events have been collected, from which will be obtained the first accurate measurement of $\nu_\mu C$ charged-current scattering near threshold.

can be separated into two different types—those from decay in flight and those from decay at rest. The muon decay-at-rest neutrino energy spectrum has a maximum energy of 52.8 MeV, while the pion decay-in-flight spectrum has an average energy of 100 MeV with an energy tail extending beyond 250 MeV. As π^- produced in the beam stop are strongly absorbed, the decay-at-rest neutrino flux is almost entirely due to ν_μ from π^+ decay and $\bar{\nu}_\mu$ and ν_e from μ^+ decay. The neutrino flux is calculated from measured pion cross sections,² and the uncertainty in the decay-at-rest and decay-in-flight neutrino fluxes are estimated to be 7% and 12%, respectively.

The LSND detector was completed during the past year, and the experiment began data collection in late August 1993 and took data smoothly through the September and October running periods. The integrated number of protons on the A6 target during this interval corresponds to about 2000 Coulombs. The trigger rate averaged 35 Hz during the run and resulted in 150 million total triggers written on 200 8-mm tapes (or approximately 1 TB of data). The average proton intensity at the A6 beam stop was $\sim 700 \mu\text{A}$, resulting in a total decay-at-rest neutrino flux of $9 \times 10^{12} \nu/\text{cm}^2$ at the center of the tank, and the average beam duty factor was 7%. The primary trigger threshold was 100 hit phototubes in a 200-ns interval; however, this threshold was lowered to 21 hit phototubes for a period of 1 ms following energetic events with > 300 hit phototubes in order to trigger on 2.2 MeV γ from neutron capture on free protons. In addition, all activities with > 17 hit detector phototubes or > 5 hit veto phototubes within 50 μs of a primary event were triggered. Furthermore, there were no primary triggers for a period of 15 μs following veto shield events with > 5 hit veto phototubes in order to reject both cosmic muons and their decay electrons.

Several publications are expected to result from the 1993 data sample. Figure 2(b) shows the electron energy distribution from muon decay, where the muons are produced by $\nu_\mu C \rightarrow \mu^- X$ scattering. Approximately 250 events have been collected, from which will be obtained the first accurate measurement of $\nu_\mu C$ charged-current scattering near threshold. Preliminary results indicate that the cross section is half that expected from the Fermi-Gas model.³ Figure 3(a) shows the electron energy distribution from $\nu_e C \rightarrow e^- N$ scattering, $\nu e \rightarrow \nu e$ elastic scattering, and $\nu C \rightarrow \nu C^*$ (15.11-MeV γ) inelastic scattering (electrons cannot be distinguished from photons in the detector), and as shown in the figure, the observed number of events agrees with the expected number. Figure 3(b) shows the same events plotted versus $\cos \theta$, where θ is the angle between the electron direction and the incident neutrino direction. A clear excess due to $\nu e \rightarrow \nu e$ elastic scattering is observed near $\cos \theta = 1$. In addition, excellent sensitivity for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations has been obtained with a total estimated background of about 10^{-3} in mixing probability, and a sample of about 100 νp elastic events has been observed.

Fig. 3. (a) The electron energy distribution from $\nu_e C \rightarrow e^- N$ scattering, $\nu e \rightarrow \nu e$ elastic scattering, and $\nu C \rightarrow \nu C^*$ (15.11-MeV γ) inelastic scattering (electrons cannot be distinguished from photons in the detector). (b) The same events plotted versus $\cos \theta$, where θ is the angle between the electron direction and the incident neutrino direction. A clear excess due to $\nu e \rightarrow \nu e$ elastic scattering is observed near $\cos \theta = 1$.

The LSND collaboration is looking forward to the 1994 and 1995 running periods, which should increase the data sample by close to an order of magnitude. With sufficient running time, the experiment should reach its goals of a 2×10^{-4} sensitivity for neutrino oscillations and a 10% measurement of neutrino-proton elastic scattering, which will determine $G_1^e = \Delta s$ to about 0.04. In addition, the experiment will make the world's best measurements of $\nu_\mu C$ scattering and $\nu_e e$ elastic scattering.

References

1. R. A. Reeder, B. D. Dieterle, C. Gregory, F. Schaefer, K. Schum, W. Strossman et al., *Nucl. Instrum. Methods A* **334**, 353 (1993).
2. R. L. Burman, M. E. Potter, and E. S. Smith, *Nucl. Instrum. Methods A* **291**, 621 (1990).
3. T. K. Gaisser and J. S. O'Connell, *Phys. Rev. D* **34**, 822 (1986).

**THE $\pi^+ p \rightarrow \pi^+ \pi^0 p$ REACTION NEAR THRESHOLD:
A STUDY OF CHIRAL SYMMETRY BREAKING**

Participants

D. Počanić, E. Frlež, K. A. Assamagan, J. P. Chen, K. J. Keeter,
R. M. Marshall, R. C. Minehart, L. C. Smith, G. E. Dodge, S. S. Hanna,
B. H. King, and J. N. Knudson

Institutions

University of Virginia, Stanford University,
and Los Alamos National Laboratory

ABSTRACT

We have measured total cross sections for the reaction $\pi^+ p \rightarrow \pi^+ \pi^0 p$ at incident pion kinetic energies of 190, 200, 220, 240, and 260 MeV. We use this result to deduce a new value of the chiral symmetry breaking parameter, $\xi = -0.25 \pm 0.10$, in a global constrained fit of the five $\pi\pi N$ near-threshold amplitudes, within the framework of the Olsson-Turner model. Consequently, we report new soft pion model values for the s -wave $\pi\pi$ scattering lengths.

Motivation

Chiral symmetry is essential to the understanding of the lightest hadrons, and it provides the framework for all low-energy effective Lagrangian models, e.g., the chiral perturbation theory (ChPT) [1], and recent QCD formulations of the Nambu-Jona-Lasinio model in SU(2) and SU(3) flavor space (for a comprehensive recent review see [2]). The $\pi\pi$ system at zero momentum is particularly suitable for studying of chiral symmetry breaking, since $\pi\pi$ scattering lengths vanish in the chiral limit [3]. Early models of chiral symmetry breaking gave predictions of $a_0^{0,2}(\pi\pi)$, the $I = 0, 2$ s -wave scattering lengths, based mainly on current algebra and PCAC [3–5]. Using soft-pion theory, Olsson and Turner [6] parameterized the different predictions in terms of ξ , a single chiral symmetry breaking parameter. More recent calculations of $\pi\pi$ scattering lengths include the work of Jacob and Scadron [7], Gasser and Leutwyler [8] (ChPT), Ivanov and Troitskaya [9] (model of dominance by quark loop anomalies, QLAD), and Roberts et al. [10] (the “Global Color-symmetry Model”).

Aside from the decay $K^- \rightarrow \pi^- \pi^+ e^- \bar{\nu}$, all of the information on the $\pi\pi$ interaction has been extracted from studies of the $\pi N \rightarrow \pi\pi N$ reactions. In particular, the past few years have brought about a number of measure-

ments of the $\pi N \rightarrow \pi\pi N$ reactions close to threshold [11–13]. Burkhardt and Lowe [14] recently performed a comprehensive soft-pion analysis of the existing $\pi\pi N$ data, producing a consistent global solution for the isospin amplitudes, and, hence, a new value for ξ . Arguably, the biggest deficiency in the data set was due to the scarce $\pi^+\pi^0 p$ data. Unlike the other channels, only a handful of $\pi^+ p \rightarrow \pi^+\pi^0 p$ events had been recorded below 300 MeV, providing a poor constraint on the global solution.

In LAMPF Exp. 1179, we studied the $\pi^+ p \rightarrow \pi^+\pi^0 p$ channel in the region of incident pion kinetic energy from 190 to 260 MeV (the threshold is at 164.8 MeV). Our purpose was twofold: (i) to extract the angle-integrated cross sections needed for a comprehensive soft-pion analysis, and (ii) to measure exclusive cross sections with sufficiently high accuracy and phase-space coverage to allow a model-independent $\pi\pi$ phase shift analysis. We report below the measured integrated cross sections and their soft-pion analysis.

Experimental Method

Our measurements were performed at the Low Energy Pion beam-line of the Los Alamos Meson Physics Facility. Pion beams with momentum spread $\Delta p/p = \pm(0.15\text{--}0.2)\%$ were focused on a specially constructed thin-walled liquid hydrogen target. Beam charge was monitored by means of a sealed ion chamber and a current integrator. Almost all protons were removed from the beam by means of a thin degrader at the beam focal point in the middle of the beam line. For each beam energy, a residual proton contamination of 0.2–0.7% was measured by varying the central momentum of the beam line bending magnets downstream of the degrader. Pion content of the beam was determined by activation of ^{11}C in plastic scintillator disk detectors [15]. Long-term reproducibility of this method was about $\pm 2\%$ or better, while the π^+ activation cross sections carry uncertainties of 0.9–4% [15].

Neutral pion decays were detected in the LAMPF π^0 spectrometer [16]. Protons and charged pions were detected in a specially constructed 14-telescope array of plastic scintillator detectors. Each telescope included at least one thin (3 mm) and one thick (25 mm) ΔE counter, as well as a full absorption counter capable of stopping the pions allowed by the kinematics of our reaction. Six telescopes positioned at $\theta_{\text{lab}} \geq 40^\circ$ subtended a larger solid angle than the remaining eight. In order to maintain uniform angular resolution, we arranged the thin and thick ΔE counters on each of the six telescopes into a 4×2 hodoscope. In all, 56 distinct angular bins were covered simultaneously.

Efficiency of the π^0 spectrometer was determined in a series of measurements using the pion charge exchange reaction at $T_{\pi}^{\text{lab}} = 30$ MeV on a CH_2

target, and studying the spectrometer response to penetrating cosmic muons. Individual efficiencies were measured for every detector in the spectrometer, and the entire π^0 spectrometer assembly was simulated with Monte Carlo code GEANT3 [17]. The overall uncertainty in the efficiency, $\pm 4\%$, is dominated by the shower tracking efficiency uncertainty (3%). We determined the thickness of our liquid hydrogen target to 3% accuracy by comparing the charge exchange yield at 30 MeV with the yield from a known CH_2 target. We determined the efficiency of the charged particle detectors by detecting elastically scattered π^+ and protons in a separate, prescaled trigger, throughout the experiment. This trigger also served as an on-line monitor of the liquid hydrogen target thickness.

We detected and recorded $\pi^0\pi^+$ and π^0p coincident events, as well as the triple coincidences, $\pi^0\pi^+p$. Detector acceptances, particle kinematics and background sources for the three types of events were very different. Thus, the three sets of data had to be analyzed separately, and can be regarded as three essentially independent measurements. In this way, the experiment has a built-in consistency check. Acceptances were calculated using a suitably modified version of the PIANG code [18], and checked independently using GEANT3 [17], with excellent agreement. Combining the effects of instrumental resolution and acceptance, charged particle detection thresholds, and target size, we obtain a FWHM of the missing mass spectra of about $30 \text{ MeV}/c^2$ for both $\pi^+\pi^0$ and π^+p events, in excellent agreement with the observed values. In addition, measurements at $T_\pi = 160 \text{ MeV}$ demonstrated that the signal vanished for all three event types below the threshold of π^0 production.

Once the acceptances and resolution functions of our detector system were well understood in terms of realistic Monte Carlo calculations, we proceeded to examine the exclusive angular and invariant mass distributions. Measured distributions of $\theta_{\pi\pi}$, the dipion polar angle, of $m_{\pi\pi}$, the dipion invariant mass, as well as the Dalitz plot, did not show statistically significant departures from pure phase-space distributions [20]. Hence, the evaluation of angle-integrated cross sections from the recorded yields is straightforward.

Final values of angle-integrated cross sections were determined as appropriately weighted averages of the three "independent" measurements: π^0p , $\pi^0\pi^+$, and triple coincidences. In addition to statistical uncertainties, an overall systematic uncertainty of approximately 9% applies to all data points. This uncertainty is due to six approximately equal contributions, associated with the target thickness, incident π^+ normalization, π^0 absorption, π^0 and charged particle detection efficiencies, and detector acceptances.

Results and Discussion

The measured total cross sections are listed in Table I, and plotted against beam energy in Fig. 1(a), which also includes all previously published data in the energy region under study [19,21,11].

Following the method of Olsson and Turner [6], we have extrapolated the moduli of the reaction matrix elements $a(\pi\pi N)$ to zero kinetic energy in the $\pi\pi N$ barycentric system, T^* , for all five charge channels, adding our data to the existing database, and imposing the constraints at $T^* = 0$:

$$a(\pi^+\pi^+n)/2 = -\sqrt{2}a(\pi^\pm\pi^0p) = a(\pi^0\pi^0n) + a(\pi^+\pi^-n).$$

In our analysis we have used $m_\pi = 137.5$ MeV, $f_\pi = 90.1$ MeV, $M = 938.9$ MeV, and $g_A/g_V = 1.29$, as in Ref. [14], and exact relativistic phase space factors to extract the matrix element moduli. We have used the linear energy dependence of the individual amplitudes above threshold. Fig. 1(b) shows the constrained fit of the $\pi^+\pi^0p$ amplitudes (the other four channels display similar agreement). The minimum χ^2 of the global fit is 96 for 93 degrees of freedom [20], resulting in the new value of the chiral symmetry breaking parameter $\xi = -0.25 \pm 0.10$. Within the soft-pion model of Olsson and Turner [6], this fixes the $\pi\pi s$ -wave scattering lengths at:

$$a_0^0(\pi\pi) = 0.177 \pm 0.006 m_\pi^{-1},$$

and

$$a_0^2(\pi\pi) = -0.041 \pm 0.003 m_\pi^{-1}.$$

Table I. Total cross sections of the reaction $\pi^+p \rightarrow \pi^+\pi^0p$ deduced from measurements of $(\pi^0\pi^+)$, (π^0p) , and triple coincidences, respectively, as a function of incident pion energy. The incident energy ranges indicated in the first column correspond to the beam momentum spread. Missing entries in the table correspond to measurements with acceptances too small to allow a statistically significant determination of the cross section after background subtraction. The last column lists the appropriately weighted average values. The quoted cross section uncertainties are statistical. There is an additional overall systematic uncertainty of 9%, which applies to all data points.

T_π^{lab} (MeV)	$\pi^0\pi^+$ $\sigma(\mu\text{b})$	π^0p $\sigma(\mu\text{b})$	$\pi^0\pi^+p$ $\sigma(\mu\text{b})$	Average $\sigma(\mu\text{b})$
259.5 ± 0.7	26.1 ± 3.7	24.8 ± 5.5	27.0 ± 5.4	26.0 ± 2.7
239.5 ± 0.7	15.5 ± 3.7	14.9 ± 4.5	11.1 ± 6.4	14.6 ± 2.6
219.5 ± 0.6	7.0 ± 2.2	—	6.2 ± 3.4	6.8 ± 1.8
199.5 ± 0.6	2.6 ± 1.3	—	2.9 ± 2.9	2.7 ± 1.2
189.5 ± 0.5	1.5 ± 2.1	—	0 ± 3	1.0 ± 1.7

Fig. 1. (a) Total cross sections for the reaction $\pi^+p \rightarrow \pi^+\pi^0p$ as measured in this work (full circles), and as previously published [19,21,11]. Full curve: new global fit of $\pi N \rightarrow \pi\pi N$ isospin amplitudes. (b) Absolute values of the $\pi^+\pi^0p$ matrix element corresponding to the total cross sections shown in (a), as a function of T^* , the total c.m. kinetic energy. Solid and broken lines: global linear fit and the associated uncertainties, respectively.

In conclusion, our total cross sections are close to those measured in the $\pi^-\pi^0 p$ channel [11], which is to be expected near threshold based on symmetry. Inclusion of our data in a global soft-pion fit results in new values of the $\pi\pi$ scattering lengths, which are close to the predictions of Weinberg [3] and ChPT [1]. It will be interesting, however, to compare these soft-pion results with an evaluation of $a_0^{0,2}(\pi\pi)$ free of dynamical model assumptions, following the approach suggested by Bolokhov et al. [22], using the now available exclusive data.

We thank the staff of LAMPF groups MP-7 and MP-8 for strong technical support, without which our measurements would not have been possible. We are particularly indebted to Bob Garcia who was responsible for the liquid hydrogen target design and construction. We gratefully acknowledge the help of T. Averett, L. Suddarth, M. Lesko, and A. Wall, of the University of Virginia in detector assembly and data taking. Our thanks are due to Julian Noble for many useful discussions and for his support of the experiment from the very beginning. We also thank A. Bolokhov for a number of useful discussions. This work was supported by the U.S. National Science Foundation and Department of Energy.

References

1. J. Gasser and H. Leutwyler, *Ann. Phys. (N.Y.)* **158**, 142 (1984); *Nucl. Phys. B* **250**, 465 (1985).
2. S. P. Klevansky, *Rev. Mod. Phys.* **64**, 649 (1992).
3. S. Weinberg, *Phys. Rev. Lett.* **17**, 616 (1966); *Phys. Rev. Lett.* **18**, 188 (1967); *Phys. Rev.* **168**, 1568 (1968).
4. J. Schwinger, *Phys. Lett.* **24B**, 473 (1967).
5. P. Chang and F. Gürsey, *Phys. Rev.* **164**, 1752 (1967).
6. M. G. Olsson and L. Turner, *Phys. Rev. Lett.* **20**, 1127 (1968); *Phys. Rev.* **181**, 2141 (1969), L. Turner, Ph.D. Thesis, University of Wisconsin, 1969 (unpublished).
7. R. Jacob and M. D. Scadron, *Phys. Rev. D* **25**, 3073 (1982).
8. J. Gasser and H. Leutwyler, *Phys. Lett.* **125B**, 325 (1983).
9. A. N. Ivanov and N. I. Troitskaya, *Yad. Fiz.* **43**, 405 (1986) [*Sov. J. Nucl. Phys.* **43**, 260 (1986)].
10. C. D. Roberts, R. T. Cahill, M. E. Sevier, and N. Iannela, Argonne National Laboratory preprint ANL-PHY-7512-TH-93.
11. G. Kernel et al., *Phys. Lett. B* **216**, 244 (1989); *Phys. Lett. B* **225**, 198 (1989); *Z. Phys. C* **48**, 201 (1990); in *Particle Production Near Threshold*, Nashville, 1990, H. Nann and E. J. Stephenson, Eds. (AIP, New York, 1991).
12. M. E. Sevier et al., *Phys. Rev. Lett.* **66**, 2569 (1991).
13. J. Lowe et al., *Phys. Rev. C* **44**, 956 (1991).
14. H. Burkhardt and J. Lowe, *Phys. Rev. Lett.* **67**, 2622 (1991).

15. B. J. Dropesky et al., *Phys. Rev. C* **20**, 1844 (1979); G. W. Butler et al., *Phys. Rev. C* **26**, 1737 (1982).
16. H. W. Baer et al., *Nucl. Instrum. Methods* **180**, 445 (1981).
17. R. Brun et al., GEANT3, publication DD/EE/84-1, CERN, Geneva, 1987.
18. S. Gilad, Ph.D. Thesis, Tel Aviv University, 1979 (unpublished).
19. Yu. A. Batusov et al., *Yad. Fiz.* **21**, 308 (1975).
20. More details of the data analysis can be found in E. Frlež, Ph.D. Thesis, University of Virginia, 1993 (Los Alamos National Laboratory report LA-12663-T, 1993), and D. Počanić et al., *Phys. Rev. Lett.* **72**, 1156 (1994).
21. D. I. Sober et al., *Phys. Rev. D* **11**, 1017 (1975).
22. A. A. Bolokhov, V. V. Vereshchagin, and S. G. Sherman, *Nucl. Phys. A* **530**, 660 (1991).

Experiment 1188 — LANSCE

THE STUDY OF PARITY AND TIME REVERSAL SYMMETRY VIOLATION IN THE COMPOUND NUCLEUS

Participants

J. D. Bowman (spokesman), C. M. Frankle, J. Knudson, R. Mortensen, S. Penttilä, S. J. Seestrom, V. W. Yuan, C. R. Gould, L. Lowie, G. Mitchell, S. Stevenson, N. R. Roberson, B. Crawford, E. I. Sharapov, Yu. Popov, Y. Masuda, H. M. Shimizu, A. Masaïke, Y. Matsuda, M. Iinuma, S. Takahashi, P. P. Delheij, and H. Postma

Institutions

Los Alamos National Laboratory, North Carolina State University,
Duke University, Joint Institute on Nuclear Research (Dubna, Russia),
KEK (Japan), Kyoto University (Japan), TRIUMF,
and Technical University of Delft (The Netherlands)

The aim of this work is to study the violation of fundamental symmetries such as time reversal and parity using the compound nucleus as a laboratory. Highly excited nuclear states of the daughter nucleus are formed when epithermal neutrons are captured by nuclear targets. Because the compound-nuclear levels are closely spaced, small symmetry-violating nuclear interactions can produce large symmetry-violation components in the compound-nuclear wave functions. Symmetry tests can be carried out by observing the dependence of the neutron resonance cross section on neutron spin, neutron momentum, and target spin.

The Los Alamos Proton Storage Ring and Spallation Neutron Source provides the world's most intense source of pulsed neutrons. These neutrons are polarized by passing them through a "spin filter" consisting of a cell of dynamically polarized protons. Since 1990 we have carried out measurements of parity-violating longitudinal asymmetries by measuring the helicity dependence of the resonance part of the total cross section $A_L = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$.

During 1992 and 1993 we made extensive improvements to our apparatus. A new cryogenic "spin filter" was installed that increased the neutron polarization from 25% to 70% and the beam diameter from 4 cm to 8 cm. A new detector for transmitted neutrons, which allowed us to count neutrons at the rate of 500 MHz, was built. A prototype detector for neutron-captured γ rays was built. In order to accommodate the increased beam size, a new spin flipper and a new ^3He ion chamber for neutron flux measurements

were built. Taken together, these improvements reduced the statistical errors in the measurement of parity-violating asymmetries by a factor of 20 in transmission mode measurements. The capture gamma detector allowed the use of isotopically separated targets in capture mode experiments.

As the summer 1993 run began, a number of questions needed to be resolved. Measurements of parity-violating (PV) asymmetries had shown non-statistical behavior. Seven out of seven parity-violating asymmetries measured in ^{232}Th were positive. Furthermore, thirteen out of fifteen asymmetries measured in all nuclei were positive and the positive asymmetries were larger in magnitude than the negative asymmetries. These results called into question the statistical model of the compound nucleus, which predicts that PV asymmetries should have random signs. The twenty-fold improvement in statistical error allowed us to obtain high-quality data for a number of targets. Figure 1 shows the neutron transmission spectrum and the PV transmission asymmetry for the 63.5-eV p -wave resonance in ^{238}U vs. neutron time of flight. The much stronger 65.0-eV s -wave resonance occurs to the left of the weak p -wave resonance. The large PV asymmetry results from the admixture of the strong nearby s -wave resonance into the weak p -wave resonance by the parity-violating nuclear interaction. The statistical error in the PV asymmetry is less than 1%.

Fig. 1. Plot of neutron yield and neutron yield asymmetry $[(Y_+ - Y_-)/(Y_+ + Y_-)]$ vs. neutron time of flight.

The data from the summer 1993 run are now being analyzed, but preliminary results are available. The sign tendency of PV asymmetries in ^{232}Th has been confirmed. Eight out of eight asymmetries that are non-zero with greater than 3 standard deviation statistical significance are positive. The probability of this occurring by chance is $2^{-7} = 0.8\%$. However, PV asymmetry measurements carried out in other targets show random signs. Table I summarizes the signs of measured asymmetries.

Table I. Summary of the signs of measured asymmetries.			
Nucleus	$A > 0$	$A < 0$	Technique
^{232}Th	8	0	Transmission
^{238}U	3	2	Transmission
^{133}I	0	1	Transmission
^{115}In	2	1	Transmission
^{113}Cd	2	1	Capture γ
$^{107,109}\text{Ag}$	5	4	Transmission

These data place severe constraints on models that attempt to understand the tendency of PV asymmetries in ^{232}Th to have a common sign. The phenomenon is not universal but is apparently restricted to ^{232}Th . All models proposed so far, based on single-particle components in the nuclear wave function [1], spin-flip dipole doorway states [2], and weak optical models [3], predict that the phenomenon should be universal. The most likely explanation seems to be that a pair of nearby doorway states is involved. These states must have opposite parity, be nearly degenerate, and be weakly coupled to the compound nuclear resonances.

The second contribution of the 1993 data is to demonstrate that PV is a universal phenomenon in the compound nucleus. All of the nuclei studied in Table I showed several resonances with non-zero PV asymmetries. When the data are completely analyzed, we will use statistical techniques [4] to extract M^2 (the mean squared matrix element) of the PV nuclear interaction from the measured asymmetries. The value of M^2 for each target will provide a constraint on the weak meson-nucleon couplings F_π and F_ρ using the statistical theory of parity mixing in the compound nucleus [5]. The consistency of the constraints for the range of nuclei in Table I will provide a test of the theory.

References

1. J. D. Bowman, G. T. Garvey, C. R. Gould, A. C. Hayes, and M. B. Johnson, *Phys. Rev. Lett.* **68**, 780 (1992).
2. N. Auerbach, *Phys. Rev. C* **45**, R514 (1992).

3. S. E. Koonin, C. W. Johnson and P. Vogel, *Phys. Rev. Lett.* **69**, 1163 (1992).
4. J. D. Bowman, C. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould et al., *Phys. Rev. Lett.* **65**, 1192 (1990).
5. M. B. Johnson, J. D. Bowman, and S. H. Yoo, *Phys. Rev. Lett.* **67**, 310 (1991).

Experiment 1207 — EPICS

THE NATURE OF T_{π} STATES OBSERVED IN DCX ON MEDIUM MASS NUCLEI

Participants

H. T. Fortune (Spokesperson), P. Hui, R. B. Ivie, Z. Mao,
M. G. McKinzie, D. A. Smith (Spokesperson), S. VanKirk,
and A. L. Williams

Institutions

University of Pennsylvania

Most experiments that studied the (π^+, π^-) reaction on various nuclei had concentrated on reactions which lead to the double isobaric analog states (DIAS) or to high-lying giant resonances in the residual nuclei. However, in these pion double charge exchange (DCX) experiments, states in the residual nuclei which are between the ground states and the DIAS in excitation energy were frequently observed [1-4]. These states are referred to as the T_{π} states.

The purpose of Exp. 1207 was to measure the forward-angle excitation functions of $^{93}\text{Nb}(\pi^+, \pi^-)$ and $^{56}\text{Fe}(\pi^+, \pi^-)$ leading to the T_{π} states. By studying these states, we attempt to improve our understanding of the reaction mechanism of pion-nucleus DCX. At present, theoretical accounts of the reaction mechanism of pion-nucleus DCX remain inadequate [5]. The ^{93}Nb part of this experiment was done in 1991 using the Energetic Pion Channel and Spectrometer (EPICS) facility, and the results have been published [6].

The second half of this experiment was partly done in 1993, also using the EPICS facility. Measurements of the cross sections of $^{56}\text{Fe}(\pi^+, \pi^-)$, leading to the T_{π} states of ^{56}Ni , were made at the laboratory angle of 5° , with incident pion kinetic energies of 164, 230, and 292 MeV. The target used was natural iron with an areal density of 1.8 g/cm^2 . The 164- and 230-MeV spectra are shown in Fig. 1. Both the ground state of ^{56}Ni and the DIAS were populated and can be seen clearly in the spectra. Four T_{π} states were also strongly populated at $T_{\pi} = 164 \text{ MeV}$. Analysis of the data is continuing and we expect to report the results shortly.

Fig. 1. Spectra of $^{56}\text{Fe}(\pi^+, \pi^-)^{56}\text{Ni}$ at $\theta_{\text{lab}} = 5^\circ$.

References

1. P. A. Seidl, M. A. Bryan, M. Burlein, G. R. Burleson, K. S. Dhuga, H. T. Fortune et al., *Phys. Rev. C* **42**, 1929 (1990).
2. C. F. Moore, K. Johnson, G. P. Kahrmanis, J. McDonald, M. Snell, H. J. Ward et al., *Phys. Rev. C* **44**, 2209 (1991).

3. D. A. Smith, H. T. Fortune, G.-B. Lui, J. M. O'Donnell, M. Burlein, S. Mordechai, and A. R. Fazely, *Phys. Rev. C* **46**, 477 (1992).
4. J. M. O'Donnell, H. T. Fortune, J. D. Silk, S. Mordechai, C. L. Morris, J. D. Zumbro, S. H. Yoo, and C. F. Moore, *Phys. Rev. C* **46**, 2259 (1992).
5. *Proceedings of the Second LAMPF International Workshop on Pion-Nucleus Double Charge Exchange*, Los Alamos, New Mexico, 1989, W. R. Gibbs and M. J. Leitch, Eds. (World Scientific, Singapore, 1990).
6. M. A. Kagarlis, H. T. Fortune, P. Hui, S. Loe, D. A. Smith, A. L. Williams, and J. Urbina, *Phys. Rev. C* **47**, 1219 (1993).

ENERGY DEPENDENCE OF DOUBLE RESONANCES IN PION DCX

Participants

H. Ward, J. Johnson, K. Johnson, S. Greene, Y. Grof,
C. Fred Moore (Co-Spokesman), S. Mordechai (Co-Spokesman),
C. L. Morris, J. M. O'Donnell, and C. Whitley

Institutions

University of Texas at Austin, Ben-Gurion University,
and Los Alamos National Laboratory

Two exotic vibrational nuclear modes have been observed in several experiments carried out at the Los Alamos Meson Physics Facility (LAMPF). These new collective modes are the giant dipole built on the isobaric analog state (GDR@IAS) [1] and the double giant dipole resonance (GDR@GDR) [2]. The two resonances have now been confirmed on a wide range of nuclei [3]. All previous data have been measured at a single pion beam energy of 295 MeV. Experiment 1209 provides the first measurement of the energy dependence of double resonances in nuclei excited by DCX. Measurements were taken at a constant momentum transfer that corresponds to the peak cross section of the GDR@IAS angular distribution at energies ranging between 110 and 295 MeV.

The measurements were performed at EPICS with the standard pion DCX setup on two target nuclei: ^{13}C (90% enrichment, 0.425 g/cm^2) and ^{51}V (100% enrichment, 1.94 g/cm^2). The data on ^{13}C have been published recently [4]. The cross section increases with energy and the excitation function for the GDR@IAS has a typical non-spin-flip signature, expected from simple consideration and verified by sequential model calculations. Figure 1 shows the $^{13}\text{C}(\pi^+, \pi^-)^{13}\text{O}$ missing-mass spectra at five different incoming pion beam energies. In addition to the ground state (g.s.) and the three low-lying narrow states reported earlier [5] (at $Q = -22.0\text{ MeV}$, $Q = -23.4\text{ MeV}$, and $Q = -25.0\text{ MeV}$), most spectra clearly show the existence of a wider peak located in the continuum region at $Q = -27.6\text{ MeV}$ ($E_x = 8.7\text{ MeV}$ above the g.s. of ^{13}O). This resonance was previously identified as the $T_z = 3/2$ component of the giant dipole resonance built on the isobaric analog state [6]. In Fig. 1 this resonance is labeled GDR@IAS. Figure 1 demonstrates that the cross section for the GDR@IAS increases significantly with beam energy. The three low-lying states at $E_x = 3.1, 4.5,$ and 6.1 MeV exhibit a substantially different excitation function. Figure 2 displays the excitation function for the g.s., the states at 3.1, 4.5, and 6.1 MeV

Fig. 1. Double-differential cross section spectra for (π^+, π^-) reaction on ^{13}C target at 295, 260, 220, 180, and 140 MeV. The dashed lines are the fitted background with a polynomial shape and the solid lines are the fits to the spectra using NEWFIT.

and the GDR@IAS. The figure indicates that the GDR@IAS can be fitted with a $\cos^2(\theta)$ dependence, similar to non-spin-flip transitions in inelastic scattering [7]. The solid line in Fig. 2(e) is the result of simple sequential model analysis. The calculations with a fixed transition strength for the GDR and the IAS give an adequate representation of the measured excitation function for the resonance and indicate that the excitation of the GDR@IAS in this energy region proceeds by a two-step sequential $(\pi^+, \pi^0), (\pi^0, \pi^-)$ mechanism. Therefore, pion DCX should be a unique probe for exciting isotensor double giant resonances in nuclei. The data for the low-lying states in ^{13}O have been discussed elsewhere [4] and will not be repeated here.

Figure 3 presents the double differential cross section spectra on ^{51}V obtained from E1209 at six different beam energies between 110–295 MeV. The scattering angles were varied to give a constant momentum transfer

Fig. 2. Excitation function at 140–295 MeV for the g.s., the three low-lying states, and the giant dipole built on the isobaric analog state. The dashed lines are $\sin^2(\theta)$ or $\cos^2(\theta)$ curves, normalized arbitrarily to the data. The solid line labeled CCIA in (e) is the result of simple sequential model calculations using the computer code NEWCHOP.

($q = 82.7$ MeV/c), which corresponds to the peak cross section of the GDR $\otimes$ IAS. The data are currently replayed for further analysis. Again, the cross section for the GDR $\otimes$ IAS clearly increases with pion energy and is well reproduced by the simple sequential model analysis. However, the ^{51}V data show that in addition to the DIAS ($Q = -14.0$ MeV) and the GDR $\otimes$ IAS ($Q = -32.4$ MeV), the spectra contain a new interesting narrow resonance at $Q = -17.8$ MeV. The resonance is most clearly seen at 260 MeV and has a smaller cross section at the upper and lower energies. A

Fig. 3. Same as Fig. 1 but for ^{51}V and beam energies indicated in the figure.

new proposal has been submitted at LAMPF to identify the nature of this new resonance observed in the $^{51}\text{V}(\pi^+, \pi^-)^{51}\text{Mn}$ reaction at $Q = -17.8$ MeV ($E_x = 14.9$ MeV) with a width of 2.6 ± 0.4 MeV [8]. Possible identification of this resonance located highly in the continuum has been suggested [8]; however, further measurements (especially angular distribution) are essential to discover the origin of this new phenomenon.

References

1. S. Mordechai, N. Auerbach, G. R. Burleson, K. S. Dhuga, M. Dwyer, J. A. Faucett et al., *Phys. Rev. Lett.* **60**, 408 (1988).
2. S. Mordechai, N. Auerbach, M. Burlein, H. T. Fortune, S. J. Greene, C. F. Moore et al., *Phys. Rev. Lett.* **61**, 531 (1988).
3. H. Ward, K. Johnson, G. Kahrmanis, D. Saunders, C. F. Moore, S. Mordechai et al., *Phys. Rev. C* **45**, 2723 (1992).
4. H. Ward, J. Johnson, K. Johnson, S. Greene, Y. Grof, C. F. Moore et al., *Phys. Rev. Lett.* **70**, 3209 (1993).

5. F. Ajzenberg-Selove, *Nucl. Phys. A* **253**, 1 (1991).
6. S. Mordechai, C. L. Morris, J. M. O'Donnell, M. A. Kagarlis, D. Fink, H. T. Fortune et al., *Phys. Rev. C* **43**, 1111 (1991).
7. S. Seestrom-Morris, D. Dehnhard, D. B. Holtkamp, and C. L. Morris, *Phys. Rev. Lett.* **46**, 1447 (1981).
8. LAMPF Proposal 1297. Spokespersons: C. Fred Moore and Shaul Mordechai.

Experiment 1216 — P3

π^+/π^- CROSS SECTION RATIOS IN THE $(\pi, \pi'p)$ REACTION ON ^2H , ^3He , AND ^4He

Participants

C. R. Whitley, K. Johnson, J. Johnson, C. F. Moore,
M. K. Jones (Spokesperson), J. L. Langenbrunner (Spokesperson),
D. Dehnhard (Spokesperson), C. M. Edwards, M. A. Espy, M. Palarczyk,
P. D. Yurek, B. J. Kriss, B. K. Park, K. Maeda, J. M. O'Donnell,
M. Rawool-Sullivan, R. M. Whitton, C. L. Morris, and J. D. Zumbro

Institutions

University of Texas, Rutgers University, University of Minnesota,
University of Colorado, New Mexico State University, Tohoku University,
and Los Alamos National Laboratory

Very large cross-section ratios $R = \sigma(\pi^+, \pi'p)/\sigma(\pi^-, \pi'p)$ were reported [1–3] for the exclusive $(\pi^\pm, \pi'p)$ reaction on ^4He at the incident pion energy $T_\pi = 180$ MeV. Whereas measurements [4] of the inclusive $(\pi^\pm, \pi^\pm)$ cross sections on ^4He gave π^+/π^- ratios of ≈ 1 as expected from charge symmetry, the ratios for the exclusive reaction were found to be as large as 50 [1,2]. If the $(\pi^\pm, \pi'p)$ reaction were purely quasifree, one would expect $R \approx 9$ as for the free π - p reaction. Distorted wave impulse approximation (DWIA) calculations with the code THREEDIE [5] predict the peak position and the shape of the π^+ data quite well, which indicates that the quasifree amplitude is the major component of the $(\pi^+, \pi'p)$ reaction. But the π^- data exhibit a fairly flat angular distribution where the DWIA calculation predicts a maximum.

The angular dependence of the π^- data suggests strongly that one or more reaction amplitudes must interfere with the quasifree scattering amplitude. The interference effect is expected to be strongest for $(\pi^-, \pi'p)$, where the quasifree amplitude is relatively weak. Some suggested amplitudes are from the excitation and decay of short-lived states in the target [1,2] and π -triton knockout [3], which would be stronger for π^- than π^+ . A third possible amplitude, proton knockout by the intermediate Δ , was proposed [6] in order to explain large ratios observed in the $^{16}\text{O}(\pi^\pm, \pi'p)$ reaction.

In order to investigate the importance of the different amplitudes, we took $(\pi^\pm, \pi'p)$ data on ^2H and ^3He over a range of incident energies and some additional data on ^4He . By varying the incident energy, we change the free π -proton amplitude, which should help in isolating the quasifree

amplitude. Complications arising from resonance excitations in the target are minimized in reactions on ^2H and ^3He nuclei since they have no known excited states. In addition, excellent wave functions are now available for these light nuclei, which should facilitate the analysis of the data.

We measured triple differential cross sections, $d^3\sigma/(d\Omega_\pi d\Omega_p dE_x)$ for the $(\pi^\pm, \pi^\pm' p)$ reaction on ^2H , ^3He , and ^4He at the Los Alamos Meson Physics Facility. The incident pion energies were 180, 210, 240, and 300 MeV, i.e., at and above the $P_{3,3}$ π -nucleon resonance. The cooled gas target that had been employed in Ref. [1] was used at a temperature of 40 K and a pressure of ~ 1.5 atm. The pions were detected with a large acceptance magnetic spectrometer in coincidence with protons in several fast CsI "phoswich" detectors that could be moved and centered about the quasifree angle.

As in Refs. [1-3], the $d^3\sigma/(d\Omega_\pi d\Omega_p dE_x)$ were integrated over a range of excitation energies of the target to extract double differential cross sections and the ratios, R , of the π^+ and π^- double differential cross sections. Measurements were also made of R for $\pi^\pm + p$ elastic scattering with the $\pi^\pm$ and proton detected in coincidence. The experimental values for $\pi^\pm + p$ agree with the predictions of the π -nucleon phase shift program SAID [7] (Fig. 1).

The cross-section ratios R for ^2H , ^3He , and ^4He were measured at the constant momentum transfer $q \cong 0.95 \text{ fm}^{-1}$ as the incident pion energy was changed. Some data were taken at $\cong 1.5 \text{ fm}^{-1}$. At $q \cong 0.95 \text{ fm}^{-1}$, the ratios were found to be considerably larger than the free π -nucleon ratio for all three targets.

Some preliminary results for $^2\text{H}(\pi^\pm, \pi^\pm' p)$, summed over deuteron excitation energies between 6 to 40 MeV, are shown in Fig. 1. The ratio R is of order 20 at $q \cong 0.95 \text{ fm}^{-1}$ at all incident energies with a maximum at 210 MeV. The large deviation from the free pion-nucleon ratio of 9 implies that, at this momentum transfer, the proton-knockout reaction does not proceed exclusively by quasielastic scattering. At the larger momentum transfer of 1.5 fm^{-1} and at $T_\pi = 300 \text{ MeV}$, the ratio R is closer to the free π -nucleon values (Fig. 1). Our new data for ^4He at $T_\pi = 180 \text{ MeV}$ and $q \cong 0.95 \text{ fm}^{-1}$ for ^4He are in good agreement with the previous results reported in Refs. [1] and [2]. The ratios obtained for ^3He (not shown here) are similar to those for ^2H .

Previous work [8] on $^2\text{H}(\pi^\pm, \pi^\pm' p)$ measured the proton momentum distribution at $T_\pi = 228 \text{ MeV}$ and several combinations of scattered pion and knockout proton angles. At angular settings corresponding to free $\pi + p$ kinematics, the measured R is near 9, as expected for quasifree scattering and the measured proton momentum distributions are qualitatively reproduced by a DWIA calculation. At pion-proton angular combinations that

Fig. 1. Preliminary cross section ratios R of this work for the $(\pi^\pm, \pi'^\pm p)$ reaction on ^2H as a function of T_π at constant momentum transfer $q \cong 0.95 \text{ fm}^{-1}$ (filled circles). At $T_\pi = 300 \text{ MeV}$, R is plotted also for $q = 1.5 \text{ fm}^{-1}$ (X). Also shown are ratios for $\pi^\pm + p$ elastic scattering at the same q (open circles). The solid line is the prediction from SAID [7] for $\pi^\pm + p$ elastic scattering.

are different from the quasifree values, the experimental ratios R are 9 or smaller and the DWIA calculations fail to fit the proton momentum distribution.

Garcilazo [9] performed a relativistic Faddeev calculation for the $(\pi^\pm, \pi'^\pm p)$ reaction on ^2H . The full three-body calculations fit the data of Ref. [8] better than the simple DWIA calculations. The fit is good in the region of the proton momentum distribution where the invariant mass of the outgoing pion-proton pair is near or below the Δ mass. When the pion-proton invariant mass is above the Δ mass, the full three-body calculation gives a poor fit to the data with the exception of a few pion-proton angular combinations. For the data presented in this paper, the invariant mass of the outgoing pion-proton pair is near or below the Δ mass. Thus, it would be interesting to see whether the full three-body calculation will predict the large ratios observed in our experiment.

Measurements [10] on ^2H for the $(\pi^-, \pi'^- n)$ and $(\pi^-, \pi'^- p)$ reaction at $T_\pi = 150 \text{ MeV}$ and momentum transfers $q = 1.4$ and 1.7 fm^{-1} gave generally

smaller ratios than our values, but were consistent with the energy- and q -dependence of our data.

In conclusion, at the momentum transfer $q \approx 1 \text{ fm}^{-1}$ and at all incident energies, the cross sections ratios R for the $(\pi^\pm, \pi^\pm p)$ reaction on ^2H , ^3He , and ^4He are much larger than the free $\pi^\pm + p$ scattering values. This result suggests that one or more other processes interfere with quasifree scattering, even in a system as simple as deuterium. At the momentum transfer $q \approx 1.5 \text{ fm}^{-1}$ at 300 MeV, the cross section ratios are consistent with those for quasifree scattering.

This work was supported by the U.S. Department of Energy and the Robert A. Welch Foundation.

References

1. M. K. Jones, D. Dehnhard, S. K. Nanda, S. M. Sterbenz, C. L. Morris, M. Plum et al., *Phys. Rev. C* **42**, R807 (1990) and *Phys. Rev. C* **46**, 52 (1992).
2. M. K. Jones, Ph.D. thesis, University of Minnesota, 1990, Los Alamos National Laboratory report LA-12015-T.
3. J. Langenbrunner, M. K. Jones, D. Dehnhard, C. L. Morris, and W. R. Gibbs, *Phys. Rev. Lett.* **69**, 1508 (1992).
4. C. L. Blilie, D. Dehnhard, D. B. Holtkamp, S. J. Seestrom-Morris, S. K. Nanda, W. R. Cottingham et al., *Phys. Rev. Lett.* **57**, 543 (1986).
5. L. Rees, N. S. Chant, and P. G. Roos, *Phys. Rev. C* **26**, 1580 (1982).
6. G. S. Kyle, P.-A. Amaudruz, Th. S. Bauer, J. J. Domingo, C. H. Q. Ingram, J. Jansen et al., *Phys. Rev. Lett.* **52**, 974 (1984).
7. R. A. Arndt et al., program SAID, unpublished.
8. J. H. Hoftiezer, S. D. Baker, J. M. Clement, W. H. Dragoset, I. M. Duck, R. D. Felder et al., *Phys. Rev. C* **23**, 407 (1981).
9. H. Garcilazo, *Phys. Rev. Lett.* **48**, 577 (1982).
10. F. Goetz, E. Bovet, J.-P. Egger, J.-F. Germond, P. Gretillat, C. Lunke et al., *Phys. Rev. C* **31**, 1563 (1985).

Experiment 1217 — EPICS

ACCURATE DETERMINATION OF THE T_+ GDR IN LIGHT $T = 1/2$ NUCLEI

Participants

H. Ward, K. Johnson, S. Greene, C. Fred Moore (Spokesman),
S. Mordechai (Spokesman), C. L. Morris, J. M. O'Donnell, L. Peters,
and C. Whitley

Institutions

University of Texas at Austin, Ben-Gurion University,
and Los Alamos National Laboratory

Recent high-statistics (π^+ , π^-) data from Exp. 1154 have revealed for the first time that pion DCX can provide a new general method for accurate determination of the $T_+ = T + 1$ giant dipole state in $T = 1/2$ nuclei [1]. This new implication of pion DCX and the phenomena of double giant resonances in nuclei are described in Ref. 1. The main idea of Exp. 1217 is illustrated in the schematic energy level diagram shown in Fig. 1. Our goal was to use the above method in order to determine the T_+ giant dipole state on two light $T = 1/2$ nuclei: ^9Be and ^{11}B . It is well known [2,3] from photonuclear reactions that the giant dipole resonance in non-self-conjugate nuclei has two isospin components $T_- = T$ and $T_+ = T + 1$, where T is the isospin of the target nucleus. For nuclei with large neutron excess, the upper-isospin component is weak and therefore difficult to measure experimentally. For the light nuclei, comparable strengths are expected for the two isospin components; however, the fragmentation of the GDR strongly obscures the measurement of the isospin splitting. In both cases, no clear assignments are given to the energy centroid of the two isospin components of the GDR.

Previous DCX measurements have shown that for $T = 1/2$ nuclei, one can accurately determine the T_+ component of the GDR by measuring the GDR@IAS in the $T_- = T - 2$ nucleus, which has a single isospin value ($T = 3/2$). The GDR@IAS is therefore the analog of the T_+ GDR in the target nucleus. Pion DCX gives, therefore, a powerful tool for studying isovector excitations without the interference from isoscalar excitations.

The measurements were performed at EPICS with the standard pion DCX setup on two target nuclei: ^{11}B (97.5% enrichment, 0.675 g/cm²), and ^9Be (100% enrichment, 0.482 g/cm²).

Fig. 1. Schematic energy level diagram of isospin fragment of the GDR and the GDR $\otimes$ IAS on $T = 1/2$ nuclei. The listed Q values refer to the case of DCX on ^{13}C (Ref. 5).

Figure 2 presents the on-line doubly differential cross-section spectra on ^{11}B obtained from Exp. 1217 at incoming pion energy of 295 MeV at two different scattering angles. The data are currently being replayed for further analysis. The lowest peak in the spectra displayed in Fig. 2 appears at $Q = -15.44 \pm 0.06$ MeV. This state might actually be the first excited state of ^{11}N . Theoretical calculations [4] as well as systematics suggest that the first excited state of ^{11}N should be at about 0.34 MeV above the ground state (g.s.), which is expected at $Q = -15.20 \pm 0.14$ MeV. The g.s. of ^{11}N is not yet observed in any experiment; however, the first excited state was seen in heavy-ion transfer reactions. The wider resonance at about $Q = -24.0$ MeV corresponds to the giant dipole built on the isobaric analog state (labeled GDR $\otimes$ IAS in Fig. 2).

DCX spectra (π^+ , π^-) on enriched ^{10}B (99.1% enrichment, 0.730 g/cm 2) were taken simultaneously, under the same kinematical conditions, using a strip enriched ^{11}B - ^{10}B target. The ^{10}B spectra show no signs of the |GDR $\otimes$ IAS>, which is forbidden on a self-conjugate nucleus.

Figure 3 displays the $^9\text{Be}(\pi^+, \pi^-)^9\text{C}$ spectra at two different angles, 18 $^\circ$ and 33 $^\circ$. The |GDR $\otimes$ IAS> is strong at 18 $^\circ$ but vanishes at 33 $^\circ$. In the 33 $^\circ$ spectrum, the ground-state transition becomes the dominant feature. The 18 $^\circ$ spectrum shows that two new low-lying states are observable in ^9C .

Fig. 2. Double differential cross-section spectra for the (π^+, π^-) reaction on ^{11}B at $T_\pi = 295$ MeV at scattering angles of (a) $\theta_{\text{lab}} = 5^\circ$ and (b) $\theta_{\text{lab}} = 18^\circ$. The arrows indicate the fitted location of the g.s., the new resonances and the giant dipole built on the IAS. Short vertical lines represent statistical uncertainty of the data. The dashed lines are the fitted background with a polynomial shape and the solid lines are the fits to the spectra using NEWFIT.

Our data do not allow a unique identification of the new resonances observed in DCX on ^9Be and ^{11}B . In a previous study of DCX on ^{13}C [5], we indicated that the low-lying resonances observed in the $^{13}\text{C}(\pi^+, \pi^-)^{13}\text{O}$ might be associated with a new type of double resonance state, not observed so far, namely the Gamow-Teller resonance built on the isobaric analog

Fig. 3. Same as Fig. 2, but for ${}^9\text{Be}$ and scattering angles of (a) $\theta_{\text{lab}} = 18^\circ$ and (b) $\theta_{\text{lab}} = 33^\circ$.

state $|\text{GT} \otimes \text{IAS}\rangle$. The identification was based on the excitation energy, the observed cross section, and the spin-flip signature of the excitation function. Further high-resolution studies (e.g., excitation function measurement) are needed to investigate the nature of the low-lying narrow resonances observed in ${}^9\text{C}$ and ${}^{11}\text{N}$ above particle threshold.

References

1. S. Mordechai, C. L. Morris, J. M. O'Donnell, M. A. Kagarlis, D. Fink, H. T. Fortune et al., *Phys. Rev. C* **43**, 1111 (1991).

2. B. L. Berman and S. C. Fultz, *Rev. Mod. Phys.* **47**, 713 (1975).
3. T. J. Bowles, R. J. Holt, H. E. Jackson, R. D. McKeown, A. M. Nathan, and J. R. Specht, *Phys. Rev. Lett.* **48**, 986 (1982).
4. A. Hayes, private communications.
5. H. Ward, J. Johnson, K. Johnson, S. Greene, Y. Grof, C. F. Moore et al., *Phys. Rev. Lett.* **70**, 3209 (1993).

**LASER POLARIZED MUONIC ATOMS AND
SPIN DEPENDENCE OF NUCLEAR MUON CAPTURE**

Participants

P. Bogorad, W. Cummings, G. D. Cates (Spokesman), M. Hasinoff,
O. Häusser, R. Holmes, K. F. Kumar, W. Lorenzon, J. McCracken,
H. Middleton, E. Saettler, P. A. Souder (Spokesman),
D. R. Swenson, D. Tupa, X. Wang, and A. R. Young

Institutions

Princeton University, Syracuse University,
Los Alamos National Laboratory, TRIUMF, Simon Fraser University,
and University of British Columbia

Introduction

We have built and tested an apparatus that serves both as a target designed to produce highly polarized muonic ^3He and an ion chamber to detect the recoil tritons from the reaction

We believe that we are now ready to use this apparatus to measure the induced pseudoscalar coupling constant g_P .

In this progress report, we will review the theory of measuring g_P by determining the spin-dependence of muon capture and briefly describe our method for polarizing muonic ^3He . Finally, we will present results of our apparatus tests at LAMPF. Convincing triton signals of excellent quality for both neutron and muon captures have been isolated.

Theory of Muon Capture In Polarized Muonic ^3He

As has been discussed by a number of authors [1], the muon capture reaction (1) can provide unique information about the charged weak current of ^3He . This current may be written in terms of four form factors, g_V , g_M , g_A , and g_P , which depend upon the four momentum transfer Q^2 . The form factor g_P , which arises from the fact that the quarks are confined in the proton by QCD forces, is important in muon capture because the mass of the initial state lepton, the muon, is significantly different from that of the final state lepton, the neutrino.

Numerical estimates for the form factors are given by: $g_V = 0.82$; $g_M = -4.73$; $g_A = -1.06$; and $g_P = 0.68$. The first two form factors are obtained from CVC and electron scattering data, the third from beta decay of ^3H , extrapolated to our value of Q^2 , and the last estimate comes from PCAC. One way of viewing our experiment is that we are testing the degree to which the PCAC prediction holds true. It has also been suggested that the difference between g_P for ^3He and the proton may be significant and is in and of itself interesting [2].

To see the full potential of our experiment, it is useful to write the neutrino rate per solid angle as:

$$\frac{d^2\omega}{d\hat{k}} = \frac{R}{4\pi} \left(A + B \cdot P_V(\hat{k} \cdot \hat{z}) + C \cdot P_T \left[(\hat{k} \cdot \hat{z})^2 - \frac{1}{3} \right] + D \cdot \Delta \right). \quad (2)$$

where $\hat{z}$ is the polarization direction and $\hat{k}$ is the direction of momentum of the neutrino, and P_V and P_T are the vector and tensor polarizations of the muonic helium core. The parameter Δ is a measure of the degree to which there is a non-statistical distribution in the singlet and triplet states, and is expected to be zero. The average rate $\Gamma = RA$ for an unpolarized initial state defines the constant R , and the constants A , B , C , and D are given in terms of the form factors g_V , g_M , g_A , and g_P evaluated at the appropriate Q^2 .

The constant A has been measured using unpolarized ^3He , but no other experimental information exists on this system. In fact, the quantities B and C are more sensitive to g_P than is A . The present effort is aimed at determining B by measuring the triton rate as a function of $\cos \theta_T$, the direction of the recoil triton relative to the muon polarization.

Experimental Techniques

The experiment requires an apparatus that combines the two functions of being a polarized target and also a direction-sensitive triton detector. We have developed a high-pressure ^3He ion chamber that can operate at high temperature with ample Rb density, which serves both purposes.

Polarizing Muonic Helium Directly with Polarized Rb

We will first describe the polarized target function of the apparatus. We have developed an approach for producing polarized muonic helium that yields average values for the vector polarization P_μ an order of magnitude larger than with previous techniques [3]. The muonic He is polarized by collisions with laser optically pumped Rb. Polarization occurs during both neutralization and subsequent spin-exchange collisions. The cross sections of these processes are sufficiently large that with a Rb number density

$[Rb] \sim 10^{15} \text{ cm}^{-3}$, both occur with time scales comparable to the 2.2- μsec muon lifetime. This number density is achieved by attaching a Rb reservoir to the detector and enclosing the apparatus in an aluminum box with electric heater panels on the interior walls which serves as an oven to heat the cell to $\sim 200^\circ\text{C}$. Tests at Princeton in late 1993 and early 1994 have established that our diagnostics are sufficient to allow careful control and monitoring of rubidium number densities in the active region of our detector.

After the short lived collision which affects only the spin of the valence electrons, the polarization is shared with the pseudo-nucleus. We have obtained average values of P_μ of $26.8 \pm 2.3\%$ in ^3He .

Description of the Ionization Chamber

Our detector is constructed from stainless steel. The body consists of 6-in-diameter tubing with two viewports and a 50- μm -thick, 2.5-cm diameter stainless steel muon window set in the sides. Laser light enters through a window mounted on the end flange and passes through the 4-in-diameter transparent mesh cathode.

For charged particles stopping in the cathode—grid region, the size of the pulse induced on the grid—anode voltage is proportional to the number of ion pairs created and is independent of the position of the track [4]. The shape of the pulse gives information about the track direction and orientation, as described below. We also digitize the cathode—grid pulse, which gives information about the distance between the track and the grid. To help identify which tracks are from stops in the central, polarized region of the detector, the central 2 in of the anode is instrumented separately from the outer annulus. However, for the analysis presented here, the outer anode pulses are not used.

Results

We took data at the Stopped Muon Channel at LAMPF in 1993. The detector was mated to the end of the beam line through an insulating spool piece, which was lined with Kapton to reduce possible backgrounds due to nuclear muon capture in iron; an Invex ($\text{C}_{10}\text{H}_{22}\text{N}_2\text{O}_4$) collimator with a 1-cm-diameter hole likewise was added before the muon window.

A novel muon beam tune, discussed elsewhere, was required to stop the muons in this relatively thin target [5]. Data acquisition was triggered by running the inner anode signal through an integrating amplifier and discriminating on its output. In addition, by closing the beam plugs and running at a lower trigger threshold, we were able to observe the thermal neutron capture reaction,

with a Q of 0.8 MeV, at any time when the accelerator was operating.

Figure 1 shows a pedestal subtracted pulse height spectrum for neutron capture data. The clearly evident peak provides a calibration of our energy scale. The width of the peak is about 30 channels, corresponding to an energy resolution of $\sigma = 8\%$. The non-beam background rate at around 300 channels, where we expect to find the tritons from muon captures, is negligible.

For data taken with the muon beam, the uncut pulse height spectrum shows no obvious structure. However, the events of interest are those in which the triton track has a large component perpendicular to the grid; tracks with $|\cos \theta_T| < 0.6$ will make a small contribution to an asymmetry measurement. These events should have the unique signature of a very long rise time and width. We have imposed cuts requiring the rise time to be greater than $10 \mu\text{s}$ (we estimate that this value corresponds to $|\cos \theta_T| \sim 0.6$) and FWHM greater than $15 \mu\text{s}$. The resulting pulse height spectrum has a prominent feature at approximately 300 channels (Fig. 2). This is about twice the energy of the peak seen in the neutron capture data, as

Fig. 1. Pulse height spectrum for data taken with no incident muon beam, showing a peak due to thermal neutron capture.

Fig. 2. Pulse height spectrum for muon data from a single 90-minute run of 9543 events, with cut on rise time $> 10 \mu\text{s}$, FWHM $> 15 \mu\text{s}$.

expected. Note that two features of the muon capture events—the presence of a muon, which increases the pulse height, and the duration of the pulse that is on the same order as the RC time constant of the system, which lowers the pulse height—mean that the pulse height is only roughly proportional to the triton energy. Indeed, the width of the peak is dominated by the distribution of the pulse heights of the stopping muons.

Six consecutive events that pass the cuts are shown in Fig. 3. Note that noise is low; in general performance of the ion chamber, even at elevated temperature with Rb vapor and laser light present, has been excellent.

We fit these pulses using a function based on a mathematical model of the ionization along the muon and triton tracks and the behavior of our detector. The fits for the pulses in Fig. 3 are shown as solid lines, with the muon and triton components shown as dotted and dashed lines. Floating parameters for these fits are the starting times of the muon and triton pulses, $\cos \theta$ for the muon and triton, and the length of the muon track in the fiducial region of the detector. Other parameters such as the electron drift velocity and the time constants of the detector and electronics are held fixed at values determined by making several fitting passes for a portion of the full data set. The triton pulse height may be fixed or varied.

Fig. 3. Six consecutive pulses from a muon run, passing cuts on rise time and width, with pulse height within the peak shown in Fig. 2. Solid curves are from a fit to a model of our apparatus, and consist of a muon pulse (dotted line) summed with a triton pulse (dashed line). In events (a), (b), and (d) the triton track was "up" (away from the grid); in events (c), (e), and (f) the triton track was "down."

The triton track may be "up" ($\cos \theta_T > 0$, corresponding to a trajectory away from the grid) or "down" ($\cos \theta_T < 0$). An "up" triton signal appears in our detector after the corresponding muon pulse [Fig. 3(a),(b),(d)] while the reverse is true for most "down" tritons [Fig. 3(c),(e),(f)], since the projected triton track length is longer than the distance the muon track ionization drifts during the muon lifetime. About 1/3 of the pulses that pass our cuts do not have good fits; bad fits are characterized by large values of χ^2 or by unphysical combinations of parameters, e.g., $\cos \theta_T > 0$ with the muon

pulse starting later than the triton pulse. These appear to be mostly tracks starting or ending outside the fiducial region or events with an extra muon, as well as a small amount of background from neutron captures.

With six floating parameters, some of which may be highly correlated, many of the pulses have local minima in the χ^2 function. Depending on the starting values, the fit may converge on a local minimum corresponding to incorrect values of the parameters. One way to mitigate this effect is to select only events where the fit converges to the same parameter values from different starting points. For such "convergent events," the distribution of triton pulse heights is shown in Fig. 4. The resolution is $PH/\delta PH = 15\%$. Fixing the triton pulse height parameter at the peak value of 0.94 greatly reduces the severity of the local minima for most pulses.

A check on our ability to fit the pulses correctly involves comparing events from the upper and lower parts of the detector. Since the grid pulse starts as soon as the muon enters the cell, but the anode pulse starts after the charge has drifted across the grid, the relative timing Δt of the two pulses is roughly proportional to the minimum z coordinate (perpendicular to the grid) of each event. Large ($>18 \mu s$) and small ($<14 \mu s$) values of Δt correspond to events whose minimum distance from the grid are large or

Fig. 4. Distribution of triton pulse height from fits to "convergent events," selected by the requirement that the same parameter values be found in fits with different starting points. Scale is arbitrary.

Fig. 5. Asymmetry in number of events with large and small values of z , as a function of minimum $\Delta\chi^2$. Horizontal axis is labeled with bin numbers, corresponding nonlinearly to $\Delta\chi^2$ as described in the text.

small, respectively. We generally expect events with $\cos \theta_T < 0$ to have z closer to the grid than those with $\cos \theta_T > 0$.

To verify this, we divide our events that pass the cuts into bins according to $\Delta\chi^2$, defined as the difference in χ^2 obtained from fits assuming $\cos \theta_T > 0$ and $\cos \theta_T < 0$; events with "up" ("down") tritons should have $\Delta\chi^2 < 0$ (> 0). In each bin we compute an asymmetry $A = (N_L - N_S)/(N_L + N_S)$, where $N_L(N_S)$ is the number of events with large (small) values of Δt . We expect A to be positive when $\Delta\chi^2$ is negative and negative when $\Delta\chi^2$ is positive.

The result is shown in Fig. 5. Each point represents the asymmetry computed for events in a range of values of $\Delta\chi^2$. (The binning of $\Delta\chi^2$ is nonlinear. Bins 1 to 9 cover $5 < \Delta\chi^2 < 100$; bins 10 to 13 cover $100 < \Delta\chi^2 < 500$; bin 14 contains $\Delta\chi^2 > 500$. Negative bin numbers correspond similarly to negative values of $\Delta\chi^2$.) The asymmetry is seen to be stable and nonzero for $|\Delta\chi^2|$ above about 35. This result gives us confidence in our ability to reconstruct the triton track parameters from the pulse shapes, and demonstrates that we are able to measure asymmetries using our apparatus.

References

1. B. R. Holstein, *Phys. Rev. C* 4, 764 (1971); W.-Y. P. Hwang, *Phys. Rev. C* 17, 1799 (1978).
2. N. C. Mukhopadhyay, private communication (1993).
3. A. S. Barton et al., *Phys. Rev. Lett.* 70, 758 (1993).
4. G. F. Knoll, *Radiation Detection and Measurement* (Wiley, New York, 1979).
5. R. Holmes et al., *Nucl. Instrum. Methods A* 303, 226 (1991).

Experiment 1240 — SMC

MEASUREMENT OF THE MICHEL PARAMETER ρ WITH THE MEGA POSITRON SPECTROMETER

Participants

J. F. Amann, R. D. Bolton, M. D. Cooper (Co-Spokesman), W. Foreman,
R. Harrison, G. Hart, G. E. Hogan, T. Kozlowski, M. A. Kroupa,
R. E. Mischke (Co-Spokesman), C. Pillai, S. Schilling, D. Whitehouse,
S. C. Wright, P. S. Cooper, Y. Chen, M. Dziedzic, E. V. Hungerford III,
K. Lan, B. W. Mayes II, L. Pinsky, W. von Witsch, J. E. Knott, K. M. Stantz,
J. J. Szymanski, C. C. H. Jui, J. N. Otis, C. A. Gagliardi, F. Liu,
R. E. Tribble, X.-L. Tu, L. A. Van Ausdell, D. D. Koetke, R. Manweiler,
T. D. S. Stanislaus, B. K. Wright, K. O. H. Ziock, D. Haim,
L. E. Pilonen (Co-Spokesman), Y. Zhang, and W. Zhou

Institutions

Los Alamos National Laboratory, University of Chicago, Fermilab,
University of Houston, Indiana University, Stanford University,
Texas A&M University, Valparaíso University, University of Virginia,
and Virginia Polytechnic Institute & State University

The positron arm of the MEGA detector [1,2] has been used to measure the Michel parameter [3] ρ in normal muon decay, $\mu \rightarrow e \nu \bar{\nu}$. This decay is an easily accessible, purely leptonic process, which makes it an important testing ground for models of the weak interaction. In recent years, sufficient information about muon decay has been accumulated to permit a model independent analysis of the interaction [4], but improved precision is needed to distinguish between the currently accepted standard model of the weak interaction [5] and proposed extensions.

The muon decay rate is given by

$$\frac{d\Gamma}{x^2 dx d(\cos \theta)} \sim 3(1-x) + \frac{2\rho}{3}(4x-3) \mp P_\mu \xi \cos \theta \left[1-x + \frac{2\delta}{3}(4x-3) \right],$$

where $x = E_e/E_{\max}$; θ is the angle between the positron direction and the muon spin; ρ , δ , and ξ are Michel parameters; and P_μ is the average muon polarization. The positron mass, the W mass, and the Michel parameter η have been neglected.

The best previous value [6,7] for ρ is

$$\rho = 0.7518 \pm 0.0026.$$

A deviation of ρ from the standard model value of 0.75 would indicate new physics. An example of a candidate extension is the left-right symmetric model [8] based on the gauge group $SU(2)_R \otimes SU(2)_L \otimes U(1)$. In this model, the weak charged current is carried by right as well as left handed bosons (W_R, W_L). The mass eigenstates W_1 and W_2 of the quark interaction, with masses m_1 and m_2 , could be a mixture of the chirality eigenstates with mixing angle ζ . The Michel parameter ρ becomes

$$\rho = \frac{3}{4}(1 - 2\zeta^2).$$

The constraint on the mixing angle provided by the precision of the previous measurement of ρ is shown in Fig. 1. This result complements other experiments that test the left-right symmetric model.

The experiment is performed by measuring the energy spectrum of positrons from Michel decay. Theoretical spectra for three values of ρ are shown in Fig. 2. The abscissa is the energy of the positron in units of $x = E_e/E_{\max}$. These spectra are independent of the angle of the positron

Fig. 1. Parameter space limits for the Minimal Left-Right Symmetric Model taken from Ref. [9]. The present constraint on the mixing angle comes from Ref. [8]; the limits implied by the statistical precision of this experiment are indicated by the dashed lines.

Fig. 2. Theoretical Michel spectra of unpolarized muon decay with three ρ values for the fractional energy $x \geq 0.7$.

with respect to the muon spin even for a polarized muon beam if the solid angle for $\pm \cos \theta$ is matched.

Although the MEGA apparatus was not designed for this measurement, it is a very low-mass apparatus with many independent, essentially digital parts. The large number of elements allows many checks for systematic errors. Another important feature is the high degree of symmetry for the upstream and downstream elements of the spectrometer. The MEGA apparatus has good acceptance for positrons with $0.75 < x < 1.0$ in a single setting of the magnetic field and a subset of the data has a reasonably flat acceptance over this range of x .

A schematic view of the MEGA apparatus is shown in Fig. 3. It is contained in a superconducting solenoid with a bore of 1.9 m and a length of 2.5 m and is operated at a field of 1.5 T. A beam of about 5 KHz of "surface" muons (29 MeV/c) enters along the axis of the solenoid and stops in a vertical 250- μ m mylar target. Positrons from $\mu \rightarrow e \nu \bar{\nu}$ are confined to the central region (30-cm radius) and are measured in a set of thin high-rate MWPCs [10]. A Michel decay event is triggered by a hit in any scintillator contained in barrels of 87 scintillators each located at the upstream and downstream ends of the central region. The photon pair spectrometers outside the positron arm are not needed for the ρ measurement.

Fig. 3. Schematic side view of the MEGA apparatus.

Data were taken in two short runs during 1992 and 1993. The 1993 data are of better quality and are being analyzed presently. Over 500 million triggers were recorded in a 5 day period. Figure 4 shows the reconstructed energy spectra for a sample of the data from each of the three data configurations. The nominal data set was taken with a surface beam tune and 1.5 T magnetic field. A second data set was taken with the magnetic field reduced to test our understanding of the acceptance. The increased acceptance for lower energy positrons in the case of the reduced magnetic field is evident in the spectrum. A third data set was taken with a decay tune that reversed the muon polarization. The spectra for the normal and reversed spin data are very similar, although a detailed analysis reveals small differences due primarily to differences in the beam phase space. For the range of x included with good acceptance, the expected statistical precision on ρ is $\sqrt{7.5/N}$, where N is the number of events. For the subset of the data with flat acceptance, the sum of the three data sets will yield a statistical precision on ρ of 0.00044.

In Fig. 5, the data spectrum for the decay tune is reproduced together with preliminary Monte Carlo spectra calculated for $\rho = 0.75$ and for the derivative of the theoretical spectrum with respect to ρ . A χ^2 minimization program is used to find a best fit of a linear combination of the two Monte

Fig. 4. Reconstructed energy spectra for each of the three data configurations. There are about 2.5 million events in each plot, representing about 15% of the data.

Fig. 5. (a) Energy spectrum of positrons from the decay tune data. (b) Monte Carlo spectrum with $\rho = 0.75$ for the experimental conditions of the decay tune data. (c) Monte Carlo spectrum for the same experimental conditions as (b), but using the derivative of the theoretical spectrum with respect to ρ .

Carlo spectra to the data. If the normalization coefficient of the derivative spectrum, (c), is nonzero, that would indicate that the preferred value of ρ deviates from the nominal value of 0.75. To extract an accurate value for ρ from the data requires that the Monte Carlo simulation accurately reproduces the experimental apparatus. The critical requirements include reproducing the geometry of the detectors and simulating the efficiencies of the chambers and scintillators. The detector geometry comes from physical measurements and analysis of the data. The chamber efficiencies are extracted from the data. In the case of the scintillators, because they were the trigger for the experiment, it was necessary to take auxiliary data to determine their efficiencies. This was accomplished by using a signal from one of the chambers for a trigger.

The analysis of the spectrum from muon decay will need to include radiative corrections. The first order radiative corrections have been parameterized by Sachs and Sirlin [11] as two functions of x , one associated

with ρ and one associated with δ . If second-order radiative corrections are not available, the analysis procedure can be modified to reduce the sensitivity of ρ to radiative corrections at some cost in statistics.

The analysis of the experiment is dominated by understanding and minimizing sources of systematic error. Monte Carlo studies indicate that systematic errors will contribute at the level of $\delta\rho\rho = 0.0003$, which is well below the level required. For some contributions, the required level of understanding has been reached; for the others more work is in progress and we expect to reach the desired level for all known potential sources of systematic error. For example, the energy resolution from the data is about 600 keV. Our knowledge of the match between the data and Monte Carlo resolution is currently limited by the Monte Carlo statistics to a precision of about 50 keV. We want to achieve a match at the level of 10 keV. As the Monte Carlo statistics are increased, some fine tuning of the Monte Carlo may be required.

The chamber alignment, chamber efficiencies, and scintillator efficiencies are being determined from data. Adequate statistics exist to reach the required level of precision; the problems lie in developing algorithms to extract the necessary values and then implement sufficiently accurate representations of the physics in the Monte Carlo. Our understanding of the beam phase space and the magnetic field are at the required levels.

In summary, if the systematic errors can be reduced below the level of the statistical errors, the improvement in the precision of ρ will be about a factor of six. The schedule for completing the analysis is to have a preliminary value, based on about 25% of the data by early June 1994, and the full analysis by the end of this summer.

References

1. M. Cooper et al., LAMPF Proposal No. 969 (1985).
2. J. F. Amann, K. Black, R. D. Bolton, S. Carius, M. D. Cooper, W. Foreman et al., in *Proc. of the 25th International Conference on High Energy Physics*, Singapore, 1990, K. K. Phua and Y. Yamaguchi, Eds. (World Scientific, Singapore, 1991), p. 1070.
3. L. Michel, *Proc. Phys. Soc. A* **63**, 514 (1950).
4. W. Fetscher, H.-J. Gerber, and K. F. Johnson, *Phys. Lett. B* **173**, 102 (1986).
5. S. L. Glashow, *Nucl. Phys.* **22**, 579 (1961); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity* (Nobel Symposium No. 8), N. Svartholm, Ed. (Almqvist and Wiksell, Stockholm, 1968), p. 367; S. Weinberg, *Phys. Rev. Lett.* **19**, 1264 (1967).
6. M. A. B. Beg, R. V. Bundy, R. Mohapatra, and A. Sirlin, *Phys. Rev. Lett.* **38**, 1252 (1977).

7. Particle Data Group, *Phys. Lett. B* **239** (1990).
8. J. Peoples, Columbia University, Thesis, Nevis 147, 1966 (unpublished).
9. D. H. Wilkinson, *Nucl. Phys. A* **527**, 689c (1991).
10. V. Armijo, K. Black, R. D. Bolton, S. Carius, M. D. Cooper, C. Espinoza et al., *Nucl. Instrum. Methods A* **303**, 298 (1991).
11. A. M. Sachs and A. Sirlin, in *Muon Physics*, V. Hughes and C. S. Wu, Eds. (Academic, New York, 1975), Vol. III, p. 50.

Experiment 1245 — EPICS

PION DCX ON ODD Z NUCLEI: AN EXPERIMENT TO CLARIFY APPARENT SHELL EFFECTS IN DIAS CROSS SECTIONS

Participants

D. A. Smith and H. T. Fortune

Institutions

University of Pennsylvania

The mass dependence of the DIAS is still not completely understood. It was first thought to go as [1]:

$$\frac{d\sigma}{d\Omega} = f(N-Z)(N-Z-1)A^{-10/3} . \quad (1)$$

But it was found later that this expression does not provide a good fit over all nuclei. A better fit for the $T = 1$ nuclei was found with an $A^{-7/3}$ mass dependence [2]. This provided an exceptionally good fit for the $T = 1$ nuclei, and the $A^{-10/3}$ dependence was a reasonable fit for the rest of the data, giving a χ^2 of 2.8. Recent measurements have carried this trend a step further. New data for ^{56}Fe and ^{60}Ni show that the mass dependence for the $T = 2$ nuclei is $A^{-7/3}$ [3,5]. Preliminary data on ^{64}Ni and ^{76}Se suggest that this is true for $T = 4$ nuclei also [5,6]. Is this a global dependence? All isospins may follow the same trend. But for each isospin the cross section is lowered when the $(N-Z)(N-Z-1)$ factor is added. We now have a mass dependence with a stair-step like shape, with a different step for each isospin, and the slope of these stairs is close to the $A^{-10/3}$ dependence. A reasonable fit to the $A^{-10/3}$ dependence will be found for a random sample of the data because of this. The $A^{-7/3}$ dependence was hidden within this global set and did not show up until more data were measured.

This mass dependence over different isospins is still not well understood. There are data at several isospins, but there are many holes. We will measure a large set of data to fill in these holes. Odd Z nuclei work nicely for this experiment, because we will get a single stable isotope for each target naturally, and not need any isotopic enrichments. Up to now the only published values for odd-even nuclei are ^{51}V and ^{209}Bi [2,4]. We will measure a set of data that fill in these holes, namely ^{55}Mn , ^{75}As , ^{89}Y , ^{109}Rh , ^{127}I , ^{139}La , ^{165}Ho , and ^{181}Ta . The targets of ^{55}Mn and ^{89}Y have the same isospins as other nuclei already measured. Data on these nuclei will provide information on the slope of odd- A nuclei of the same isospin. Data

from the targets of ^{75}As and ^{103}Rh will help complete the set of isospins from $T = 1$ to $T = 7$. This will provide data for the mass dependence of the different isospins. The other targets of ^{127}I , ^{139}La , ^{165}Ho , and ^{181}Ta will fill in the lack of data between $T = 7$ and $T = 21.5$, where there are apparent shell effects. These measurements, with the existing data, should give a complete set of isospins to be able to find shell structure dependences in the DIAS cross sections.

In August 1993, the EPICS spectrometer was set-up for small-angle DCX measurements, and this experiment was started. The spectrometer was set at 5° for each target to give the maximum value of the DIAS cross section. A beam of π^+ at 292 MeV was used to give us the maximum beam flux that we can achieve. We were able to measure data on ^{55}Mn , ^{75}As , and ^{89}Y , and get some data for ^{165}Ho . Preliminary fits to these data are shown in Fig. 1. The large central peaks are the DIAS; the smaller peaks around the DIAS are other states that are not well determined. Analysis continues to normalize these peaks to produce cross sections that will be compared to other DIAS measurements. The rest of this experiment is still on the EPICS queue and will be completed in the future.

References

1. M. B. Johnson, *Phys. Rev. C* **22**, 192 (1980).
2. J. Zumbro, H. T. Fortune, M. Burlein, C. L. Morris, Z.-F. Wang, R. Gilman et al., *Phys. Rev. C* **36**, 1479 (1987).
3. P. Seidl, G. Rai, S. J. Greene, C. L. Morris, D. S. Oakley, M. S. Plum, Z. F. Wang et al., *Phys. Rev. C* **42**, 1929 (1990).
4. C. L. Morris, H. A. Thiessen, W. J. Braithwaite, W. B. Cottingham, S. J. Greene, D. B. Holtkamp et al., *Phys. Rev. Lett.* **45**, 1233 (1980).
5. D. Benton, H. T. Fortune, J. M. O'Donnell, R. Crittenden, M. McKinzie, E. Insko, R. Ivie, D. A. Smith, and J. D. Silk, *Phys. Rev. C* **47**, 140 (1993).
6. P. P. Hui et al., to be published.

Fig. 2. Preliminary fits to data on ^{55}Mn , ^{75}As , ^{89}Y , and ^{165}Ho .

ELASTIC SCATTERING OF π^+ FROM POLARIZED ^3He

Participants

B. Davis, D. Dehnhard (Spokesperson), C. Edwards, M. Espy, J. Langenbrunner, M. Palarczyk, G. R. Burleson (Spokesperson), S. Blanchard, B. Lail, B. Nelson, B. Park, Q. Zhao, W. Cummings, P. Delheij, O. Häusser (Spokesperson), W. Lorenzon, R. Henderson, D. Thiessen, E. Brash, M. Jones, B. Larson, B. Brinkmüller, K. Maeda, C. L. Morris, S. Penttilä, D. Swenson, D. Tupa, and J. M. O'Donnell

Institutions

University of Minnesota, New Mexico State University, TRIUMF and Simon-Fraser University, Rutgers University, Ohio University, Universität Karlsruhe, Tohoku University, and Los Alamos National Laboratory

Recent work on pion elastic scattering from polarized 1p-shell nuclei of spin $J = 1/2$ revealed large discrepancies between theoretical predictions and experiment. For example, experiments on ^{15}N [1] and ^{13}C [2,3] measured small analyzing powers or asymmetries, A_y , whereas theory [4–6] predicts that A_y should be large. The theoretical A_y for elastic scattering from 1p-shell nuclei show a strong dependence [2,6] on the details of the nuclear structure input, implying that valuable information on the nuclear spin density is contained in the data. However, as indicated by the failure of current reaction models to reproduce the measured asymmetries, either the π -nucleus interaction and specifically its spin-dependent part is not yet understood, or the nuclear wave functions of ^{13}C and ^{15}N are not sufficiently well known, or both. Thus, pion data on a nucleus of well-known structure are needed in order to test the validity of reaction models without the complications of nuclear structure. ^3He appears ideal for such a study because reliable wave functions have been obtained by rigorous Faddeev calculations [7–9]. We note that pion scattering on polarized nuclei is sensitive to the isoscalar part of the ground state spin density whereas the transverse magnetic form factor from electron scattering measures the isovector part.

Asymmetry measurements on polarized ^3He have become possible with the development of the high-density, optically pumped ^3He gas target at TRIUMF. This target was used at TRIUMF in a pion scattering experiment and very large values of A_y were found in π^+ scattering at 100 MeV [10,11]. At this energy, the asymmetry is sensitive to neither the reaction model nor the nuclear wave function. Thus, there is considerable interest

in an extension of these measurements to energies at and above the P_{33} resonance where the asymmetries are predicted to become increasingly sensitive to the details of the reaction model and of nuclear structure. However, these measurements could not be done at TRIUMF because of the lack of a suitable spectrometer and the relatively low beam fluxes at the incident energies where the differential cross sections decrease significantly with increasing energy. Therefore, the TRIUMF target was set up in the P^3E area at LAMPF where high beam fluxes are available at P_{33} resonance energies and above. The scattered pions were detected with the Large Acceptance Spectrometer (LAS). Measurements were taken at incident energies $T_\pi = 100, 142, 180,$ and 256 MeV and laboratory scattering angles ranging from 40° to 100° . The data are currently being analyzed.

The TRIUMF target apparatus [10] was used with one key modification, which was the addition of a diode laser [12] during the experiment. The diode laser added power to the optical pumping system and significantly increased the polarizations. Polarizations were typically 35–45%, once reaching as high as 55%. Data were taken almost exclusively with π^+ because beam fluxes are typically five times larger than with π^- . A future experiment should be dedicated to taking data with π^- because, at P_{33} resonance energies, the spin-dependent amplitude for π^- is expected to be three times larger than for π^+ since the spin of ^3He is primarily due to that of the neutron.

The target cells were cylindrical in shape, 4.8 cm in diameter and 6.5 cm in length. These cells were "large" by TRIUMF standards in order to accommodate the larger beam spot at LAMPF (2.2 cm by 2.2 cm). The relatively large size of the cells limited the polarizations attained in this experiment to smaller values than at TRIUMF. The target cells were made of quartz glass that was about 1.5 mm thick at the cylindrical cell walls and 0.4 mm thick at the hemispherical endcaps (where the pion beam entered and exited the cell). The cells were heated to a temperature of approximately 175°C in order to achieve the required Rb density for optical pumping. This made a correction necessary for ^3He leaking from the quartz cell when hot. The pressure in the cell and the cell temperatures were measured periodically. In addition, the time periods when the cells were hot were recorded so that a correction for the pressure loss could be made.

The orientation of the ^3He spins (and thus the sign of A_y) was defined by use of a liquid crystal which only transmits left-hand circularly polarized light. This device determines the helicity of the laser light, and thus the direction of the target polarization. The magnitude of the polarization was measured using the nuclear magnetic resonance (NMR) technique of adiabatic fast passage (AFP). Absolute normalization factors for the NMR signals were obtained by comparing the NMR signals from the ^3He with the

weak signals from the protons in a water-filled cell of the same dimension [10].

The front wire chambers of the LAS allow trace back of the scattered particle trajectories to a plane at the target. This plane is perpendicular to the central ray of the LAS. The projections of the reaction vertices onto this x - y plane (with x being perpendicular to the reaction plane) were used to discriminate between events from ^3He and the glass of the cell walls. The regions of high density of the events in Fig. 1 are from scattering from the glass in the endcaps of the cell. The events from inside the cell are concentrated in an area within the limits of about $-20 \text{ mm} \leq x \leq +10 \text{ mm}$ and $-33 \text{ mm} \leq y \leq 0 \text{ mm}$, and a two-dimensional software cut was placed on this region. Events from the side walls could not be eliminated by software cuts. Thus, the beam striking the side walls (and the top and bottom) of the cells was reduced by a conical lead collimator that was specially machined to match the beam divergence.

From a preliminary replay of the data, the top and center panels of Fig. 2 show missing mass spectra measured at 180 MeV and $\theta_{\text{lab}} = 80^\circ$, normalized to integrated beam flux for the two target spin orientations. The

Fig. 1. Two-dimensional spectrum of pion vertices at the target, projected onto the x - y plane.

80 80.PLT

Fig. 2. Typical normalized yield spectra at $T_\pi = 180$ MeV and $\theta_{lab} = 80^\circ$. Top panel: target spin parallel ($\uparrow$), center panel: target spin antiparallel ($\downarrow$) to the normal to the reaction plane. The difference between the spectra in the top and center panels is shown in the bottom panel.

target polarization parallel to the norm of the reaction plane is indicated by ($\uparrow$), the one antiparallel by ($\downarrow$). The ^3He elastic peak has a width of about 4 MeV (FWHM). The difference spectrum is shown in the third panel of Fig. 2. The asymmetries were obtained using

$$A_y = \left(\frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \right) \frac{1}{p}.$$

Here $N_\uparrow$ and $N_\downarrow$ are the normalized number of counts in the ^3He elastic peak with the ^3He spins oriented "up" and "down," respectively. p is the target polarization. A large positive asymmetry is apparent in the region of the elastic peak from ^3He (Fig. 2, bottom panel, Missing Mass = 0).

Figure 3 shows a preliminary angular distribution of A_y for π^+ elastic scattering at $T_\pi = 180$ MeV. The first-order theoretical predictions of Kamalov [13] and Gibbs [14] are also shown. None of the calculations gives a satisfactory description of the data. We observe large positive

Fig. 3. Asymmetry angular distribution for elastic π^+ scattering from polarized ^3He at $T_\pi = 180$ MeV compared to the first-order theory curves of Kamalov [13] (solid line) and Gibbs [14] (dashed and dot-dashed lines). The analysis of the data is *preliminary*.

asymmetries near 80° , but the maximum of A_y is shifted towards larger angles than predicted by the first-order calculation. The calculations of both Kamalov and Gibbs use up-to-date Faddeev wave functions for ^3He ; however, different approximations are used in their reaction models (see Refs. [15] and [16]). The dot-dashed curve was obtained with an energy shift of 20 MeV, that is, the pion-nucleus amplitude was derived from the pion-nucleon amplitude at an energy 20 MeV below its actual value. The numerical values of the asymmetries are likely to change somewhat as we make progress in the analysis of the data.

We note that at 142 and 180 MeV at scattering angles near 50° , there is evidence for negative asymmetries of about -0.2 (not shown) in contradiction to any of the conventional model calculations that predict positive

asymmetries. Negative asymmetries at these angles can be reproduced [17] by introducing a strong modification of the spin-dependent part of the pion-nucleon scattering amplitude in the nuclear medium. We are still investigating the possibility of a systematic asymmetry at these angles. We also note that a theoretically predicted energy-dependent sign reversal of A_y at about 80° is observed, but between 180 and 256 MeV and not between 140 and 180 MeV as in the full calculation of Bennhold et al. [15].

References

1. R. Tacik et al., *Phys. Rev. Lett.* **63**, 1784 (1989).
2. Yi-Fen Yen et al., *Phys. Rev. Lett.* **66**, 1959 (1991); Yi-Fen Yen, Ph.D. Thesis, University of Minnesota, 1991, and Yi-Fen Yen et al., *Phys. Rev. C*, 1994, in press.
3. J. T. Brack et al., *Phys. Rev. C* **45**, 698 (1992).
4. R. Mach and S. S. Kamalov, *Nucl. Phys. A* **511**, 601 (1990).
5. S. Chakravarti et al., University of Minnesota, Annual Report 1990.
6. P. B. Siegel and W. R. Gibbs, *Phys. Rev. C* **48**, 1939 (1993).
7. R. A. Brandenburg, Y. E. Kim, and A. Tubis, *Phys. Rev. C* **12**, 1368 (1975).
8. J. L. Friar et al., *Phys. Rev. C* **34**, 1463 (1986).
9. D. R. Tilley, H. R. Weller, and H. H. Hasan, *Nucl. Phys. A* **474**, 2 (1987).
10. B. Larson et al., *Phys. Rev. Lett.* **67**, 3356 (1991); B. Larson et al., *Phys. Rev. A* **44**, 3108 (1991).
11. TRIUMF Annual Report, 1991, pp. 37–39.
12. TRIUMF Annual Report, 1993, Chapter on Polarized ^3He Target.
13. S. S. Kamalov, private communication.
14. W. R. Gibbs, private communication.
15. C. Bennhold, B. K. Jennings, L. Tiator, and S. S. Kamalov, *Nucl. Phys. A* **540**, 621 (1992).
16. W. R. Gibbs and B. F. Gibson, *Phys. Rev. C* **43**, 1012 (1991).
17. B. Jennings, private communication.

Experiment 1268 — NMS

MEASUREMENTS OF PION-NUCLEON CHARGE EXCHANGE NEAR THE Δ RESONANCE USING THE NMS

Participants

M. Sadler (Spokesperson), J. Redmon, D. Isenhower, C. Mertz, C. Gaulard, J. Comfort, H. C. annell, L. Nguyen-Tansill, S. Matthews, J. Amann, R. Boudrie, C. Morris, M. Rawool-Sullivan, M. Whitton, B. Park, Q. Zhao, P. Hui, D. Smith, A. Marusic, I. Supek, N. Kozlenko, and S. Kruglov

Institutions

Abilene Christian University, Arizona State University,
Catholic University of America, University of Colorado at Boulder,
George Washington University, Los Alamos National Laboratory,
New Mexico State University, University of Pennsylvania,
Petersburg Nuclear Physics Institute (Russia),
and Rudjer Boskovic Institute (Croatia)

ABSTRACT

The measurement phase of LAMPF Exp. 1268, $\pi^-p \rightarrow \pi^0 n$ cross sections near the Δ resonance, has been completed. The new Neutral Meson Spectrometer at Los Alamos was used to detect the π^0 through the $\gamma\gamma$ decay mode. The goals of the experiment are: (1) to check existing data that do not agree well with partial wave analyses (PWAs) at the back angles near the Δ , (2) to provide accurate data for input to charge-dependent PWAs, (3) to investigate charge splitting of the Δ , and (4) to complement existing and future measurements of $\pi^\pm p \rightarrow \pi^\pm p$ that should help clarify the discrepancies at lower energy through analyticity constraints of the PWAs.

The LAMPF Neutral Meson Spectrometer (NMS) is shown in Fig. 1. LAMPF Exp. 1268 was the first to use this detector in the two-arm coincidence mode. The configuration used for each arm during most of Exp. 1268 was a plane of scintillators for vetoing charged particles, two converter planes, and a calorimeter. Each converter plane consisted of an active layer of bismuth germanate (BGO), dimensions 14" $\times$ 28" $\times$ 0.25" (thickness), followed by cathode-strip chambers to reconstruct the $\gamma \rightarrow e^+e^-$ vertex. The calorimeter consisted of a 6 $\times$ 10 array of pure CsI crystals, each 4" $\times$ 4" $\times$ 12" (thickness). The thicknesses of each BGO converter and the CsI calorimeter correspond to slightly more than 0.5 and 16 radiation lengths, respectively. The final configuration will have a total of three conversion planes in each arm. The NMS is designed to provide an order-of-magnitude improvement over the π^0 spectrometer in rate and energy

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

2 of 3

Fig. 1. The LAMPF Neutral Meson Spectrometer.

resolution, and provides more than a factor of two increase in solid angle. The enhanced energy resolution of the NMS is not required for measurements of $\pi^- p \rightarrow \pi^0 n$, but it does aid in background rejection.

The low-energy-pion (LEP) channel at LAMPF was used to provide π^- beams at kinetic energies of 138.8, 163, 190, 214.6, 237, and 263 MeV. These energies were selected to complement the measurement of elastic $\pi^\pm p \rightarrow \pi^\pm p$ cross sections at TRIUMF [1]. The NMS was placed at central angles in the laboratory of 20° , 75° , and 180° for each of these energies. Additional measurements were made at 47.5° and 108° for some energies. The arms of the NMS were positioned to detect γ -rays from the π^0 decay out of the $\pi^- p \rightarrow \pi^0 n$ scattering plane, as approximately depicted in Fig. 1. with the

π^- beam going into the figure at a height between the crates of the active elements. For the 20° and 180° measurements, the beam passed between the crates, inside the support structure. The radial distance of the arms was slightly more than one meter, so that π^0 s were detected at angles of approximately $\pm 20^\circ$ from the central angle. The scattering angle of each π^0 is reconstructed in software from the determination of the direction and energy of the γ rays.

The primary target used in the experiment was 2 cm of CH_2 . A carbon target with the same energy loss for the incident π^- was used for background subtraction. An example of the reconstructed π^0 kinetic energy at $T_{\pi^-} = 190 \text{ MeV}$, $\theta_{\text{NMS}} = 20^\circ$, is shown in Fig. 2 for both of these targets. Here, the situation is quite favorable because of the difference in Q values for charge exchange scattering on protons and carbon. The width of the peak in Fig. 2 is dominated by the kinematic broadening of detecting π^0 s over the angular interval $0^\circ \leq \theta_{\text{lab}} \leq 40^\circ$.

Fig. 2. Reconstructed π^0 kinetic energy for charge-exchange scattering from CH_2 and C targets. The central NMS angle here is 20° .

The solid angle acceptance of the γ -rays from the $\pi^0 \rightarrow \gamma\gamma$ decay must be calculated from a Monte Carlo simulation. Programs have been developed to incorporate precise coordinates obtained from surveys of each NMS geometry and to calculate acceptances for different bins of the lab scattering angle. This angle is calculated from

$$\cos \theta_{\text{lab}}^{\pi^0} = \frac{E_1 \cos \theta_1 + E_2 \cos \theta_2}{[E_1^2 + E_2^2 + 2E_1 E_2 \cos \eta]^{1/2}}, \quad (1)$$

where $E_{1,2}$ are the energies of the two γ rays, $\theta_{1,2}$ are their lab angles, and η is the opening angle between them. The programs must accurately model both the energy response and the vertex determination of the NMS before reliable acceptances (and hence absolute cross sections) can be obtained.

Very preliminary results from Exp. 1268 at mid and back angles for 190 MeV are shown in Fig. 3 (statistical errors only). The most comprehensive existing data for $\pi^- p \rightarrow \pi^0 n$ cross sections near the Δ resonance are those of Jeneffsky et al. [2]. Neutrons were measured using TOF. The data are compared with the VPI [3] and Karlsruhe-Helsinki [4] partial-wave analyses in Fig. 3. The preliminary results from Exp. 1268 are systematically lower than the previous data and the partial wave analyses. The results for the angle bins at the edge of the acceptance are particularly suspect until more detailed comparisons with a GEANT-based simulation of the NMS can be completed. The Jeneffsky data are seen to be systematically higher than the PWAs at the back angles in this energy interval at and above the Δ . A forward-angle measurement by Bayer et al. [5] is also shown in Fig. 3.

The present measurements will provide a means to check the existing data over the complete angular distribution using a totally different detection technique. Combined with the measurements of Ref. [1], new data will be available to investigate the charge splitting of the Δ .

References

1. M. M. Pavan et al., Vol. I of the proceedings of this symposium.
2. R. F. Jeneffsky et al., *Nucl. Phys. A* **290**, 407 (1977).
3. R. A. Arndt, J. M. Ford, and L. D. Roper, *Phys. Rev. D* **32**, 1085 (1985). The SM90 solution was obtained from the SAID program, available from the authors.
4. R. Koch and E. Pietarinen, *Nucl. Phys. A* **336**, 331 (1980); G. Höhler, F. Kaiser, R. Koch, and E. Pietarinen, *Handbook of Pion-Nucleon Scattering*, Physics Data No. 12-1 (1979).
5. W. Bayer et al., *Nucl. Instrum. Methods* **134**, 449 (1976).

300 MeV/c (190 MeV) $\pi^- p \rightarrow \pi^0 n$

Fig. 3. Existing data and analyses for $\pi^- p \rightarrow \pi^0 n$ at the Δ resonance.

PION INDUCED SINGLE CHARGE EXCHANGE IN DEUTERIUM

Participants

H. T. Park, J. L. Matthews, S. F. Pate, J. F. Amann, C. L. Morris,
R. M. Whitton, E. R. Kinney, C. Mertz, and J. Redmon

Institutions

Massachusetts Institute of Technology, Los Alamos National Laboratory,
University of Colorado, Arizona State University,
and Abilene Christian University

In the first experiment to make use of a major component of the Neutral Meson Spectrometer, the differential cross section for $d(\pi^-, \pi^0)nn$ was measured at incident pion energies of 164, 263, and 371 MeV.

A single calorimeter crate consisting of a 6×10 array of pure CsI crystals was used to detect both decay photons from a π^0 produced in a CH_2 , CD_2 , or C target, as shown in Fig. 1. Hydrogen (in the CH_2) was used in order to measure the acceptance of the crystal array, as the $p(\pi^-, \pi^0)$ cross section is reasonably well known [1]. The large solid angle (about 100 msr) allowed us to reduce the incident pion flux to a level (approximately one million/sec instantaneous) that permitted the use of in-beam scintillators. A tight time coincidence (8 ns) between the first two scintillators (S0 and S1) registered a single beam particle. The absence of a similar coincidence in the downstream scintillator S2 signified that a particle had been removed from the beam. If, in addition, a hardware sum of the CsI pulse heights exceeded a threshold corresponding to 60 MeV, then the event was recorded—thus, the hardware trigger was $(S0 \cdot S1 \cdot \overline{S2} \cdot \text{CsI})$. The veto scintillators in front of the crystal array were not part of the hardware trigger, but were used in software to identify and reject the events in which charged particles entered the crystal array. For the measurements near 0° , the crystal array was placed in the path of the pion beam—pure CsI is highly radiation resistant [2] and no permanent damage resulted.

The segmentation of the calorimeter was sufficient to allow identification of the pulse heights associated with each photon shower and reconstruction of the π^0 angle with a resolution of 10° . A Monte Carlo simulation of the electromagnetic shower processes in the detector aided the event-by-event reconstruction by providing effective photon conversion depths for use in determining the photon angles. This simulation also indicated that the optimal compromise between resolution and solid angle would be attained if

Fig. 1. Scale depiction of the apparatus. The crystal array is shown at 90° at a distance of 38 cm from the target. The "fiducial volume" (the unshaded area) consisted of all the crystals except those on the perimeter of the detector.

only those events were accepted wherein the pulse height distribution from each photon peaked in a "fiducial volume" (see Fig. 1) consisting of all the crystals except those on the perimeter. Requiring further that the two photon momenta add up to give the correct π^0 invariant mass removed any remaining background particles.

Spectra of π^0 energy from CD_2 and CH_2 targets, for $T_{\pi^-} = 164$ MeV, and with the carbon background subtracted, are shown in Fig. 2. The width of the hydrogen peak is partially due to kinematic broadening—after removing this effect, we are left with a resolution of 12 MeV, in agreement with the Monte Carlo simulation. The yield from deuterium per incident pion was converted into a differential cross section by comparing it to the yield from hydrogen per incident pion at the same angle and beam energy. The values of the hydrogen differential cross section were taken from a phase-shift calculation [3].

Fig. 2. Energy spectra for π^0 's detected at $50^\circ < \theta_{\text{lab}} < 60^\circ$, for $T_{\pi^-} = 164$ MeV, for CD_2 (a) and CH_2 (b) targets. The raw target spectrum (dashed line) and the measured C background (dotted) are shown in each case, along with the final background-subtracted spectrum (solid). The vertical arrows indicate the limits used in summing the area of the peak to obtain a yield.

Our results are shown in Fig. 3. The 164-MeV data are well reproduced by the relativistic Faddeev calculation of Garcilazo [4]. An overall reduction of the cross section compared with that for $p(\pi^-, \pi^0)$ is observed, an effect presumably due to multiple scattering. The data at higher energies, away from the $\Delta(1232)$ resonance, do not show this reduction. No calculations exist at present at these energies.

At all three energies, the cross section is suppressed at small angles, as expected from the Pauli principle, which forbids a non-spin-flip transition to a spin-symmetric nn final state.

Fig. 3. Differential cross sections for $d(\pi^-, \pi^0)$ at 164, 263, and 371 MeV. The error bars represent statistical uncertainties only. The solid line is the full Faddeev calculation of Garcilazo [4], while the dashed lines are cross sections for $p(\pi^-, \pi^0)$ from a phase-shift solution [3].

We acknowledge the contributions of R. L. Boudrie, P. Hui, L. Nguyen-Tansill, M. Rawool-Sullivan, and D. Rowntree in the acquisition of these data.

References

1. P. A. Berardo et al., *Phys. Rev. D* **6**, 756 (1972); S. C. Comiso et al., *Phys. Rev. D* **12**, 738 (1975); R. F. Jeneffsky et al., *Nucl. Phys. A* **290**, 407 (1977).
2. S. Childress, in *Proc. Third International Conference on Calorimetry in High Energy Physics*, P. Hale and J. Siegrist, Eds. (World Scientific, 1993), p. 253.
3. R. A. Arndt, Z. Li, L. D. Roper, R. L. Workman, and J. M. Ford, *Phys. Rev. D* **43**, 2131 (1991); *Scattering Analysis Interactive Dial-in (SAID)*, solution SM92, private communication.
4. H. Garcilazo, *Phys. Rev. Lett.* **65**, 293 (1990).

**STUDY OF THE NEUTRON-NEUTRON SCATTERING LENGTH
USING THE $^3\text{H}(\pi, nn)\gamma$ REACTION**

Participants

A. Hussein, S. Sterbenz, A. Obst, C. Morris, C. Howell, R. Walter,
W. Tornow, C. Roper, F. Salinas, G. Mertens, C. Whiteley, C. Fred Moore,
E. Pasyuk, E. Korikmaz, M. Whitton, F. Guber, C. F. deTera mond,
F. C. Khanna, G. C. Neilson, G. Edwards, and I. Slaus

Institutions

University of Northern British Columbia, Los Alamos National Laboratory,
Duke University, Tübingen University, University of Texas at Austin,
Joint Institutes of Nuclear Research (Dubna, Russia),
Rudjer Boskovich Institute (Croatia), University of Costa Rica, and
University of Alberta

The nucleon-nucleon scattering lengths are fundamental quantities in nuclear physics whose relative magnitudes are constrained by charge symmetry and charge independence of the strong nuclear force. However, measuring the neutron-neutron scattering length with high enough accuracy to address fundamental charge symmetry issues has been a difficult and elusive experimental task.

The neutron-neutron scattering length, a_{nn} , is difficult to measure directly because of the lack of a free neutron target (although direct measurements have been proposed [1]). On the other hand, the proton-proton scattering length, a_{pp} , is amenable to study via direct p - p scattering. It is therefore not so difficult to approach experimentally, though inference of the scattering length is still somewhat model dependent because of the presence of the Coulomb force [2]. The neutron-proton scattering length, a_{np} , is not only relatively straightforward to study experimentally but is also free from Coulomb force complications.

Charge symmetry requires that $a_{pp} = a_{nn}$. However, a small difference between a_{pp} and a_{nn} should exist because of charge symmetry violation effects already known to occur [3]. For example, the mixing between the rho and the omega mesons is thought to follow from a mass difference between u and d quarks, which obviously implies lack of charge symmetry. This effect is also thought to be responsible, at least in part, for the difference between ^3H and ^3He Coulomb-corrected binding energies [4].

Most attempts at measuring a_{nn} described in the literature involve studies of nuclear reactions which produce three hadrons (two of them neutrons, of course) in the final state. Since the three particles exist in the continuum, each one may carry a continuous range of momenta, and the way in which they share the total momentum is sensitive to the interactions among them [5]. The ${}^2\text{H}(n,nn)p$ has been the reaction most commonly used to study a_{nn} . However, since the proton affects the final state interaction between the two neutrons, theoretical interpretation of the experimental data in terms of the scattering length is not straightforward [6]. This is a general feature of the measurements involving three final state hadrons.

More than thirty years ago, Wilkinson suggested that the ${}^2\text{H}(\pi^-,nn)\gamma$ reaction would provide a powerful approach to a_{nn} measurements [7], assuming, even in 1972, that it would be a high priority at LAMPF and other meson facilities. The ${}^2\text{H}(\pi^-,nn)\gamma$ reaction has only two strongly interacting particles in the final state. Since all three final-state particles are detectable, the experimental situation is very favorable. Theoretical interpretation of measurements involving this reaction is in principle much more reliable than in reactions with three strongly interacting particles in the final state.

The present status of the n - n and p - p scattering lengths is summarized below.

The accepted value of a_{pp} is -17.3 ± 0.2 fm [4,8].

A suggested average value of a_{nn} from the ${}^2\text{H}(n,nn)p$ reaction is -16.8 ± 0.4 fm [8], but values from different measurements range from above -16 fm down to -23 fm. Other reactions, such as ${}^3\text{H}(d,2n){}^3\text{He}$ and ${}^3\text{H}(t,2n){}^4\text{He}$, yield results ranging from -16 to -17 fm [8].

Measurements of a_{nn} using the ${}^2\text{H}(\pi^-,nn)\gamma$ have also been published. A value of -18.7 ± 0.6 fm [2,8] was obtained in a recent measurement. An earlier study had obtained a value of -16.7 ± 1.3 fm [9].

This summary of a_{nn} values reveals sizable differences even in the ${}^2\text{H}(\pi^-,nn)\gamma$ experiments. One value is close to that obtained from ${}^2\text{H}(n,nn)p$ data, while the other is more negative by some 2 fm. It bears noting that a difference between a_{nn} values inferred from reactions involving two and reactions involving three final-state hadrons could be an experimental indication of the existence of the elusive three-body force [10].

In order to confirm the value of a_{nn} as inferred from studies of the ${}^2\text{H}(\pi^-,nn)\gamma$ reaction and reduce its experimental uncertainty, we have carried out measurements of neutron spectra in coincidence with high-energy gamma rays from stopped pions in the LEP cave. The target was a

cylinder of liquid deuterium 5 cm in diameter. A 1.75" beryllium slab was used to bring the 50-MeV pion beam to rest in the middle of the target. Neutrons were detected by an array of 24 neutron detectors, and a single arm of the neutral meson spectrometer (NMS) was used to detect gamma rays. The large solid angle, high efficiency and high x-y position resolution of the NMS was a critical ingredient in the success of Exp. 1286. Our neutron detectors were cylindrical cells of pulse-shape-discrimination-capable liquid scintillator about 5" in diameter and 3" thick. Their arrangement relative to the NMS is depicted in Fig. 1. Data were accumulated over a period of two weeks, with liquid hydrogen and empty target runs included.

Fig. 1. Experimental arrangement.

Fig. 2. Neutron counter array. The numbered circles are the neutron detector cells. The lettered rectangles are charged-particle veto scintillator paddles.

Figure 2 shows the array of the neutron detectors, which was arranged in a honeycomb pattern for maximal symmetry. The detectors were placed in an array of five rows. The top and bottom rows contained four detectors each, the second and fourth rows contained five detectors each, and the third (middle) row contained six detectors. At 2.5 m from the target, each neutron detector subtended an angle of about 3° , while the angular separation between adjacent detectors was about 4.8° . Pulse Shape Discrimination (PSD) was used to separate neutron events from gamma events in each neutron detector. Plastic scintillators 0.25" thick were used in front of the neutron detectors to veto charged particles.

Data analysis is presently under way. We will extract a_{nn} for two classes of events: those involving only one neutron and a gamma (kinematically complete), and those involving two neutrons and a gamma (kinematically overcomplete). Figure 3 shows a neutron TOF spectrum for detector number 11 from the $^1\text{H}(\pi^-, n)\gamma$ reaction, which, owing to its simple kinematics, is ideal for the study of our entire system response. The arrows indicate the window used to gate the NMS gamma x-y position spectrum shown in Fig. 4. Figure 5 shows a Monte Carlo simulation of the NMS

Fig. 4. The position spectrum of the gamma rays measured in coincidence with neutrons detected in detector number 11 on the opposite side of the beam axis.

Fig. 3. Neutron time-of-flight spectrum for the $^1\text{H}(\pi, n)\gamma$ reaction from detector number 11, which was located at the extreme left side of the scintillator array. The TDC is started by an NMS trigger (timing from Cal detectors) and stopped by the anode signal from the neutron detectors. The arrows indicate the window used to gate the position spectrum measured using the wire chambers. The threshold on the neutron detector was about 0.5 MeV and gammas were rejected in the liquid scintillator using the charge-comparison technique.

Fig. 5. Monte Carlo simulation of the position spectrum of the gamma rays in coincidence with neutron detector number 11. This simulation was done with a uniform incident beam intensity, which may account for the departure from the observed distribution shown in Fig. 4. Further Monte Carlo work will focus on improving the agreement between experiment and simulation.

gamma position spectrum in coincidence with a neutron in detector 11. This simulation, after further work, will be used to guide our data analysis and to generate spectra from theoretical modeling, which will be compared with data for the purpose of extracting a_{nn} . Preliminary results show that the statistical accuracy of our results will be much better than in the previous measurements. Finally, we note that careful neutron detector efficiency measurements have been carried out at TUNL and at the Los Alamos Ion Beam Facility. Data from these measurements will be reduced to provide a complete determination of our experimental system response.

References

1. D. N. Glasgow et al., *Rad. Effects* **92-96**, 913 (1985); private communication (1992).
2. B. Gabioud et al., *Nucl. Phys. A* **420**, 496 (1984).
3. E. M. Henley, in *Isospin in Nuclear Physics*, D. H. Wilkinson, Ed. (North-Holland, Amsterdam, 1969).
4. A. W. Thomas, *Adv. Nucl. Phys.* **13**, 1 (1983).
5. K. W. McVoy, *Phys. Rev.* **121**, 1401 (1961).

6. D. H. Wilkinson, in *Few Particle Problems in the Nuclear Interaction*, I. Slaus et al., Eds. (North-Holland, Amsterdam, 1972).
7. R. Phillips and K. Crowe, *Phys. Rev.* **96** , 484 (1954).
8. O. Schori et al., *Phys. Rev. C* **35** , 2252 (1987).
9. R. W. Salter et al., *Nucl. Phys. A* **245** , 241 (1975).
10. I. Slaus et al., *Phys. Rev. Lett.* **48** , 993 (1982).

**THE SPIN-FLIP ELECTRIC DIPOLE IN
PION SINGLE CHARGE EXCHANGE**

Participants

D. A. Smith and H. T. Fortune

Institutions

University of Pennsylvania

The isovector monopole (IVM) has been observed, using the old π^0 spectrometer, on six nuclei from ^{40}Ca to ^{208}Pb [1,2]. The resonance was found to be around 35 MeV in excitation in π^+ , and 25 MeV in π^- , and has a width of 20 MeV. The state was identified in these nuclei by fitting a Lorentzian to the data and comparing the cross sections found to theoretical calculations for the IVM. The data fit the theory quite well, showing there is a broad resonance with a 0^+ shape in this region of excitation. But there are other giant resonances close in excitations to the IVM, viz., the isovector giant quadrupole (IVQ), and the spin-dipole resonance (SDR). The group that found the IVM, at the time, stated that the data could not prove or disprove the existence of the IVQ, and they ignored the possible existence of the SDR [1,2]. This experiment is to measure the SDR in pion SCX using the new NMS.

The spin-dipole resonance is the giant dipole coupled with a nucleon spin-flip, or an $L = 1, S = 1$ transition. The combination of $L = 1, S = 1$ gives the SDR an angular distribution similar to that of a 0^+ state, i.e., like the IVM [3]. This SDR must be in the pion SCX data, but how strong will it be? Using a microscopic pion distorted-wave code, the absolute magnitude of the SDR and the GDR have been calculated for $^{40}\text{C}(\pi^-, \pi^0)$. The code calculated the 0^+ strengths using the full $(sd) \rightarrow (fp)$ nuclear wave functions for the SDR, and, $(2s1d) \rightarrow (3s2d)$ and $(1p) \rightarrow (2p)$ for the IVM. The components of these calculations have been added together to get the total resonance cross section. The calculations matches the data remarkably well in both shape and magnitude. The data probably contain both IVM and SDR contributions. The SDR calculation has almost the same shape as that of the IVM calculation, and there is no way to tell the difference between the two from the data [4].

How do we tell the difference between the IVM and the SDR if they have almost exactly the same angular distributions?—by measuring the energy dependences. The IVM has a cross section that increases with pion

momentum, while the SDR cross section will decrease with the pion momentum. This difference in energy dependence will give us the ability to separate the two resonances. Also, the SDR should be about 5 MeV lower in excitation than the IVM. Given the resolution of the new NMS, this energy difference will help to resolve the difference between the IVM and the SDR.

The experiment will use a π^- beam for the measurements. This is mostly because the isovector giant resonances will have no isospin-splitting with the use of π^- . But also the giant resonances will be lower in excitation, so there will be a lower background to worry about. The experiment will also use two different nuclei, ^{40}Ca and ^{56}Fe . These have been chosen because of previous measurements of the GDR and IVM on ^{40}Ca and ^{60}Ni [1,2], where ^{56}Fe is a nucleus comparable to ^{60}Ni but less expensive. For heavy nuclei, the dipole resonances will be Pauli blocked, making the (π^-, π^0) cross section decrease with mass, and making the SDR harder to observe. Also, the nuclei ^{40}Ca and ^{56}Fe are related to an approved proposal at EPICS. Experiment 1233 is approved to look for giant resonances built on the IVM using DCX.

The experiment is to measure pion SCX using a π^- beam. Three energies will be measured to separate the IVM from the SDR; these energies will be 120, 165, and 230 MeV. Angular distributions will be measured at each energy for identification of the states, but this will require only two angular settings of the NMS at each energy, two settings will measure eight angles from 0° to 40° . Data will be taken using two targets at each setting, ^{40}Ca and ^{56}Fe , and using a target thickness of 1.0 g/cm^2 .

In October 1993, half of the PAC approved beam time was used to measure one of these targets. ^{56}Fe was used for small angle measurements at the given three energies. This was hoped to be enough data to show the existence of the SDR in this nucleus. Measurements of ^{40}Ca were done for 164 MeV, the other two energies were not done. One hundred fifty hours are still approved at A⁻ priority in the NMS queue. We will use this time to continue measurements of the large angle data, and the other two energies for ^{40}Ca . Figure 1 shows the data on ^{56}Fe at 120 MeV. The NMS was divided into 5° angle bins, and the 20° spectrum was subtracted from the 5° spectrum. Forward peaked resonances will be positive peaks in the spectrum, such as the SDR. The GDR peaks at 18° and is observed as a negative peak. The spectrum shows a forward peaked resonance at an excitation around 20 MeV, and the GDR is observed at the excitation of 15 MeV. The nature of the forward-peaked resonance is still not known, and the data analysis continues.

Fig. 1. Data on ^{56}Fe at 120 MeV.

References

1. A. Erell, J. Alster, J. Lichtenstadt, M. A. Moinester, J. D. Bowman, H. W. Baer et al., *Phys. Rev. C* **34**, 1822 (1986).
2. F. Irom, J. D. Bowman, G. O. Bolme, E. Piasetzky, U. Sennhauser, J. Alster et al., *Phys. Rev. C* **34**, 2231 (1986).
3. L. Bland, Ph.D. Thesis, Los Alamos National Laboratory report LA-9960-T (January 1984).
4. LAMPF Proposal 1289: The Spin-Flip Electric Dipole in Pion Single Charge Exchange.

Experiment 1293 — BR

np ELASTIC ANALYZING POWER

Participants

M. W. McNaughton, K. H. McNaughton, G. Glass, P. J. Riley,
G. Gülmez, J. C. Hiebert, R. H. Jeppeson, R. Ransome,
H. Spinka, I. Supek, G. E. Tripard, and H. Woolverton

Institutions

Los Alamos National Laboratory, University of Texas at Austin,
Texas A&M University, Argonne National Laboratory,
University of Montana, Washington State University,
University of Central Arkansas, Rudjer Boskovic Institute (Croatia),
Boğaziçi University (Turkey), and University of Manitoba

The *np* elastic analyzing power has been measured from about 30° to 180° c.m. by scattering 485- and 788-MeV polarized neutrons from a liquid hydrogen target. In 1992, we measured the analyzing power from about 60° to 180° [1]. The data reported here confirm the previous data and extend the angular coverage to forward neutron angles by detecting the recoil proton at backward lab angles.

There are three reasons for these new measurements, as follows.

1. The absolute normalization of the *np* analyzing power affects all the LAMPF polarization measurements, both in area B and at the NTOF facility, taken since the polarized neutron beam became available in 1977. The data that were taken in 1992 [1] disagree with previous measurements [2]. The preliminary data reported here agree with reference [1].
2. By extending the data to 30° c.m., we overlap with quasifree data measured by scattering polarized protons from deuterium [3]. The agreement between the free *np* data and the quasifree *pn* data ties the absolute normalization of the neutron beam to the proton beam, and the *np* data to the *pp* data.
3. The shape of the angular distribution arises from interference between the isospin-0 and isospin-1 amplitudes, and is a sensitive probe of the isospin-0 inelasticities. These inelasticities are the major source of disagreement between the phase-shift analysis of Arndt [4] and Bugg [5]. Arndt follows the prescription of Bystricky et al. [6] and

assigns substantial isospin-0 inelasticity near 800 MeV. Bugg restricts the inelasticity to a few partial waves, and finds evidence for coupling to a pair of delta resonances below threshold.

Figure 1 shows excellent agreement with the pre-existing phase-shifts of Bugg, though the final angle and background corrections are not included in these preliminary data. For most of the data, these corrections are small (about 0.3° in c.m. angle and 0.003 in the analyzing power), but they are larger at the extreme angles. The corrections will improve the agreement between the data and the fit. The agreement seems to support the analysis of Bugg.

The status of the nucleon-nucleon program is summarized as follows.

1. The pp elastic data are complete at 500, 580, 650, 730, and 800 MeV and have been used to obtain the isospin-1 amplitudes [7]. The various phase-shift analyses are in satisfactory agreement. The final pp elastic paper from LAMPF, measuring absolute differential cross sections to better than 1%, was published in 1993 [8], and includes references to other cross-section data. References to spin-dependent data are listed in Ref. [9].

Fig. 1. np elastic analyzing power for 788-MeV polarized neutrons scattered from liquid hydrogen. The curves are Arndt's and Bugg's pre-existing 1992 phase-shift solutions.

2. The most recent np elastic data are contained in Refs. [1,10–13]. Earlier data are referred to in these papers. Some data have been corrected or omitted, as discussed in Ref. [4].
3. The np total cross section measurements from LAMPF [14] and TRIUMF [15] disagree beyond their quoted uncertainties. At this time there seems to be no satisfactory way to resolve this discrepancy.
4. The estimates of the np inelasticities by Arndt and VerWest [16] disagree with those of Bystricky et al. [6]. These inelasticities are based on sparse and very old data, most of which are inaccurate or inconsistent. There is no foreseeable possibility of checking these data. However, the elastic data constrain the phase-shift analysis well, so the best procedure may be to omit the old inelastic data, and allow the inelasticity to adjust to the total and elastic data.

References

1. M. W. McNaughton, K. Johnston, D. R. Swenson, D. Tupa, R. L. York, D. A. Ambrose et al., *Phys. Rev. C* **48**, 256 (1993).
2. C. R. Newsom, C. L. Hollas, R. D. Rasmussen, P. J. Riley, B. E. Bonner, J. G. J. Boissevain et al., *Phys. Rev. C* **39**, 965 (1989).
3. G. Glass, T. S. Bhatia, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe et al., *Phys. Rev. C* **41**, 2732 (1990).
4. R. A. Arndt, L. D. Roper, R. L. Workman, and M. W. McNaughton, *Phys. Rev. D* **45**, 3995 (1992).
5. D. V. Bugg and R. A. Eryan, *Nucl. Phys. A* **540**, 449 (1992).
6. J. Bystricky, P. LaFrance, F. Lehar, F. Perot, T. Siemiarczuk, and P. Winternitz, *J. Phys. (Paris)* **48**, 1901 (1987).
7. M. W. McNaughton, S. Penttilä, K. H. McNaughton, P. J. Riley, D. L. Adams, J. Bystricky et al., *Phys. Rev. C* **41**, 2809 (1990).
8. A. J. Simon, G. Glass, M. W. McNaughton, T. Noro, K. H. McNaughton, P. J. Riley et al., *Phys. Rev. C* **48**, 662 (1993).
9. G. Glass, T. S. Bhatia, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe et al., *Phys. Rev. C* **45**, 35 (1992).
10. K. H. McNaughton, D. A. Ambrose, P. Coffey, K. Johnston, P. J. Riley, M. W. McNaughton et al., *Phys. Rev. C* **46**, 47 (1992).
11. W. R. Ditzler, D. Hill, J. Hoftiezer, K. F. Johnson, D. Lopiano, T. Shima et al., *Phys. Rev. D* **46**, 2792 (1992).
12. T. Shima, D. Hill, K. F. Johnson, H. Shimizu, H. Spinka, R. Stanek et al., *Phys. Rev. D* **47**, 29 (1993).
13. L. C. Northcliffe, M. Jain, M. L. Evans, G. Glass, J. C. Hiebert, R. A. Kenefick et al., *Phys. Rev. C* **47**, 36 (1993).
14. P. Lisowski, R. E. Shamu, G. F. Auchampaugh, N. S. P. King, M. S. Moore, G. L. Morgan, and T. S. Singleton, *Phys. Rev. Lett.* **49**, 255 (1982).

15. R. K. Keeler, R. Dubois, E. G. Auld, D. A. Axen, M. Comyn, G. Ludgate et al., *Nucl. Phys. A* 377, 529 (1982).
16. B. VerWest and R. A. Arndt, *Phys. Rev. C* 25, 1979 (1982).

Experiment 1294 — NTOF

SPIN DECOMPOSITION OF THE GIANT RESONANCE REGION FOR THE $\text{Ca}(p,n)$ AND $\text{Pb}(p,n)$ REACTIONS AT 795 MeV

Participants

D. Prout (Spokesman), E. Sugarbaker (Spokesman), T. N. Taddeucci,
J. B. McClelland, C. D. Goodman, J. Rapaport, F. Todd Baker,
B. K. Park, D. Cooper, S. D. DeLucia, and B. Luther

Institutions

The Ohio State University, Los Alamos National Laboratory,
Indiana University Cyclotron Facility, Ohio University,
University of Georgia, and New Mexico State University

In September 1993, spin observable measurements of the giant resonance region on Pb were performed at NTOF at 795 MeV. The purpose of this experiment was to investigate the substantial cross section appearing above the GT resonance in Pb at 795 MeV. This feature is absent in 200-MeV Pb data where most of the experimental and theoretical charge exchange effort has been focused. Sophisticated DWIA calculations that work well at 200 MeV have shown that some of this strength may be dipole excitation ($\Delta L = 1, \Delta S = 0$); however, these calculations cannot account for a significant fraction of the strength at higher excitation. There is the intriguing possibility that this cross section is due to the Isovector Monopole (IVM). Indeed, charge exchange reactions at 795 MeV have been singled out as promising reactions with which to search for the IVM [1].

Spin transfer observables are an excellent way of examining the spin character of the continuum. We have measured D_{NN} and D_{LL} over this region of excitation at 0° . Replay and data reduction have been completed at Ohio State University for the 0° portion of the experiment. These data have been decomposed into longitudinal and transverse partial cross sections and are shown in Fig. 1 along with the spin transfer observables. This allows us to distinguish between $\Delta S = 1$ and $\Delta S = 0$ cross section and has led to interesting results. Unlike the predictions, most of the strength is $\Delta S = 1$. The vertical and horizontal lines are transverse strength ($\Delta S = 1$) and the diagonal lines indicate the longitudinal strength ($\Delta S = 1$). The $\Delta S = 0$ strength is shown in white. The proportion of each of these partial cross sections does not change in going from the GT into the high excitation region of the bump. Since the GT is pure unnatural parity, this implies that this extra strength is also unnatural parity. There is the possibility that this strength represents high lying "missing" GT strength. G. Love

Fig. 1. The top panel shows the $^{\text{nat}}\text{Pb}$ 0° cross section data from Exp. 1294. The partial cross sections for the two transverse (horizontal and vertical lines), longitudinal (diagonal lines) and $S = 0$ (white) are shown. The bottom panel shows the D_{NN} (solid) and D_{LL} (open) results that were used to decompose the cross section. This shows that the strength in the bump at 30–40 MeV energy loss is predominantly of unnatural parity. The experiment was only partially finished and no angular distribution was obtained, so a decomposition of the data into different multipoles was not possible.

has indicated that as the beam energy is increased a larger fraction of the integrated 0° spectrum should consist of GT strength [2]. Analysis of these data are continuing at OSU.

References

1. N. Auerbach, J. D. Bowman, M. A. Franey, and W. G. Love, *Phys. Rev. C* **28**, 280 (1983).
2. G. Love, presentation at LAMPF workshop supporting the NTOF facility circ. 1985 (unpublished). See also G. Love, *Can. J. Phys.* **65**, 543 (1987).

Experiment 1296 — NTOF

HIGH-RESOLUTION COINCIDENCE STUDY OF $^{12}\text{C}(p,n\pi^+)^{12}\text{C}$

Participants

R. Gilman, E. Brash, G. Edwards, C. Glashausser, M. K. Jones, F. T. Baker, S. Bastea, D. P. Beatty, L. Bimbot, J. Brusoe, J. Chiba, D. Cooper, G. Kumbartzki, C. Mauger, T. Nagae, B. Park, D. Prout, R. D. Ransome, M. Rawool-Sullivan, P. Rutt, B. Storm, E. Sugarbaker, T. Taddeucci, and J. Zumbro

Institutions

Rutgers University, College of William & Mary,
University of Tokyo (Japan), Institut de Physique Nucleaire (France),
Los Alamos National Laboratory, KEK (Japan), Ohio State University,
University of Georgia, and New Mexico State University

Experiment 1296 was a coincidence measurement of the $^{12}\text{C}(p,n\pi^+)$ reaction, using the NTOF channel at LAMPF supplemented by a pion spectrometer. It was designed to look for coherent pion production, with ^{12}C left in its ground state. The pion spectrometer used a straw chamber for tracking, and scintillators for timing, particle identification, and triggering. All detectors were mounted in the yoke of the NTOF beam dump magnet. Detectors were built in mid 1993. Pion spectrometer development runs took place in August and September, with data runs during October 1993.

The physics motivation is the study of the Δ resonance in nuclei. Hadronic charge exchange reactions show a strong and attractive shift in the Δ peak position, which is believed to result from spin-longitudinal (pionic) correlation effects. Only modest shifts are observed in electron scattering, where such effects should be absent. The first charge-exchange measurements, which looked also at Δ decay products, gave some evidence for coherent pion production. Studies [1] at KEK of decay particles in coincidence with neutrons from $^{12}\text{C}(p,n)$ showed evidence for single pion events that left ^{12}C in its ground state. Such events, with a strongly forward-peaked angular distribution, have also been seen in $(^3\text{He},t)$ [2,3]. Such coherent pion production has been suggested [4–6] as a signature of pionic collectivity. The experimental resolution, however, has been too poor to make definitive claims. Experiment 1296 extends the range of measurements to 0° , where cross sections are expected to be larger and the signature clearer, and improves the energy resolution by a large factor over that available in previous experiments.

Fig. 1. A schematic diagram of the NTOF facility at LAMPF. The straw chamber and trigger scintillators are placed inside the yoke of the sweeping magnet BM-05.

A schematic description of our set-up is shown in Fig. 1. Neutrons created in the $^{12}\text{C}(p,n)$ reaction at 0° went straight toward the Neutron Time Of Flight Facility (NTOF) liquid scintillator detector array, 170 m away. The proton beam was swept into a beam dump by a sweeping magnet. This magnet also bent pions emitted at angles from 0° to 10° with momenta from 150–400 MeV/c into a straw chamber mounted inside the magnet yoke, but just outside the magnet pole faces. The chamber was 90 cm long and 15 cm high, with four planes consisting of from 64 to 80 individually instrumented vertical wires and three planes of horizontal wires. Particle positions were determined to $\sigma \sim 700 \mu\text{m}$ in each plane with straight line fits; this resolution is consistent with the expected 200- μm resolution of the chamber plus the curvature of the tracks in the magnetic field. Angular information is good to a few mr, once the curvature of the track is considered. Monte Carlo studies indicate that the resolution of this system was $\sim 5 \text{ MeV}/c$, but varied across the acceptance of the chamber.

Two scintillators placed behind the straw chamber provided trigger signals and time-of-flight information for distinguishing pions from the more intense proton background. CH_2 absorbers between these scintillators were used to range low-energy protons out of the trigger, so that the proton trigger rate was only a few times the pion trigger rate. The absorber also reduced accidental coincidences from (n,p) scattering in the scintillators. Shielding stacked between the detectors and the target, and between the detectors and the beam dump, further reduced unwanted hits.

A coincidence system had to be set up with detectors separated by 170 m. The NTOF neutron data were obtained as singles data, with NTOF operating in essentially its standard configuration for nonpolarization measurements. Typical rates were ~ 200 Hz. The charged particle detectors were recorded by a separate computer system. A singles trigger started analog-to-digital conversion of this data, at rates of several kHz. Neutron triggers were also sent to the charged-particle electronics. The charged-particle trigger was set to automatically fast clear the event, unless a coincident neutron trigger came in about $2 \pm 0.15 \mu\text{s}$ later. The $0.3\text{-}\mu\text{s}$ width corresponds to a neutron energy range of about 300 to 800 MeV. The real + random coincidence rate was about 5 Hz. Dead time from fast clearing the singles triggers was about 20%.

The data streams are synchronized in replay in the following ways. Alignment events were generated by the NTOF electronics when acquiring data, and sent to both data streams at a rate of 1 Hz. The 80 beam pulses per second are then aligned by data events indicating the end of each macropulse. Ramp generators read into ADC's indicate the time of events within a macropulse, so that the charged particle may be aligned with one of the three or so neutrons from that same macropulse.

Because the real to random ratio is small, it was decided to also measure a spectrum of purely random coincidences from early neutrons. This allows the real spectrum to be determined by a simple subtraction. To identify whether the event was definitely random or possibly real, long-range TDCs were used to measure the neutron and charged particle trigger times with respect to the start of the macropulse with 1-ns precision. Comparison of real and real + random event rates on line suggested a net rate of about 100 real events per hr.

The pions, protons, and background are shown in Fig. 2. The background events appear as the intermediate β and mass peaks. β is calculated from the ratio of path length, derived from the track in the straw chamber, to time of flight, which is the difference in scintillator and RF times plus an offset. Mass is calculated from the momentum, also derived from the track, divided by $\beta\gamma$. Both β and mass peaks for the pions and protons show up at about the correct centroids, indicating that the time, path length, and momentum calibrations are approximately correct.

A neutron energy spectrum is shown in Fig. 3. The Δ peak, visible at about 500 MeV neutron energy, or $\omega = 300$ MeV, is not as prominent as typical for NTOF data. Two effects increase the background. First, NTOF usually measures neutron polarization; with the requirement that the incident neutron hits two scintillators, some background is removed from the spectrum. Second, for this measurement the NTOF detector was moved 30 m closer to the cave, outside a trench in which it usually sits. This

Fig. 2. Top: β spectrum for charged particles triggering the magnet detectors. Pions are expected at $\beta \sim 0.9$ and protons at $\beta \sim 0.4$. Bottom: Mass spectrum for charged particles triggering the magnet detectors.

Fig. 3. Spectrum of neutron energies measured by NTOF.

decreased the shielding between it and the Area A beam stop, leading to background rates of about 30 Hz when Line A was running. Each of these effects should be removed in the real/random subtraction.

A summed energy spectrum for real plus random events is shown in Fig. 4. At this point, no clear signature has been seen for the $^{12}\text{C}(\text{g.s.})$ coherent π peak, although such a signature would be expected for the statistics shown. In addition to the possibility that there is no coherent peak in the spectrum, we are investigating several possible aspects of the experiment and replay that could cause the peak to not appear. These include potential problems in the particle identification, momentum measurement, detector alignment, and the coincidence matching algorithm. The time scale for these efforts is anticipated to be several months.

Fig. 4. Summed energy spectrum, $E_{\pi^+} + T_n + \text{calculated } ^{12}\text{C} \text{ recoil energy}$. The coherent π peak would appear as a peak of width a few MeV at energy 800 MeV.

References

1. J. Chiba et al., *Phys. Rev. Lett.* **67**, 1982 (1991).
2. T. Hennino et al., *Phys. Lett. B* **283**, 42 (1992).
3. T. Hennino et al., *Phys. Lett. B* **303**, 236 (1993).
4. T. Udagawa, S.-W. Hong, and F. Osterfeld, *Phys. Lett. B* **245**, 1 (1990).
5. P. Oltmanns, F. Osterfeld, and T. Udagawa, *Phys. Lett. B* **299**, 194 (1993).
6. E. Oset, P. Fernandez de Cordoba, J. Nieves, and M. J. Vicente-Vacas, talk given at the *XI International Conference on Relativistic Nuclear Physics and Quantum Chromodynamics*, Dubna, September 1992. See also the talk by E. Oset in these proceedings.

**A HIGH-INTENSITY He-JET PRODUCTION SOURCE FOR
RADIOACTIVE BEAMS AND THE Cs-PNC EXPERIMENT**

Participants

Y. Bai, D. Rosenauer, K. E. G. Loebner, G. W. Butler, J. M. Wouters,
D. J. Vieira, and the LAMPF He-Jet Collaboration

Institutions

Los Alamos National Laboratory, Utah State University,
Giessen University (Germany), and Munich University (Germany)

Introduction

As the nuclear science community prepares the scientific and technical case for a high-intensity, high-beam-quality, broad-mass-range radioactive beam facility, such as the IsoSpin Laboratory (ISL) [1,2], one of the most critical questions regards the ability to scale-up the target/ion source system to higher beam intensities. More specifically for the ISL initiative, can the thick-target approach be advanced to operate reliably at the 100- μ A level? And given that many species (especially non-volatile, refractory elements) are not readily released from thick-target matrices, what alternatives are available?

Herein we explore an alternate approach, that of a thin-target, He-jet system, which is well suited to the production and rapid transport of non-volatile species. As such, the thin-target He-jet approach is complimentary to the thick-target method, but it also has its own set of advantages and disadvantages (see Refs. [3] and [4] for more details). One important difference is that the production target can be well removed from the ion source. This means that the target can be made more robust and can be separately disposed of, while the ion source can be reused and maintained. As such, a He-jet system thus provides an opportunity to employ a more sophisticated set of ion sources. However, there are losses associated with transporting the activity from target to the ion source and the ion sources must be designed to operate under the conditions of continuous gas flow and aerosol (NaCl and KCl in the present case) loading. Finally, to compensate, if only partially, for the reduced target thickness, the He-jet system should be designed to operate with multiple targets and at as high a beam intensity as possible. In this report we feature the first successful demonstration of a thin-target, He-jet system operating at beam intensities of up to 700 μ A!

Beyond its importance as an alternate source for radioactive beams, this work also benefits our efforts to measure the $6S-7S$ atomic parity nonconservation (PNC) transition rate in a series of Cs radioisotopes (Cs-PNC experiment [5]). This experiment is extremely important as a high-precision test of the Standard Model of electroweak interactions in nuclei, but it is also extremely challenging to undertake. One of the initial steps in mounting this experiment is to provide a long-term, low-maintenance source of radioactive Cs species capable of delivering these species for several months at a time with intensities on the order of $\sim 10^6$ atoms/s. Given limitations in the number of atoms that can be optically trapped and thus measured batchwise in the proposed PNC experimental apparatus, higher Cs intensities cannot be effectively utilized. The He-jet system thus represents a good match to the needs of this experiment.

The LAMPF Thin-Target, He-Jet Demonstration Experiment

A sketch of the He-jet target chamber is shown in Fig. 1. The chamber consists of two thin-walled (0.7 mm) stainless steel coaxial tubes that are actively cooled by high-pressure water flowing between the inner and outer tubes. The target has been designed to withstand beam intensities of up to $1000 \mu\text{A}$ with total beam deposition powers of $\sim 5 \text{ kW}$. Finite-element stress and temperature calculations were carried out during the design stage to ensure that the target surface temperatures could be kept low ($\sim 200^\circ\text{C}$) in order to reduce potential collection losses from heat/gas turbulence effects. Moreover, special gas flow, smoke studies were carried out with a plastic mock-up to verify that uniform gas flow throughout the helium gas stopping volume was achieved.

Fig. 1. Sketch of the LAMPF He-jet target chamber.

The production target consists of a thin ($\sim 12 \text{ mg/cm}^2$) coating of $^{238}\text{U}_2\text{O}_3$, which was electroplated onto the inside surface of the inner tube. The entire assembly was then welded together with the capillaries being brazed into the endcap beforehand. Fission and spallation products that recoil out of the targets: (1) are stopped in the central volume of helium gas; (2) attach themselves to aerosols suspended in the helium; (3) are swept out of the target chamber by the gas flow; and (4) are entrained in one-to-seven differentially pumped capillary tubes. The activity is then transported $\sim 30 \text{ m}$ in times on the order of a second to a moving tape collection and detection station where the various activities are measured.

A closed-loop, gas recirculating system (see Fig. 2) is used to contain radioactive gas emissions and to facilitate operation at high flow rates. This system, which consists of several pumps, purifying filters, a cold trap, and an evaporative, oven-type aerosol generator, is fully computer controlled. It is designed to operate at target pressures of up to 6 atm and at flow rates of 1 std l/s or less.

Upon exit from the capillary, the transported activity is deposited on a moving tape collection system [6] that sequentially or continuously moves the activity in front of a high-purity Ge gamma-ray detector. Because of the large amounts of activity transported (typically several Ci), the Ge was removed from the counting tape position by 1.6 m. Moreover, the Ge

Fig. 2. Schematic of the He-jet gas recirculation system.

detector was well shielded and collimated to limit the detectors point of view to only the correct tape counting position. Finally, a combination of aluminum and lead attenuators were routinely used to keep the counting rates in the Ge detector below 40,000 Hz, where system performance began to degrade. Gamma-ray spectra were recorded on an IBM 386 computer using the S100 system [7] for data acquisition. Livetime performance of the overall system was monitored using a fixed-rate pulsar, and gamma-ray detection efficiencies were determined using calibrated gamma standards. Off-line, we extracted the transported yields of individual, gamma-ray-emitting radionuclides using modified versions of the automated multi-peak gamma-ray analysis code GAMANAL [8] and the decay-curve analysis code CLSQ [9].

By changing the sample collection and counting length sequence, data were acquired for a wide variety of species spanning the half-life range from seconds to days. In a few cases, long-lived samples were collected and chemically separated off-line using a resin column method [10]. Each eluted fraction was then quantitatively gamma counted to extract the yields of individual isotopes. Fig. 3 shows a typical gamma-ray spectrum obtained from one of the eluted samples containing several cesium radioisotopes. In general, the on-line gamma spectra were considerably more complex.

Fig. 3. A gamma-ray spectrum measured from a sample eluted off of a AG50WX8 cation column with 0.2 N HNO₃. The spectrum represents a 20-minute count of the Cs-dominated chemical fraction taken 22.6 hours after the termination of a 3-hour sample collection period. ¹²⁷Cs ($T_{1/2}$ = 6.2 hrs.), ¹²⁹Cs ($T_{1/2}$ = 1.34 days), and ¹³⁸Cs ($T_{1/2}$ = 13.2 days) are clearly evident, among other activities.

Results

After a through checkout and debugging of the system, a variety of measurements were performed to characterize and optimize the performance of the thin-target, He-jet system. These included: (1) the investigation of gas flow rates versus target pressure for different sized capillaries; (2) the optimization of the aerosol conditions using either NaCl or KCl at different oven temperatures; (3) the measurement of transport times by pulsing the beam on and off; and (4) the determination of transport yields as a function of beam intensity, beam position relative to the center of the target, and operating target pressure/flow rate conditions. For brevity, only a few highlights of our findings are presented here.

One important feature is the linear scaling of our yields with beam intensity from 10 to 700 μA , as illustrated in Fig. 4. At the highest beam intensity, the outside surface temperature of the target chamber reached -220°C (as measured by an array of thermocouples attached to the outside of the target chamber), in good agreement with our calculations. Moreover, we observed no signs of heat-driven turbulence effects or losses in yield as was found in a previous high-intensity attempt [11]. At all intensities, we found that the water-cooled, thin-target, He-jet system worked as expected, giving reliable and stable performance once the aerosol conditions had been optimized.

Fig. 4. Relative activity yields vs. average proton beam intensity (μA) for the LAMPF thin-target, He-jet system.

For those isotopes with measured production cross sections, we can extract the overall He-jet transport and collection efficiency, which generally ranged from 10 to 30%. The He-jet efficiency is deduced from the measured collection rate, as obtained from the gamma decay analysis, the calculated production rate using the known cross sections, and a calculation of the fraction of reaction products that recoil out of the target and the fraction of recoils that are then stopped in the central He gas volume. The latter quantities are calculated using a Monte Carlo code in which known range-energy relationships and a uniform angular distribution for the reaction products have been assumed. The results presented in Table I exemplify our findings. We consider a He-jet efficiency of 20–30% to be quite reasonable given the He-jet performance determined by the Chalk River group [12], who used heavy ion beams of 1 μ A or less.

Table I. Measured collection rates and derived He-jet efficiencies for several Cs and Rb isotopes measured in a sample collected for 2000 s using a beam intensity of 685 μ A, target thickness of 12.5 mg/cm², He gas pressure of 2.4 atm, flow rate of 0.2 std. l/s, and KCl aerosols.

Isotope ^A Z	Measured Collection Rate (atoms/s)	Escaped from Tgt. (%) ^a	Stopped in Gas (%) ^b	Calculated Production Rate (atoms/s) ^c	He-jet Efficiency (%)
¹²⁷ Cs	$(7.6 \pm 0.3) \times 10^6$	26	98	$(3.9 \pm 0.4) \times 10^7$	20 $\pm$ 2
¹²⁹ Cs	$(3.2 \pm 0.1) \times 10^7$	39	92	$(1.8 \pm 0.1) \times 10^8$	18 $\pm$ 1
¹³⁸ Cs	$(3.8 \pm 0.1) \times 10^7$	39	92	$(1.9 \pm 0.1) \times 10^8$	20 $\pm$ 1
⁸⁸ Rb	$(1.10 \pm 0.01) \times 10^8$	54	84	$(5.4 \pm 1.1) \times 10^8$	20 $\pm$ 4
⁸⁶ Rb	$(8.6 \pm 0.2) \times 10^7$	54	84	$(5.4 \pm 0.6) \times 10^8$	17 $\pm$ 1

^aNormalized to yield 100% for an infinitely thin target.

^bNormalized to yield 100% for an infinitely high gas pressure.

^cBased on cross section reported in Ref. [13].

Summary and Outlook

We have found that this water-cooled, thin-target, He-jet system works quite well, even at the highest beam intensity of 700 μ A. No loss in scaled-up yields or signs of beam heated turbulence effects were observed. Once we became knowledgeable about optimizing the He-jet aerosol conditions, reliable and stable performance was achieved. Measured collection rates for Cs radioisotopes were typically in the 10⁷–10⁸ atoms/s range with He-jet efficiencies of 10–30%. This performance encourages us to proceed with the Cs-PNC weak interaction experiment. Additional data, especially for the refractory, non-volatile species, are still undergoing analysis.

Although this demonstration experiment lasted for two months, we did not have time to test several of the features that were built into the system. These included the ability to run multiple targets, which could increase our yields by a factor of 3 or more, and the ability to use several capillaries simultaneously to reduce the transport speed (most important for short-lived species). Further checks of the target robustness should also be performed.

Acknowledgments

We would like to acknowledge the excellent engineering and target fabrication support of Hugh Kimerly, Jim Lambert, Don Grisham, Felix Olivas, Toni Mayer, and Frank Smith, whose hard work and talented craftsmanship made this project a success. We would also like to thank Dennis Phillips for helping with the off-line column chemistry runs and Will Talbert and Hermann Wollnik (Giessen Univ.) for valuable guidance during the initial design stage of this work. Finally, we thank the LAMPF operations and support groups for their valuable assistance throughout the course of this experiment.

References

1. R. F. Casten et al., "The IsoSpin Laboratory (ISL): Research Opportunities with Radioactive Nuclear Beams," Los Alamos National Laboratory report LALP-91-51 (1991).
2. *Proc. of the Workshop on the Production and Use of Intense Radioactive Beams at the IsoSpin Laboratory*, J. D. Garrett, ed., October 1992, Oak Ridge, Tennessee, Oak Ridge Institute for Science and Education Report CONF-9110121 (1993).
3. J. M. Wouters, W. L. Talbert, and D. J. Vieira, "A Radioactive Ion Production R&D Program Using a Helium-Jet Coupled Target Ion Source," *ibid.*, p. 309.
4. D. J. Vieira, H. J. Kimerly, D. L. Grisham, D. Rosenauer, Y. Bai, W. L. Talbert, and J. M. Wouters, "A High-Intensity He-jet Production Source for Radioactive Beams," in *Proc. of the 3rd International Conference on Radioactive Nuclear Beams*, East Lansing, Michigan, May 1993, D. J. Morrissey, Ed. (Editions Frontieres, Gif-sur-Yvette, 1993) p. 115.
5. D. J. Vieira, C. E. Wieman et al., "Parity Nonconservation Measurements of Trapped Radioactive Isotopes—A Precise Test of the Standard Model," Approved LAMPF Research Proposal #1303 (1992).
6. R. L. Mlekodaj, E. F. Zganjar, and J. D. Cole, "A New Concept for a Compact Tape Transport System," *Nucl. Instrum. Methods* 186, 239 (1981).
7. The S100 MCA Data Acquisition System, copyrighted and sold by Canberra Industries, Inc.

8. R. Gunnink and J. B. Niday, "Computerized Quantitative Analysis by Gamma-Ray Spectrometry," Lawrence Livermore Laboratory Report UCRL-51061, Vol. I (1972).
9. J. B. Cumming, "CLSQ, the Brookhaven Decay Curve Analysis Program," Brookhaven National Laboratory Report BNL-6470 (1963).
10. F. W. E. Strelow, R. Rethemeyer, and C. J. C. Bothma, "Ion Exchange Selectivity Scales for Cations in Nitric Acid and Sulfuric Acid Media with a Sulfonated Polystyrene Resin," *Anal. Chem.* **37**, 107 (1965).
11. W. L. Talbert, private communication (1989).
12. E. Hagberg and V. T. Koslowsky, private communication (1993).
13. B. N. Belyaev, V. D. Domkin, and V. S. Mukhin, "Isotopic Effects in Spallation and Fission Reactions and Mass-Spectrometer Investigation of them with 1-GeV Protons," *Sov. J. Part. Nucl.* **234**, 439 (1992).

Experiment 1309 — BR

**ANALYZING POWER FOR THE np INELASTIC CHANNELS
AT 790 MeV: $np \rightarrow NN\pi$**

Participants

G. Glass, P. Riley, I. Supek, K. Auer, and E. Lomon

Institutions

University of Texas at Austin, Rudjer Boskovic Institute,
Los Alamos National Laboratory,
and Massachusetts Institute of Technology

This experiment used the same setup as an elastic one, as shown in Fig. 1, but was arranged to detect protons in the spectrometer at 23° and conjugate neutrons or protons at -20° . The neutron beam energy was centered around 790 MeV and the spectrometer protons had momenta between 475 and 1000 MeV/c. The conjugate particles were distinguished as either a neutron or a proton with the use of a thin counter (V-counter) placed in front of the thick array of scintillators (N-counter). A hit in V was interpreted as a conjugate proton. Some charged pions could register as protons, but these were considerably diminished since their time of flight was usually short enough to have them eliminated by the timing gate put on the N and V counter time-of-flight values. The targets were CH_2 and carbon, the latter being used to extract the hydrogen events via subtraction. Data were obtained to give a measure of the analyzing power with respect to the $np\pi^0$ final state integrated over all proton momenta between 475 and 1000 MeV/c.

$$A(np\pi^0) = -0.138 \pm 0.068 .$$

The $pp\pi^-$ final state was more difficult to deal with due to the many components of accidentals associated with the triple coincidence between the spectrometer proton, the V-counter, and the N-counter. Here the analyzing power measurement result is

$$A(pp\pi^-) = 0.085 \pm 0.221 ,$$

where the error was increased by the usual $\sqrt{\chi^2}/\nu$ scaling factor (in this case, 2.1) to account for the difference between two sets of data. The experiment also obtained the inclusive measurement of analyzing power with results shown in Fig. 2 of analyzing power versus spectrometer proton

Fig. 1. A layout of the experiment shows the polarization directions at points along the beam. The polarization on the spectrometer was not necessary for these analyzing power measurements.

Fig. 2. The inclusive analyzing power results include both final states, $np\pi^0$ and $pp\pi^-$.

momentum. These represent events without regard to whether a neutron or proton struck the N-counter.

Another result of this experiment is the ratio of the $np\pi^0$ final-state cross section to that of the $pp\pi^-$ final state,

$$\frac{\sigma(np\pi^0)}{\sigma(pp\pi^-)} = 2.00 \pm 0.12 ,$$

and is in line with the total reaction cross section ratio prediction of VerWest and Arndt [1], and the π^- results of Thomas et al. [2] and Dubna's (1959) π^0 data. They get ratios closer to 2.8–2.9.

It is anticipated that these data will serve to pin down models* [3,4] that treat the inelastic channels in the isospin-0 and -1 states.

References

1. B. J. VerWest and R. A. Arndt, *Phys. Rev. C* **25**, 1979 (1982).
2. W. Thomas, R. Carlini, C. Cassapakis, B. Dieterle, J. Donahue, C. Leavitt et al., *Phys. Rev. D* **24**, 1736 (1981).
3. E. L. Lomon, in *Proc. of the Workshop on N-N and N-Nucleus Scattering*, Los Alamos, New Mexico, January 13–14, 1992, Los Alamos National Laboratory document LA-UR-93-778.
4. W. M. Kloet and E. L. Lomon, *Phys Rev. C* **43**, 1575 (1991).

* T.-S. Lee, R. Silbar, J. Dubach, and B. Blackleider are a few of the other modelers for pion production in NN collisions.

Atomic Physics Research

Experiment 1307 — HIRAB

MEASUREMENT OF H^0 EXCITED STATES PRODUCED BY FOIL STRIPPING OF 800-MeV H^- IONS

Participants

H. C. Bryant, S. Cohen, J. B. Donahue (Spokesperson), D. H. Fitzgerald,
S. C. Frankle, D. J. Funk, M. S. Gulley, R. L. Hutson, P. B. Keating,
R. J. Macek (Spokesperson), E. P. Mackerrow, W. A. Miller, C. W. Planner,
M. A. Plum, D. C. Rislove, N. G. Stanciu, O. B. van Dyck,
and C. A. Wilkinson

Institutions

Los Alamos National Laboratory, University of New Mexico,
and Rutherford-Appleton Laboratory

Introduction

Work at the High Resolution Atomic Beam Facility (HIRAB) concluded with a study of the interaction of relativistic H^- ions with thin foils. This was an extension of our previous work on beam-foil interactions [1] and a follow-up to an exploratory run in 1992. This work was stimulated, in part, by the problem of first-turn losses at the Proton Storage Ring. The present (1993) run featured improved on-line data acquisition and better control over systematic effects.

A comprehensive theoretical study of beam-foil interactions has not been attempted due to the complexity of the problem. Perturbational treatments do not work because the perturbations are too strong. Theoretical work has attempted to explain the interaction of highly charged ions traversing thin foils using stochastic models [2], and it may be possible to extend this work to the case of relativistic beams.

Foil stripping of H^- directly to H^+ is being considered for proton injection in the next generation of high-current proton storage rings. This technique can result in significant losses because excited states of H^0 , which are also produced in the foil, are field stripped in the downstream bending magnets. Without due care in the injection system design, many of the resulting protons will be outside the acceptance of the storage ring and will be quickly lost. This experiment combined the efforts of the Proton Storage Ring (PSR) development group and a basic research group that has been doing accelerator-based atomic physics research at Los Alamos using laser-ion colliding beams for the past twenty years.

Technique

The experiment used the "laser-quality" external H^- beam at the High Resolution Atomic Beam Facility at LAMPF. This facility features a beam kinetic energy that could be varied from 100 to 800 MeV with typical beam parameters of 2-mm spot size, 100- μ rad divergence, and 0.05% $\delta p/p$. With special tuning, the beam parameters could be improved to < 0.5-mm spot size, < 10- μ rad divergence, and $\sim 0.01\%$ $\delta p/p$ [3].

The apparatus consisted of a foil box with remotely interchangeable foils, the gradient magnet, a five-meter flight path and the detector system (see Fig. 1). The detector system was a scintillator telescope and a scanning scintillator. The scintillator telescope covered the entire beam so that the experiment could be properly normalized. The data collection and scanning scintillator were controlled from the electronics trailer using a personal computer. Foil thicknesses were comparable to those being used for injection into existing storage rings and to those being considered for storage rings at the next generation of spallation neutron sources.

As a beam of H^- ions passes through a foil, some are stripped completely to protons, H^+ , some emerge as neutral hydrogen in various excited states, $H^0(n, l, m)$, and some pass through unscathed as H^- . The various species were analyzed by measuring their trajectories in the gradient magnet downstream of the foil. Each excited state would field-strip at a particular field value in the gradient and the outgoing proton would then be bent in the field. The magnet's field shape was similar to the fringe field in a ring-bending magnet.

Fig. 1. Schematic of experiment to measure production of excited states. Standard beam diagnostics and phase-space tailoring apparatus are not shown.

The gradient magnet was a half-quadrupole turned sideways to the beam. The beam entered through a hole in the return yoke and then encountered a vertical magnetic field whose strength increased linearly with distance. The maximum field available was 1.9 T and the length of the gradient region was 0.2 m. The magnet had been used previously to study the ionization probability of the H^- ground state as a function of field [4].

We used carbon and aluminum oxide foils ranging from 20 to 500 micrograms/cm² in thickness. The foil thicknesses were determined in a separate experiment [5] using a combination of alpha ranging, Rutherford back scattering, weighing, and optical transmission.

Analysis

The analysis of the H^0 excited states depends upon a model for field stripping. When the H^0 enter a magnetic field, they are subjected to a motional electric field in their rest frame. This field is given by

$$\mathbf{F} = (3 \times 10^6) \gamma \beta \times \mathbf{B} , \quad (1)$$

where $\mathbf{F}$ is in V/m and $\mathbf{B}$ is in Tesla. The symbols γ and β are the usual relativistic parameters of the beam. For an 800-MeV atom, $\beta = 0.842$ and $\gamma = 1.85$. Thus, a magnetic field of 1 T transforms to an electric field of 4.7 MV/m in the rest frame of the atom.

This intense electric field causes the atom to become unstable since the electron can tunnel out through the potential barrier. Ionization will proceed rapidly at a critical field given, to first order, by

$$F_c [\text{V/m}] = \frac{5.142 \times 10^{11}}{9n^4} , \quad (2)$$

where n is the principal quantum number of the spherical states.

In the presence of a field, the states with definite lifetime are parabolic states represented by the quantum numbers (n_1, n_2, m) [6]. These are related to the spherical states (n, l, m) through the Clebsch-Gordon coefficients. The principal quantum number is related to the parabolic quantum numbers by

$$n = n_1 + n_2 + m + 1 . \quad (3)$$

The states in the magnetic field are described using the Damburg-Kolosov (DK) formalism [7]. DK represents the unstable states as Breit-Wigner resonances and gives a formula for the widths in terms of the field, the

Stark-shifted energy of the state, and the parabolic quantum numbers. The energies of the states are calculated to fifth order using perturbation theory.

We have tested the DK formalism by comparing it to exact numerical calculations. These numerical calculations were verified in a previous experiment where we used a laser to excite the Stark states [8]. We found that the DK energies are accurate to 0.05% and the DK widths are accurate to better than 20% in the region of interest.

Our analysis code starts with a given distribution of excited states, finds out where they ionize using the DK formalism, and then traces the H^+ trajectories through the magnet and into the detector using the measured map of the magnetic field. The input parameters are then varied using a non-linear optimization code until a best fit is obtained. Many of the software subroutines were developed in our previous series of foil experiments [1].

Results

The experiment was very clean with signal-to-background ratios of between 10^5 and 10^6 . Preliminary results for both basic physics and storage ring implications have been presented at recent conferences [9-14]. The experiment verifies that excited states of H^0 are produced in sufficient numbers (approximately 1%) to be a problem in the next generation of storage rings unless special precautions are taken. There is evidence that higher values of the orbital quantum number l are populated than would be predicted by purely statistical arguments. The dependence of the population on principle quantum number n shows a distinct break between $n = 2$ and higher values. Placing a magnetic field directly at the foil appears to alter the distribution of excited states [14].

Acknowledgments

We wish to thank Thomas Bergeman and Joseph Macek for many useful theoretical discussions. The dedication of the LAMPF staff was essential to the success of this experiment, especially the contributions of John O'Donnell, Kevin Jones, Larry Rybarcyk, John Gomez, and Lawrence Quintana. The UNM group was supported by the Division of Chemical Sciences, Office of Basic Energy Sciences.

References

1. A. H. Mohagheghi, H. C. Bryant, P. G. Harris, R. A. Reeder, H. Sharifian, C. Y. Tang et al., *Phys. Rev. A* **43**, 1345 (1991); A. H. Mohagheghi, "Interaction of Relativistic H^- Ions with Thin Foils,"

- Ph.D. Thesis, Los Alamos National Laboratory report LA-11925-T (1990).
2. J. Burgdorfer and C. Bottcher, *Phys. Rev. Lett* **61**, 2917 (1988).
 3. P. G. Harris, H. C. Bryant, A. H. Mohagheghi, R. A. Reeder, C. Y. Tang, J. B. Donahue et al, *Nucl. Instrum. Methods A* **292**, 254 (1990).
 4. A. J. Jason, D. W. Hudgings, and O. B. van Dyck, "Neutralization of H^- Beams by Magnetic Stripping," Los Alamos National Laboratory document LA-UR-81-831 (1981).
 5. M. S. Gulley and W. A. Miller, "Final Report on Foil Thicknesses," Gypsy Collaboration Technical Note No. 1 (1994).
 6. H. A. Bethe and E. E. Salpeter, *Quantum Mechanics of One- and Two-Electron Atoms* (Plenum Press, 1957).
 7. R. J. Damburg and V. V. Kolosov, "Hydrogen Rydberg Atoms in Electric Fields," in *Rydberg States of Atoms and Molecules*, R. F. Stebbings and F. B. Dunning, Eds. (Cambridge University Press, 1983).
 8. T. Bergeman, C. Harvey, K. B. Butterfield, H. C. Bryant, D. A. Clark, P. A. M. Gram et al., *Phys. Rev. Lett.* **53**, 775 (1984).
 9. E. P. Mackerrow et al, "Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions," Los Alamos National Laboratory document LA-UR-93-2038 (presented at the 1993 Annual Meeting of the Division of Atomic, Molecular and Optical Physics of the American Physical Society, Reno, Nevada, May 16-19, 1993).
 10. J. B. Donahue, D. A. Clark, S. Cohen, D. H. Fitzgerald, S. C. Frankle, R. L. Hutson et al, "Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions," Los Alamos National Laboratory document LA-UR-92-4234 (presented to the 1993 Particle Accelerator Conference, Washington, DC, May 17-20, 1993).
 11. R. J. Macek and the extended PSR Development Team, "Machine Studies at the Los Alamos Proton Storage Ring," Los Alamos National Laboratory document LA-UR-93-2941 (presented at the ICANS XII Meeting, Abingdon, UK, May 24-28, 1993).
 12. P. B. Keating et al., "Interaction of 800-MeV H^- Ions with Carbon and Aluminum Oxide Foils," presented at the 1994 Joint April Meeting of the American Physical Society and the American Association of Physics Teachers, April 18-22, 1994, *Bull. Am. Phys. Soc.* **39**, 1063 (1994).
 13. M. S. Gulley et al., "Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions," presented at the 1994 Joint April Meeting of the American Physical Society and the American Association of Physics Teachers, April 18-22, 1994 *Bull. Am. Phys. Soc.* **39**, 1124 (1994).
 14. H. C. Bryant et al., "Magnetic-Field Assisted Stripping of 800-MeV H^- Ions Passing through Thin Foils," presented at SASP 94, Innsbruck, Austria.

Radiation Effects Research

Experiment 1139 — HRS

TESTING OF RADIATION RESISTANCE OF READ-OUT CHIPS AND SILICON DETECTORS FOR USE IN HIGH-RATE NUCLEAR AND PARTICLE PHYSICS APPLICATIONS

Participants

H.-J. Ziock (Co-Spokesman), K. Holzscheiter, A. Morgan,
A. P. T. Palounek, J. Ellison, A. P. Heinson, M. Mason, S. J. Wimpenny,
E. Barberis, N. Cartiglia, A. Grillo, K. O'Shaughnessy, J. Rahn,
P. Rinalki, W. A. Rowe, H. F.-W. Sadrozinski (Co-Spokesman), A. Seiden,
E. Spencer, A. Webster, R. Wichmann, M. Wilder, M. A. Frautschi,
J. A. J. Matthews, D. McDonald, D. Skinner, D. Coupal, and T. Pal

Institutions

Los Alamos National Laboratory, UC Riverside, UC Santa Cruz,
University of New Mexico, and SSC Laboratory

The purpose of this experiment was to determine and understand the radiation damage issues for silicon detector systems exposed to very high fluence levels ($>10^{14}/\text{cm}^2$). The HRS beam line proved to be ideal for those studies, providing a well-characterized beam of heavy particles, which could cause displacement damage, and which was of sufficient intensity to provide the required fluences even when the beam spot was expanded to be over 5 cm in diameter. It is extremely unfortunate that the channel is no longer operational.

We made detailed measurements to quantify the different radiation damage effects: surface charging, leakage current increases, carrier trapping, and dopant concentration changes in silicon detectors. Following the exposure, we determined the parameters describing short-term self-annealing effects, and then followed the behavior of the devices for well over a year to determine long-term annealing effects. We found that in contrast to the beneficial nature of the short-term annealing, on a longer time scale, some of the properties of the detector actually degraded with time (following their initial short-term improvement), even without any additional radiation exposure. The degradation continued to a point, where the detectors were actually worse off than when they were initially removed from the beam. Figure 1 shows the behavior of the voltage required to deplete (operate) the detector. The temperature dependencies of both the short- and long-term annealing were determined.¹ Our results now form the basis of all plans for operating silicon detectors in high-luminosity environments.

Fig. 1. The depletion voltage of 170- μm thick Hamamatsu photodiodes as a function of fluence and as a function of annealing time for 0°C and room-temperature operation. The last points on the left-hand plot correspond to the first points on the right-hand plot.

Reference

1. H.-J. Ziöck, K. Holzscheiter, A. Morgan, A. P. T. Palounek, J. Ellison, A. P. Heinson et al., *Nucl. Instrum. Methods A* 342, 96 (1994).

Materials Science Research

**MUON LEVEL-CROSSING RESONANCE IN HEAVILY-DOPED
GaAs:Si**

Participants

D. W. Cooke (Spokesperson), K. H. Chow, S. F. J. Cox, T. L. Estle,
K. Heidersbach, B. Hitti, M. Leon, R. L. Lichti, A. Morrobel-Sosa,
J. Oostens, M. A. Paciotti, and L. Zavieh

Institutions

Los Alamos National Laboratory, California Polytechnic State
University (San Luis Obispo), ISIS (Rutherford Appleton Laboratory,
Texas Tech University, Rice University, Lindsey Wilson College, and
TRIUMF and University of British Columbia

Introduction

Muon level-crossing resonance (μ LCR) has been established as a powerful variant of the muon spin rotation/relaxation/resonance (μ SR) technique [1], and has been widely used to understand hyperfine interactions of muonium-substituted free radicals [2], and muonium defect centers in semiconductors [3]. The latter application of μ LCR has technological importance because it can be used to examine the role of hydrogen in semiconductors, especially hydrogen passivation [4]. Due to the high mobility of H and its reactivity in semiconductors, it is difficult to study isolated H in these materials. On the other hand, one can use muonium (μ^+e^-) as the hydrogen analog (mass of Mu is 1/9 mass of H) and examine its behavior in semiconductors, where previous studies have shown it to be similar to H. Much interest in the role of H in semiconductors has been generated in the past several years by the discovery that H can *passivate* the electrical activity of defects and impurities in semiconductors [5]. The primary source of information on H in semiconductors has in fact come from muonium studies. In this progress report we present experimental observations of μ LCR in heavily-doped GaAs:Si and assign the resonances to Mu interactions with ^{69}Ga , ^{71}Ga , and ^{75}As quadrupole moments. These results, in conjunction with previous transverse- and longitudinal-field data, allow us to speculate that diamagnetic Mu in GaAs:Si is due to Mu^- . If confirmed, this would be the first observation of Mu^- in a semiconductor.

Experiment

In a μ LCR experiment, positive muons (μ^+) with nearly 100% spin polarization are implanted in the sample of interest, which is subjected to

an external, longitudinal magnetic field—the direction of the field is coincident with the direction of the μ^+ spin. Muons decay via weak beta decay into positrons and two neutrinos with a lifetime t_μ of $\sim 2.2 \mu\text{s}$, with an asymmetric decay distribution. Typically, positron counters are arranged in the forward (F) and backward (B) direction of the μ^+ spin and detect the emitted positrons in a time-integral mode, thereby yielding a measure of the forward-backward asymmetry,

$$A = \frac{N_F - N_B}{N_F + N_B} \quad (1)$$

$$= \frac{\alpha}{\tau_\mu} \int_0^{\infty} e^{-\frac{t}{\tau_\mu}} P(H, t) dt$$

where α is an instrumental asymmetry and $P(H, t)$ is the time evolution of the muon polarization along the direction of applied field and initial μ^+ spin. In contrast to time-differential μSR , there is no need to keep track of when the muons enter the sample; therefore, there is no restriction on the rate of muons impinging on the sample and a higher flux is obviously advantageous. At present, the world's most intense μ^+ beam is LAMPF ($\sim 2 \times 10^7 \mu^+/\text{s}$), and advantage is taken of this high flux to do μLCR experiments.

Muon level-crossing resonance occurs when the longitudinally applied field is such that the Zeeman energy of the μ^+ matches the nuclear quadrupole splittings of the host nucleus. At this field value, there is a loss of μ^+ polarization resulting in a dip of the asymmetry plot. In a simplified case, we have

$$H_{\text{res}} \gamma_\mu \equiv H_{\text{res}} \gamma_n + \Omega_q \quad (2)$$

H_{res} is the resonance magnetic field, γ_μ and γ_n are the gyromagnetic ratios of the μ^+ and host nucleus, and Ω_q is the quadrupolar interaction. Thus, a measure of the μLCR spectrum provides H_{res} and information on Ω_q can be extracted. The experiment is performed by scanning the longitudinal magnetic field and measuring the asymmetry, as a function of temperature.

Single-crystal [100] GaAs:Si provided by Laser-Diode, Inc., was prepared by the liquid encapsulation Czochralski method with a $\sim 3 \times 10^{18} \text{ cm}^{-3}$ Si-dopant concentration (*n*-type). The effect of the heavy doping is to cause the sample to undergo an insulator-to-metal transition so that it conducts at temperatures below the ionization temperature of the impurities. Furthermore, this doping shifts the Fermi level to near the band-gap edge, producing a strong effect on the stability of the muonium states. For

temperature scans, the sample was mounted on a cold-finger of a helium-flow cryostat with automatic temperature control. Magnetic field nulling coils were used to remove extraneous fields and a scan coil was used, in addition to a large Helmholtz coil, to rapidly (0.53 Hz) scan the longitudinal magnetic field. The apparatus has been described in a previous publication [6].

Results and Discussion

The μ LCR spectrum for [100] GaAs:Si taken at 300 K is shown in Fig. 1; resonances occur at 9.6, 21.6, 26.4, 34.8, and 40.2 mT. This spectrum is temperature dependent with maximum intensity at RT. With decreasing temperature, the resonances decrease in intensity, and near 150 K the signal is barely resolvable. Thus, the muonium interaction with the surrounding quadrupole moments is temperature dependent, suggesting a transformation of the muonium species. We note that implantation of muons into semiconductors typically produces two distinct neutral paramagnetic centers Mu_T (normal muonium) and Mu_{BC} (anomalous Mu, labeled Mu^*), and a diamagnetic center Mu_D . From previous work on GaAs, the existence of Mu_T has been established. It is characterized by an isotropic hyperfine interaction and rapid diffusion [7]. Mu^* , characterized by an anisotropic hyperfine interaction, has also been experimentally verified. This center occupies a bond-centered site in a relaxed Ga-As bond [8].

As a first step in determining the muonium sites in GaAs:Si, we assume that the measured μ LCR spectrum is due to muonium interactions with neighboring quadrupole moments, and calculate a dimensionless quantity K that is proportional to the electric field gradient. Because the EFG is expected to be independent of the particular isotope for a given nucleus, K should be the same for the two resonances corresponding to either ^{69}Ga ($J = 3/2$; abundance = 60%) or ^{71}Ga ($J = 3/2$; abundance = 40%). For a nucleus with gyromagnetic ratio γ_i and quadrupole moment Q_i , the μ LCR field is given by $B_i = [KQ_i/(\gamma_\mu - \gamma_i)]$, where $\gamma_\mu/2\pi = 1.355$ MHz/mT. After checking all possible combinations of resonances, we find that K is the same (within 3%) if we make the following assignment: ^{71}Ga (21.6 mT) and ^{69}Ga (34.8 mT) correspond to one site and ^{71}Ga (26.4 mT) and ^{69}Ga (40.2 mT) correspond to another site. Thus, we suggest that we have two distinct sites in GaAs:Si where muonium interacts with neighboring quadrupole moments. Further, we assume, without calculation, that the resonance at 9.6 mT is due to ^{75}As ($J = 3/2$; abundance = 100%). These results give only the site assignment; a detailed calculation using the full Hamiltonian to describe the appropriate muon-nucleus interactions will be required to understand the details of the specific sites [8]. This calculation must start, however, with some assumptions regarding the possible sites in GaAs:Si, which are provided by the μ LCR data reported herein.

Fig. 1. The μ LCR spectrum for [100] GaAs:Si taken at 300 K.

Based on previous transverse- and longitudinal-field μ SR experiments in heavily-doped n -type GaAs:Si, it has been shown that both Mu^+ and Mu_p exist in this sample [9]. The μ LCR spectrum associated with Mu^+ occurs at high fields ($\sim$ Tesla) [10], and thus we speculate that our low-field resonances are due to Mu_p . The charge state of Mu_p is not presently known, but based on theoretical calculations for H, it has been suggested that it is likely Mu^- [9]. Further, it was shown that the likely site for Mu_p was a tetrahedral site with Ga the nearest neighbor. These suggestions are consistent with our μ LCR observations. Of considerable interest is the mechanism responsible for converting the unknown low-temperature muonium species to Mu^- above ~ 150 K. Further work will be required to unravel these questions.

Conclusions

Muon level-crossing resonance experiments were done on heavily-doped GaAs:Si (n -type) as a function of temperature. Resonances were observed at 9.6, 21.6, 26.4, 34.8, and 40.2 mT, and were assigned to muonium interactions with quadrupole moments of ^{69}Ga , ^{71}Ga , and ^{75}As nuclei.

Temperature-dependent μ LCR data show that the strongest signals occur at RT and decrease with decreasing T, becoming unobservable below about 150 K. In conjunction with previous transverse- and longitudinal-field μ SR data, we speculate that our resonances are associated with Mu_D in a tetrahedral site with Ga nearest neighbor. The charge state of Mu_D may be Mu^- , which, if confirmed, would be the first spectroscopic observation of such a state in semiconductors.

References

1. S. R. Kreitzman et al., *Phys. Rev. Lett.* **56**, 181 (1986).
2. R. F. Kiefl et al., *Chem. Phys. Lett.* **143**, 613 (1988).
3. J. W. Schneider et al., *Phys. Lett. A* **134**, 137 (1988).
4. See, for example, *Hydrogen in Crystalline Semiconductors*, S. J. Pearton, J. W. Corbett, and M. Stavola, Eds. (Springer-Verlag, Berlin, 1992).
5. S. M. Myers et al., *Rev. Mod. Phys.* **64**, 559 (1992).
6. M. A. Paciotti et al., in *Proc. of μ SR 93-Maui*, Hawaii, June 7-11, 1993. To be published in *Hyperfine Interactions*.
7. J. W. Schneider et al., *Materials Science Forum* **83-87**, 569 (1992); R. Kadono et al., *Hyperfine Int.* **64**, 635 (1990).
8. J. W. Schneider et al., *Phys. Rev. Lett.* **47**, 10193 (1993).
9. K. H. Chow et al., in *Proc. of μ SR 93-Maui*, Hawaii, June 7-11, 1993. To be published in *Hyperfine Interactions*.
10. R. F. Kiefl et al., *Phys. Rev. Lett.* **58**, 1780 (1987).

Astrophysics Research

HIGH-ENERGY GAMMA-RAY ASTRONOMY: CYGNUS/MILAGRO EXPERIMENTS

Participants

R. Burman, T. Haines, C. Hoffman (Co-Spokesman), D. Nagle,
V. Sandberg, D. Schmidt, C. Sinnis, S. Freedman, B. Fujikawa,
D. Alexandreas, S. Biller, P. Chumney, S. Delay, G. Dion, A. Shoup,
G. Yodh, T. Tumer, J. P. Wu, A. Zych, M. Cavalli-Sforza, D. Coyne,
D. Dorfan, L. Kelley, S. Klein, R. Schnee, D. A. Williams, T. Yang,
G. Allen, C. Y. Chang, M. Chen, C. Dion, J. Goodman (Co-Spokesman),
M. Stark, R. Ellsworth, A. Mincer, and P. Nemethy

Institutions

Los Alamos National Laboratory, UC Berkeley, UC Irvine,
UC Riverside, UC Santa Cruz, University of Maryland,
George Mason University, and New York University

The CYGNUS air-shower array, located near the LAMPF beam stop, detects extensive air showers that are produced by the interaction of ultra-high-energy (UHE, 40 TeV–10 PeV) cosmic rays with the Earth's atmosphere. One of the goals is to observe astrophysical point sources of UHE gamma rays. The CYGNUS array, one of the world's premier arrays, consists of 204 scintillation counters deployed over 80,000 m². CYGNUS, which grew out of the LAMPF-based nuclear physics research program, has been running continuously since 1986 and has collected nearly 500 million events. The high-altitude site, the infrastructure at LAMPF that facilitated mounting the experiment, and the availability of large, shielded detectors (the veto shields for the LAMPF neutrino experiments) to serve as muon counters, made CYGNUS a particularly cost-effective experiment. The CYGNUS array is the only Los Alamos observational facility for ground-based astronomy.

Among the achievements of the CYGNUS group are the first all-sky UHE survey, the first comprehensive search for UHE emission from a variety of point astrophysical sources, the first observation of the shadow of the sun and moon in cosmic rays, and the invention and demonstration of the advantages of large water Cerenkov counters as air-shower detectors.

In 1993, the CYGNUS collaboration had four papers published in refereed journals. They include a search for UHE emission from active galactic nuclei (AGN), a daily search for UHE emission from a variety of potential

point sources, and a search for UHE emission in the final seconds of the evaporation of primordial black holes.

By their nature, compact astrophysical objects might be expected to be episodic, rather than steady, emitters of UHE photons. It is difficult to imagine how they could sustain continuous UHE emission. The EGRET detector aboard the CGRO satellite has detected a variety of new GeV sources, all exhibiting rapid variability in emission. In this past year, the CYGNUS collaboration has performed a search for UHE emission over all time-scales, ranging from seconds to years, from a large number of potential point astrophysical UHE sources; this is the first such study. No emission has been detected. A paper on this study was submitted for publication. Figure 1 shows typical upper limits for the steady flux from these objects as a function of the declination of the source.

One of the surprising results from EGRET has been the detection of GeV emission from over two dozen active galactic nuclei (AGN). The Whipple air Čerenkov telescope has already detected one of these AGNs, Markarian 421, at 1 TeV. These measurements indicate a differential energy spectrum

Fig. 1. The 90% confidence level flux upper limit for continuous emission from a candidate point source as a function of the declination, assuming there are no excess events observed from the source position. The dashed curve (and left axis) shows the flux limit as a percent of the cosmic-ray flux; the solid curve (and right axis) shows the flux limit above 80 TeV for gamma rays, assuming a gamma-ray spectrum the same as cosmic rays.

of roughly E^{-2} . Because of its distance (~ 100 Mpc), photons with energy above 100 TeV are expected to be absorbed by (e^+, e^-) pair production off the 2.7-K cosmic microwave background. CYGNUS data from April 1986 through January 1993 yield an upper limit for the flux from Mrk 421 above 50 TeV of 7.5×10^{-14} photons/cm²s⁻¹ (at the 90% confidence level). Figure 2 shows the flux upper limit together with the fluxes measured by EGRET and the Whipple telescope. The paper also contains published stringent upper limits on UHE emission from all of the Northern Hemisphere AGNs detected by EGRET.

Density fluctuations in the early universe can lead to the formation of light black holes. The mass spectrum of these black holes is sensitive to the form of the density fluctuations and the equation of state of the universe. Primordial black holes (PBHs) should be detectable through the Hawking radiation that they emit. The emission spectrum is blackbody, characterized by a temperature that is inversely proportional to the mass of the black hole. The radiation leads to a loss of mass and therefore an increase in temperature and luminosity. This runaway process leads to UHE emission in the last seconds of the lifetime of a PBH. A PBH of initial mass

Fig. 2. The integral gamma-ray fluxes for Mrk 421 as observed by EGRET and the Whipple telescope together with the muon-poor upper limit from the CYGNUS experiment. The dotted (dashed) curve corresponds to the expected spectrum at Earth with (without) absorption by the cosmic microwave background.

5×10^{14} g would have a current temperature of 10 TeV and a residual lifetime of ~ 1 second. The CYGNUS group pioneered a novel analysis technique that allowed a sensitive search for the evaporation of PBHs. The resulting new upper limit on the rate density of evaporating PBHs (8.5×10^6 evaporations $\text{pc}^{-3}\text{yr}^{-1}$), is the most restrictive by nearly two orders of magnitude.

One of the most exciting phenomena in astrophysics is gamma-ray bursts (GRBs). Previously thought to be local (galactic) events of low luminosity, observations by the BATSE detector aboard CGRO indicate that GRBs do not cluster in the galactic plane. Even more startling, EGRET has detected gamma rays from GRBs with energies as high as 25 GeV with no evidence of a spectral cutoff. The CYGNUS group searched for UHE emission from the GRBs seen by BATSE. The upper limits for the UHE flux for some of these bursts imply that either the energy spectrum steepens significantly below 100 TeV or that the GRBs are at cosmological distances and the UHE photons are attenuated as discussed above.

There have been some observations made around 1 TeV (very high energy, VHE) with air Čerenkov detectors. One source (the Crab nebula) has been established as a constant emitter of VHE photons. Another source, the AGN Markarian 421, has also been observed to be a source of VHE photons. As optical devices, however, air Čerenkov detectors can only observe one source at a time, and only on clear, moonless nights. Thus, they are of limited value in studying highly variable sources, and are incapable of studying emission from random directions in the sky, as is necessary to search for emission from gamma-ray bursts or evaporating primordial black holes.

Thus, there is considerable interest in building an air-shower array with an energy threshold below 1 TeV that can perform all-sky, 24-hour-per-day observations. The CYGNUS group invented and demonstrated the use of a large water Čerenkov counter as a low-energy-threshold air-shower detector. The CYGNUS group, augmented with additional collaborators, has proposed such a detector, called Milagro, to detect cosmic gamma rays from below 1 TeV to several PeV. Milagro will be built in an existing large (60 m $\times$ 80 m), covered, water pond at a Laboratory site located in the Jemez Mountains near Los Alamos. Figure 3 shows an aerial view of the empty pond at the Milagro site.

The proposal for Milagro construction funds has been approved by the NSF. We expect to obtain DOE/HEP funds for site preparation. A construction period of 3–4 years is envisaged. We will continue to operate the CYGNUS detector while Milagro is being constructed. After Milagro is operational, we will move the CYGNUS scintillation detectors to the site to augment the capabilities of Milagro.

The major scientific goals of Milagro are:

1. The first all-sky VHE map.
2. The first search for VHE emission from gamma-ray bursts. These results will determine the upper end of the energy spectrum of GRBs and may allow a determination of their distance from earth.
3. A search for VHE and UHE emission from active galactic nuclei. VHE emission from one AGN, Markarian 421, will be observed. These measurements will provide constraints on the acceleration mechanisms in AGNs and the strength and spectrum of the intergalactic infrared radiation field.
4. The most sensitive direct search for primordial black holes ever performed.
5. Measurement of the VHE energy spectrum from the Crab nebula. This will distinguish between various models that have been proposed to explain high-energy emission from the Crab.
6. A search for episodic VHE emission from many point sources.
7. The measurement of VHE gamma-ray emission from the galactic plane. This measurement will help constrain models of the production and trapping of cosmic rays.
8. Observations of shifts in the apparent position of the shadow of the sun. This determines the component of the sun's magnetic field that is perpendicular to the line of sight.
9. Measurement of the time structure of energetic solar mass ejections. This will determine if these ejections involve solar trapping of high-energy particles.

Theoretical Physics Research

T-5 THEORY GROUP RESEARCH HIGHLIGHTS

Briefly summarized here are selected research topics in which members of the Medium-Energy Theory Group of the Theoretical Division have been involved during 1992-93. These topics cover a wide range of subject matter. Further information can be obtained by contacting T-5 group members: J. A. Carlson, J. L. Friar, B. F. Gibson, J. N. Ginocchio, T. Goldman (Group Leader), P. Herczeg, and R. R. Silbar. C. J. Benesh, C. W. Johnson, and R. G. E. Timmermans, who held postdoctoral appointments during this period, also contributed to this report.

Quarks and QCD

Color Transparency

In collaboration with workers at Iowa State, we have made a study of the E772 and NA3 data on J/Ψ production using nuclear targets. Final-state interactions of $c\bar{c}$ pairs are modeled using simple Glauber Theory and either a constant J/Ψ nucleon cross section of 4 mb, or a cross section that incorporates the effect of color transparency. The modification of the initial state quark distribution is modeled at small x_2 by the parton recombination picture, in which the effect of interactions between partons in different nucleons in the nucleus is calculated using perturbative QCD. At larger x_2 , a parameterization of the ratio of parton distributions to those in the proton is used. We find that both the NA3 and E772 data are well described by the constant cross section model, with no evidence for color transparency or violations of x_2 scaling in the nucleus.

Substructure Effect on Meson-Meson Mixing

We have studied the effect of quark substructure on the strength of ρ - ω mixing as a function of the square of the four-momentum of the meson and found that the effect of such substructure is to introduce a significant variation absent in the conventional fixed-mixing-amplitude assumption. Because the effect of this momentum dependence on the contribution of ρ - ω mixing to charge symmetry breaking (CSB) is disastrous (an amplitude fitted to the experimental point in the time-like region contributes less than one-fifth of the CSB found in the conventional approach), we confirmed the systematics of our result in a bosonic loop calculation. Maltman has since claimed similar results for π^0 - η mixing using loops in chiral perturbation theory. We have repeated the π^0 - η mixing calculation using the same quark loop model as in the original ρ - ω study. Although it is not possible to

match absolute scales, it is possible to compare the rate of variation of the mixing strength as the squared four-momentum varies near zero for the quark loop and chiral perturbation theory calculations. These agree within the uncertainties of the soundly-based chiral perturbation theory method. This adds support to the essential result of the original calculation, that the mixing matrix element variation cannot be ignored.

We also calculated the diagonal self-energy variation at the one-loop level. Here we found that the variation with squared four-momentum could be large, overwhelming the effect of mass terms. In fact, at this level, the diagonal corrections can amplify the CSB effect strongly and compensate for the losses in strength due to the variation of the mixing matrix element. We conclude that these diagonal self-energy corrections must be calculated fully nonperturbatively before the net result of these mixing matrix element variations on CSB can be determined.

Gluon QCD

We have studied the formation of a chirally symmetric color nonet (octet plus singlet) of scalar and pseudoscalar glueballs. A σ -model-like structure is found, where the gluon condensate appears as the analog to the σ field and mixes with it. The analogy suggests that the difficulty in observing the lowest mass color-singlet glueball state is similar to that for the σ meson. Conversely, the nonlinear σ model then suggests non-linearizing the color multiplets.

These scalars couple to color sources (quarks and gluons) with two powers of the strong coupling constant. This produces an interesting effect when the infrared growth of this coupling is taken into account: The effect of exchanges of the color-singlet scalar has the right properties to produce, using the one-boson-exchange approach familiar to nuclear physics, a color-confining scalar potential, even if the scalar field is massive. This potential dominates that from "one"-gluon exchange, and is consistent with spectral observations in heavy quark systems. We are studying experimental signals that may aid in discovery of this scalar glueball, based on our interpretation of it as a color-magnetic flux loop.

Hadron Interactions

Chiral Perturbation Theory and the Nuclear Force

Recent work on the few-nucleon systems has suggested that chiral perturbation theory may provide a framework for calculating the bulk of the potential energy in those systems. The demonstration that OPEP alone generates roughly 80% of that energy makes it imperative to determine as much of the rest as possible "from first principles." The calculation by

Coon, Friar, and Weinberg of the leading-order three-nucleon force contribution, and the calculation of the next-to-leading-order two-nucleon force by van Kolck and Ordóñez are still far from adequate. Shorter-range contributions must be calculated, and this will require a systematic treatment of as much of the correlated two-pion exchange between two nucleons as is tractable. Contributions from nucleon resonances must also be treated. It appears likely at this juncture that phenomenological verification of much of this treatment will be necessary, and it appears that the Nijmegen nucleon-nucleon partial-wave analysis group can provide the necessary sensitivity. Although it is by no means certain that chiral perturbation theory can provide the necessary framework without resorting to impractically high orders of perturbation theory, it may be possible to generate an understanding of most of the triton binding from "first principles."

Inversion Potential Analysis of Nuclear Dynamics in ^3H

Triton calculations, utilizing new Nijmegen local potentials that fit the nucleon-nucleon (NN) scattering data in the range of 0–350 MeV almost as well as the Nijmegen phase shift analysis, were recently completed by Friar and collaborators. The results were summarized as yielding a binding energy of 7.62 ± 0.01 MeV, some 0.86 MeV smaller than the experimental value of 8.48 MeV. Alternatively, the Hamburg group has developed the technique for constructing inversion potentials from quality phase-shift data to the point that one can generate equally precise partial-wave local potentials on a mesh. That is, we can now compare triton binding energy results for potentials constructed from (1) a theoretical, meson-exchange approach and (2) an inversion prescription that generates an *equivalent* partial-wave local function. Thus, one can investigate quantitatively the effect of uncertainties in the on-shell scattering data on the estimate of the error in the ^3H binding energy, as well as the effect of nonlocality in the potential models.

The discrepancy between the experimental value for the triton binding energy and results for various NN potential models has been attributed by some to the need to include a three-body force (3BF) in the Hamiltonian. It was recently shown by the Hannover group that, when the full Tucson-Melbourne (TM) three-nucleon force ($\pi\pi$, $\pi\rho$, and $\rho\rho$ terms), which was designed to be used with nucleon-nucleon potentials that incorporate only nucleon degrees of freedom, was combined with the Reid soft-core, Paris, and Nijmegen potentials, the model ^3H binding energies were quite close to 8.48 MeV. That is, a 3BF can play a role in the triton. The source of that 3BF is not necessarily established; it may come in part from nonlocality in the nucleon-nucleon force. For example, combining the TM 3BF with the Bonn-B potential leads to significant overbinding of the triton. This implies significant double counting, when one combines the TM 3BF with a non-

local potential such as Bonn-B. It has been shown by Polyzou and Glöckle that a unitary transform relationship exists between Hamiltonians comprised of local NN plus NNN potentials and Hamiltonians comprised of nonlocal NN potentials. Their mathematical study did not enforce a requirement that the interaction have a long-range one-pion-exchange (OPE) tail, but it is not difficult to conceive of restricting the unitary transformations to ranges shorter than OPE.

To test these concepts, we have completed exact ^3H binding energy calculations using inversion potentials generated from phase shifts corresponding to contemporary nucleon-nucleon potentials (including the Nijmegen models) as well as modern phase shift analyses. Using phase shifts from a given local potential model generates an inversion potential that yields the same ^3H binding as the original model. By studying variations in the NN phase shifts outside the 0–350-MeV energy range in which the potentials are fitted to the NN observables, we are able to place bounds on the triton binding energy calculated with *partial-wave local potentials* that include errors due to the underlying uncertainties in their fit to the nucleon-nucleon phase shifts: 7.7 ± 0.2 MeV. Furthermore, by comparing results for the Bonn-B potential with results for its local inversion counterpart, we find that some 0.25 MeV of the binding energy is due to a long-range nonlocality, which may correspond to a three-nucleon force when the Hamiltonian is restricted to a local function.

Novel Soft-Photon Analysis of $pp\gamma$ Below the Pion-Production Threshold

The bremsstrahlung cross section for hadron-hadron scattering can be written as $\sigma = A/k + B + Ck + \dots$, where the coefficients A and B in the expansion can be expressed in terms of the on-shell (elastic scattering) amplitudes. Numerous attempts to analyze nucleon-nucleon bremsstrahlung in terms of the soft-photon approximation ($A/k + B$) have been made. For more than 30 years the conventional Low soft-photon amplitude has been widely used for studying nuclear and particle bremsstrahlung processes. It seemingly provided a good representation for several $pp\gamma$ measurements. However, it was recently shown that the Low amplitude fails to describe the higher energy 280-MeV $pp\gamma$ cross section and analyzing power data from TRIUMF.

We have proposed a novel soft-photon amplitude to replace the conventional Low prescription. This new amplitude belongs to one of two general classes of soft-photon amplitudes, which we derived last year in conjunction with our analysis of $n\pi\gamma$ experiments such as that now under way at LAMPF. We have demonstrated that the $pp\gamma$ cross section data from low energies to energies near the pion production threshold can be consistently described by our new amplitude. We will apply the new amplitude to predict cross

sections and analyzing powers for the proposed $pp\gamma$ experiments at COSY (Jülich), CELCIUS (Uppsala), and KVI (Groningen).

In addition to reproducing the existing $pp\gamma$ data, our new soft-photon amplitude essentially eliminates the discrepancy between the soft-photon approximation and potential-model calculations. This agreement implies that "off-shell" effects in the pp bremsstrahlung measurements to date are essentially negligible. Finally, our investigation of the conventional Low amplitude has revealed why it works in some cases but fails in others.

Pion Double Charge Exchange and Generalized Seniority

The double charge exchange reaction (DCX) is a unique reaction in that it takes place, in lowest order, on two nucleons. For this reason, DCX, which is an isotensor reaction, holds the promise of determining the isotensor part of the two-nucleon density in nuclei. The pion is the least complex probe with which DCX is possible. Progress in understanding pion DCX as a probe of pairing correlations in nuclei has been made at LAMPF by studying this reaction on the calcium isotopes as a function of neutron number. It has been shown theoretically and confirmed experimentally that the DCX cross section to the DIAS is an explicit function of neutron number for targets with only valence neutrons and seniority zero and depends on only two complex amplitudes for DCX on two valence neutrons, called A and B . The amplitude A is long range and measures primarily the average DCX cross section on two valence neutrons independent of their total angular momentum. The amplitude B , on the other hand, measures the extent to which the DCX cross section on two valence neutron pairs coupled to angular momentum zero differs from this average DCX cross section. Furthermore, these amplitudes have dissimilar dependence on pion energy, and hence various aspects of the nucleus can be studied at different energies. In particular, B is comparable to A at about 50 MeV pion energy, which makes this energy preferred for studying the ground-state transition. Furthermore, in the seniority model, the transition to the ground state depends only on the amplitude B , not on any new amplitude. Since B can be determined from the DIAS transition, the ground state can be predicted within the seniority model and any deviation can then be used to determine the seniority mixing.

However, the calcium isotopes are not typical of medium weight or heavy nuclei for which configuration mixing is large. For nuclei with only valence neutrons filling a major shell with many active orbitals, generalized seniority has been shown to be approximately conserved. We have shown that, for a target with good generalized seniority, the cross section to the DIAS has the same dependence on the neutron number as that for seniority, but the expression of the two amplitudes for DCX on two valence neutrons in terms of the microscopic shell-model wave functions

differs from the amplitudes with no configuration mixing. This cross section formula gives a good fit to recent DCX measurements at LAMPF on five nickel isotopes.

In contrast, unlike seniority, in generalized seniority the transition to the ground state depends on a third amplitude. Furthermore, the ground-state transition depends on the relative normalization of the target ground state and the ground state of the residual nucleus. This relative normalization has implicit dependence on the valence neutron number through the Hamiltonian. We have calculated this relative normalization for the nickel isotopes. We are able to fit the measured ground-state cross section within the large error bars of the experiment. Clearly, more accurate data are needed.

The Interacting Boson Model With Isospin

The interacting boson model has been a successful model of the low-lying collective states of heavy nuclei. The version of the model that distinguishes between neutrons and protons (IBM-2) assumes that the low-lying collective states are composed primarily of correlated monopole, ($J^\pi = 0^+$), and quadrupole, ($J^\pi = 2^+$), pairs of protons and pairs of neutrons. IBM-2 is valid for nuclear states that have the valence protons (or neutrons) filling a major shell that is closed with respect to protons (neutrons). Such states automatically have a definite isospin. However, when the valence neutrons and protons are filling the same major shell, that is, $N \sim Z$, such as in light nuclei, then isospin must be introduced. To take into account isospin within the framework of boson models, a monopole and quadrupole neutron-proton pair must be included in addition to the proton-proton and neutron-neutron pair in order to complete the isospin triplet. Although this IBM-3 was introduced for light nuclei, there are some medium- and heavy-weight nuclei with $N \sim Z$ and, with the advent of radioactive beams, there may be more nuclei studied in this category in the future. We are studying these nuclei by two approaches.

Since these heavy nuclei have collective low-lying states, in the first approach we determine the intrinsic motion of the collective motion in a manner similar to that done for IBM-2. Because isobaric analog states are at high excitation energy, we want an intrinsic state for each isospin multiplet. We determined such a state, which is a function of the quadrupole shape parameters and used it calculate the collective energy surface of the most general isospin invariant IBM-3 Hamiltonian. We have used this energy surface to determine the possible collective motions as a function of mass number and isospin under the restriction of isospin conservation, the first time that isospin conservation has been considered in connection with collective motion of the low-lying states. We have also determined the excitation energies of the normal modes that are the band

heads for the excited collective bands. These include a "scissors"-type isovector mode; that is, a magnetic excitation due to the oscillation of the protons and neutrons with respect to each other. In the second approach, which is more quantitative, we diagonalize the isospin conserving IBM-3 Hamiltonian and determine the nuclear spectrum, eigenstates, and transition rates. As a first application we are calculating the spectroscopy of the $N \sim Z \sim 40$ nuclei. Recent measurements on these nuclei suggest that they are very deformed, but the collective motion may not be that of an axial rotor, but of a "gamma" soft rotor, a type of collective motion, which is a very rare in the well-studied nuclear isotopes near the valley of stability. We shall investigate whether or not this type of motion is a consequence of isospin conservation.

Strangeness

Physics of ΛN - ΣN Coupling in Light Hypernuclei

Based upon the 1-MeV γ transition observed between the 1^+ excited state and the 0^+ ground state in the $A = 4$ hypernuclear isodoublet, shell-model calculations predicted a similar doublet structure in the $A = 10$ system. The spin-spin interaction was inferred from the level structure of ${}^4_\Lambda\text{He}/{}^4_\Lambda\text{H}$. The low-lying states in ${}^{10}_\Lambda\text{B}$ were assumed to be dominated by a weak-coupling picture in which the Λ with $S = 1/2$ couples to the $J = 3/2$ ground-state analog of ${}^9\text{Be}$. A recent BNL experiment was designed to observe the predicted γ from the transition between the $J^\pi = 2^-$ excited state and $J^\pi = 1^-$ ground state of ${}^{10}_\Lambda\text{B}$ following the (K^-, π^-) reaction on the $J = 3$ ground state of ${}^{10}\text{B}$. The (K^-, π^-) reaction in the forward direction, where the spin-flip amplitude (proportional to $\sin \theta$) vanishes, leads to the 2^- state in ${}^{10}_\Lambda\text{B}$ but does not reach the 1^- state. If the 1^- state is the ground state, then one should observe the $2^- \rightarrow 1^-$ transition. No γ was seen.

One possible explanation for the unexpected null result is that the shell model prediction for the level ordering, based upon the observed $0^+ - 1^+$ splitting of the levels in the $A = 4$ system, is not correct. Gibson and Lehman have shown that one obtains a 0^+ ground state and 1^+ excited state in the $A = 4$ system, even though the free-space hyperon-nucleon interaction indicates that the spin-triplet interaction is stronger, by accounting for Pauli suppression of the ΛN - ΣN coupling in a proper four-body calculation. The free-space hyperon-nucleon interaction would lead to a prediction that the $1^+ A = 4$ state should lie lower in energy, being the ground state. The novel result, that one obtains instead a 0^+ ground state of the $A = 4$ system, follows from the hypothesized spin-isospin suppression of the coupling of the Σ to the trinucleon $T = 3/2$ nuclear core excited states that lie high in the continuum and have a more complex spatial structure than does the $T = 1/2$ nuclear core ground state. One might anticipate that such a spin-isospin suppression of the $(T = 0)\Lambda \leftrightarrow (T = 1)\Sigma$ conversion would

be absent in the ${}^{10}_{\Lambda}\text{B}$ hypernucleus. Consider an $\alpha\alpha\Lambda N$ model of this $A = 10$ system. Because the α has no spin, the spin of the low-lying ${}^{10}_{\Lambda}\text{B}$ levels would be determined by the spin-dependence of the interaction between the Λ in the $1s$ shell and the valence nucleon in the $1p$ shell with no suppression of the ΛN - ΣN coupling. Assuming that interaction corresponds to the free-space force, then one can easily understand a prediction that the ground state of the $A = 10$ system is the 2^- state. A model calculation is yet to be completed, but in such a picture *no* γ transition should have been observed in the BNL experiment.

$\Lambda\Lambda$ - ΞN Coupling in Light $\Lambda\Lambda$ Hypernuclei

Strangeness represents a nontrivial additional degree of freedom in nuclear physics. Unraveling the SU(3) structure of the baryon-baryon interaction is basic to our developing a fundamental understanding of the nuclear force. Investigating the ΛN , ΣN , ΞN , and $\Lambda\Lambda$ interactions is crucial to this analysis, and hypernuclear spectra provide information essential for this task. Adding one or more hyperons to the nucleus creates nuclear systems that exhibit novel aspects which do not appear in conventional, nonstrange nuclei. For example, the ${}^4_{\Lambda}\text{H}$ - ${}^4_{\Lambda}\text{He}$ isodoublet have particle-stable excited states; the trinucleons and alpha particle have none. Understanding the 0^+-1^+ splitting in this system, as well as the obvious charge symmetry breaking (CSB) is a clear challenge to our understanding the hyperon-nucleon (YN) interaction as well as our ability to model the structure of the four-baryon system. Model calculations have indicated that ΛN - ΣN coupling plays a significant role. The $(\Sigma^+, \Sigma^0, \Sigma^-)$ mass difference induces CSB in the ΛN interaction. Suppression of the ΛN - ΣN coupling, when a change in isospin ($\Lambda \sim T = 0 \leftrightarrow \Sigma \sim T = 1$) requires that the composite nuclear core make a transition to some highly excited $T = 3/2$ configuration, appears to play a crucial role in the determination of the level ordering.

Extending this analysis to $S = -2$, one finds ${}^6_{\Lambda\Lambda}\text{He}$. The single reported event has been controversial. Nonetheless, the $\Lambda\Lambda$ separation energy $B_{\Lambda\Lambda} = B({}^6_{\Lambda\Lambda}\text{He}) - B({}^4\text{He}) \approx 10.6$ MeV can be directly related to $\langle V_{\Lambda\Lambda} \rangle$, the expectation value of the $\Lambda\Lambda$ potential: $\langle V_{\Lambda\Lambda} \rangle = B_{\Lambda\Lambda}({}^6_{\Lambda\Lambda}\text{He}) - 2B_{\Lambda}({}^5_{\Lambda}\text{He}) = 4.4$ MeV, consistent with the other two reported examples of $\Lambda\Lambda$ hypernuclei. Simple Hartree-Fock calculations for ${}^6_{\Lambda\Lambda}\text{He}$ and ${}^4_{\Lambda}\text{He}$ have shown that $V_{\Lambda N}^{A=6}(r) \approx V_{\Lambda N}^{A=4}(r)$ could account for the binding energies of both systems. The ΛN interaction is only weakly attractive, which implies a similar property for $V_{\Lambda\Lambda}$. However, just as ΛN - ΣN suppression appears to play a significant role in the $A = 4$ level ordering and to result in the anomalously small Λ -separation energy for $A = 5$, we hypothesize that $\Lambda\Lambda$ - ΞN coupling is likely to be suppressed in ${}^6_{\Lambda\Lambda}\text{He}$, so that only the $\Lambda\Lambda$ component is sampled. In that case, it would be ${}^4_{\Lambda\Lambda}\text{H}$ (or ${}^5_{\Lambda\Lambda}\text{He}$) that would probe the full $\Lambda\Lambda$ - ΞN force.

One predicts significant suppression of $\Lambda\Lambda$ - ΞN coupling in ${}_{\Lambda\Lambda}^6\text{He}$, because conversion from $\Lambda\Lambda$ - ΞN in a relative 1S_0 state will require excitation of the ${}^4\text{He}$ core. One cannot have five nucleons in the $1s$ shell. That is, it is suggested that ${}_{\Lambda\Lambda}^6\text{He}$ probes primarily the diagonal $V_{\Lambda\Lambda}$ element of the $\Lambda\Lambda$ - ΞN interaction. Such would not be the case for ${}_{\Lambda\Lambda}^4\text{H}$, where the $np\Lambda\Lambda$ system can easily couple to $NN\Xi$ in a manner that leaves all baryons in the $1s$ shell. Because ${}^3\text{H}$ is bound, ${}_{\Lambda\Lambda}^4\text{H}$ will also be bound. Therefore, it is quite likely that the $\Lambda\Lambda$ - ΞN interaction is significantly stronger than is implied by the value of $\langle V_{\Lambda\Lambda} \rangle$ extracted from the three $\Lambda\Lambda$ -hypernuclei events which have been observed. Should the $\Lambda\Lambda$ - ΞN interaction strength be comparable to that of the 1S_0 neutron-neutron interaction (both lie in the same multiplet), then one could envision a total binding energy for the 1^+ ground state of ${}_{\Lambda\Lambda}^4\text{H}$ large enough to permit a 0^+ excited state to be particle stable. If so, then in addition to the reactions

for the ground state, one could also observe

for the excited state. Whether ${}_{\Lambda\Lambda}^4\text{H}$ is bound to such a degree, it should be clear that a measurement of its binding energy would probe the full $\Lambda\Lambda$ - ΞN interaction, in contrast to a measurement of the ${}_{\Lambda\Lambda}^6\text{He}$ binding energy.

Electromagnetic Interactions

Electromagnetic Dissociation in Heavy Ion Collisions

The availability of relativistic heavy ion beams has opened a new avenue for the study of electromagnetic excitations of nuclei. Experiments range from single and double nucleon-removal reactions, to the study of "halo" nuclei using radioactive beams, to the possibility of multi-photon excitations of collective nuclear states. Aside from their intrinsic interest, electromagnetic excitation processes in peripheral collisions will also be important at RHIC.

Using the semiclassical Weizäcker-Williams (WW) method, we have performed a study of E2 contributions to the two-neutron removal process for a variety of projectile nuclei. Assuming that the quadrupole contribution is dominated by the isovector giant quadrupole resonance, we calculate the correction to the two neutron removal process in ${}^{59}\text{Co}$ and ${}^{197}\text{Au}$ due to E2 processes and find that the observed discrepancies between the semiclassical calculation and experiment are resolved.

We have also calculated the fully quantum mechanical cross section for electromagnetic excitation of nuclei in first Born approximation, neglecting recoil. Our final result may be expressed in terms of correlation functions and densities convoluted in configuration space. The result agrees with the WW approximation for unretarded electric dipole radiation, but our method allows an analytic evaluation of the WW cutoff, determined by the details of the E1 transition density. Using the Goldhaber-Teller model of that density, and uniform charge densities for both projectile and target, the cutoff is determined for the total cross section in the nonrelativistic limit, and found to be smaller than those used in current E1 calculations. In addition, cross sections are calculated using a phenomenological momentum space cutoff designed to model final-state interactions. For moderate projectile energies, the calculated electromagnetic dissociation cross section is found to be smaller than the semiclassical result, in qualitative agreement with experiment.

This is the first fully quantum mechanical calculation of heavy-ion-induced electromagnetic dissociation, which does not require imposition of phenomenological cutoffs. The discrepancy between high Z_p data and semiclassical theory is explained in terms of off-shell-photon effects.

Response Functions in Light Nuclei

We have recently developed path-integral techniques to enable us to calculate Euclidean (imaginary-time) response functions of light nuclei. During the past year, we have extended our initial longitudinal calculations to include the transverse channel and also phenomenological response functions related to (p,n) and (p,p) scattering experiments at LAMPF.

These calculations address some long-standing problems of quasi-elastic scattering in nuclear physics: the quenching of the longitudinal as compared to the transverse channel in electron scattering; and the strong shift of (p,n) response to higher energies than (p,p) .

Our formalism includes a full treatment of both final-state interactions and exchange currents, both of which are required in order to explain the experimental data. As a result of these calculations, a consistent picture of nuclear dynamics in the quasi-elastic regime emerges. Its main features include (1) a quenching of the longitudinal strength due to the charge-exchange mechanism of the nuclear force, and (2) an even larger quenching in the transverse channel, which, however, is more than offset by the effects of exchange currents. These exchange currents increase the response dramatically, and produce results in accord with the experimental data. In hadronic reactions, the charge exchange mechanism provides a means for shifting the (p,n) response to higher energy, and an exact

treatment of final-state interactions in light nuclei produces a substantial quenching of the spin Longitudinal to Transverse ratio recently observed at LAMPF.

We are currently applying these techniques to explore other physics, including polarization observables in electron scattering on $A = 3$ and path-integral tests of the correlated Glauber theory used in high-energy electron scattering.

Electroweak Physics

Massive Neutrinos, Cosmology, and Tritium Beta Decay

We have considered the effects of a light scalar boson weakly coupled solely to neutrinos. A prototype of this conjecture is found in the Gelmini-Roncadelli "Majoron," but it is not necessary to assume any particular model. We find that the interaction between neutrinos induced by scalar exchange may be strong enough to profoundly affect cosmology. In particular, we find that the neutrinos may constitute a degenerate Fermi gas during the early stages of the Big Bang, forming self-bound localized clusters near the time of recombination. Such clusters would represent significant gravitational fluctuations even for low ($\sim 1 \text{ eV}/c^2$) mass neutrinos, and they could strongly affect the evolution of matter density fluctuations, including galaxy and star formation. An endpoint consistent with bounds such as those imposed by the observation of neutrinos propagating from the supernova, 1987a, is the existence of a neutrino-sphere surrounding each star and extending out for as much as 0.03 light-years, with a density on the order of $10^{16} \text{ } \nu/\text{s/cc}$. A possible test of these ideas can be found in the effect of this neutrino background on end-point measurements in β -decay experiments designed to search for neutrino mass effects: Absorption of neutrinos from such a background would provide a noticeably larger number of events near the endpoint than expected. These excess events would produce an apparent *negative* mass-squared in analyses designed to extract mass limits on the neutrino produced in the decay. Such signals have been seen in all recent high-accuracy tritium β -decay experiments, but only at the statistically questionable level of a few standard deviations except for the LLNL experiment, which reported a negative mass-squared signal on the order of ten standard deviations from zero, at the latest Asilomar meeting.

A Tensor Interaction in $\pi \rightarrow e \nu_e \gamma$ Decay?

Data from a recent experiment on $\pi \rightarrow e \nu_e \gamma$ appear to be in disagreement with the SM prediction for this decay. The discrepancy has been interpreted as a possible indication of the presence of a tensor electron-quark interaction. In the Standard Model, tensor interactions can be induced by

radiative corrections, but these are too weak to account for the discrepancy. The required tensor interactions would have to come therefore from new physics. While new experiments are needed to explore whether the Standard Model is indeed inadequate for $\pi \rightarrow e \nu_e \gamma$ decay, it is of interest to examine whether the available empirical constraints would allow the strength of the tensor interactions to be of the required size, and to consider the possible sources of quark-lepton tensor interactions.

We have investigated the constraints on tensor interactions from the available data and analyzed the tensor interactions arising from the exchange of spin-zero leptoquarks. In renormalizable gauge theories, spin-zero leptoquark exchange is the only possible source of tensor quark-lepton interactions at the tree level.

Our overall conclusion is that while the interpretation of the discrepancy in $\pi \rightarrow e \nu_e \gamma$ in terms of a tensor interaction runs into difficulties, it cannot be regarded yet as ruled out.

The Neutrinos in Muon Decay

We have analyzed the available information on the identity of the neutrinos emitted in the decay $\mu^+ \rightarrow e^+ + n + n'$, where n and n' are neutrino states. In the Standard Model, n and n' are massless left-handed neutrinos, which accompany the corresponding left-handed charged leptons in doublets of $SU(2)_L$; the interaction responsible for this decay is of the V-A form. In extensions of the Standard Model, there may be new decay modes of the type $\mu^+ \rightarrow e^+ + n + n'$, and new decay interactions may be present.

We have found that the decay mode which dominates the rate for $\mu^+ \rightarrow e^+ + n + n'$ involves the neutrino species of the Standard Model scenario. The contribution of other decay interactions and decay modes is constrained to be less than about 10%. One of the non-standard decay modes is the exotic decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$. We find that if the neutrinos in $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ are right-handed, the best limit on the strength of the corresponding interaction comes from data on muon decay and inverse muon decay, and that if the decay involves left-handed neutrinos, the best limit comes from the direct experimental search for this decay.

Right-Handed Currents in Beta Decay?

A recent measurement of the electron asymmetry parameter in neutron decay has yielded a value of the ratio of axial-vector to vector coupling constant, which is in disagreement with the value deduced from the neutron lifetime and the superallowed Fermi beta decay rates. While this discrepancy could turn out to be a consequence of as yet unidentified systematic experimental errors, the possibility that it is due to the presence

of a new interaction has to be explored. It has been pointed out that the discrepancy could be resolved in the framework of manifestly left-right symmetric models if the ratio m_1/m_2 of the masses of the left-handed and the right-handed gauge bosons is ~ 0.3 . Such a large value of m_1/m_2 is, however, inconsistent with data on muon decay. Beta decay data (including data on neutron decay) have been analyzed recently in the framework of the most general V,A interaction. The best fit gives $(a_{RR}^{(e)})_{\text{central}} = 0.077(G_F/\sqrt{2})$ for the central value of the effective coupling constant of the interaction involving a right-handed leptonic and a right-handed quark current ($a_{RR}^{(e)} = (m_1^2/m_2^2) \times G_F/\sqrt{2}$ in manifestly left-right symmetric models). The central value is 2.3σ away from zero. If the new experimental result on the electron asymmetry in neutron decay is removed from the data set, $a_{RR}^{(e)}$ becomes zero at the 1σ level.

We have investigated the question of whether an $a_{RR}^{(e)}$ of the required size could arise in some extensions of the Standard Model. In beta decay, right-handed interactions can arise at the tree level from new gauge bosons with right-handed couplings to the fermions (such as the right-handed gauge boson in left-right symmetric models), as a result of mixing of the usual fermions with exotic ones that have right-handed couplings to the W , and from the exchange of leptoquarks. Our results can be summarized as follows:

- (1) In the most general version of left-right symmetric models $|a_{RR}^{(e)}| \sim 0.1$ is not ruled out;
- (2) In models with exotic fermions $|a_{RR}^{(e)}| \leq 2 \times 10^{-4} G_F$, which is much too small to be relevant for the problem;
- (3) A nonvanishing $a_{RR}^{(e)}$ can arise in models involving either the spin-zero, Q (= electric charge) = $1/3$ isoscalar leptoquark, or the spin-one, $Q = 2/3$ isoscalar leptoquark. In both cases $a_{RR}^{(e)}$ can be of the required size.

Other Physics

Pairwise Correlations In Many-Fermion Systems

The first approximation to many-body systems is typically to consider only single-particle degrees of freedom—the mean-field approximation. Often in many-fermion systems, however, two-particle degrees of freedom—pairwise correlations—are important. A classic example is BCS superconductivity, where electrons couple to Cooper pairs of zero linear momentum. Pairing is also important in nuclei; not only angular momentum $J = 0$ pairing in the ground state, as manifested by the systematics of binding energy in even and odd nuclei, but also $J = 2$ pairing as suggested by the phenomenological Interacting Boson Model, where the spectra and transi-

tions of many low-lying states are successfully described by using only $J = 0, 2$ (s and d) bosons thought to represent pairs of nucleons.

We are developing general and systematic methods for treating pairwise correlations in many-fermion systems, including nuclei, hadrons, and condensed matter. Much of our work to date has involved mapping fermion pairs to bosons. Given any one- or two-body fermion operators, we can construct a boson representation that has the same matrix elements as the original fermion operator. These boson representations are complicated many-body operators; we have shown, however, that they factorize into a simple boson operator (for example, a one plus two-body fermion Hamiltonian yields a Hermitian boson image that has at most two-body terms), times a many-body projection operator that separates physical from unphysical states in the boson space. The projection operator can then be divided out, leaving finite boson operators. The factorization requires a completeness relation and use of all possible boson operators. We are currently investigating how to factorize using a truncated set of bosons, e.g., s - and d -bosons. This line of investigation may lead to rigorous and microscopic derivation of the Interacting Boson Model of Nuclei, a long-standing problem in nuclear physics.

We have begun to explore other applications of the fermion-pair technology. A fermion-pair-condensate is a useful variational Ansatz that includes both Hartree-Fock and generalized seniority states as limits. This may be an interesting approach to unusual condensed matter systems; some researchers have postulated that angular momentum $J = 2$ pairs are necessary to understand high- T_c superconductors. A final application, under current investigation, is modeling the quark sea in hadrons using this technology: the sea quarks are represented by a coherent state of quark-antiquark pairs.

High Spin Fields

New representations for higher spin fields have been studied with possible simplifying implications for supersymmetric field theories, as well as our discovery of the first realization of a Bargmann-Wightman-Wigner field theory and improved understanding of physical implications and features of Majorana neutrinos.

Publications

C. J. Benesh, "Quadrupole Contribution to Two Neutron Removal in Heavy Ion Collisions," *Phys. Rev. C* **46**, 2635 (1992).

D. D. Schwellenbach, J. C. Hill, F. K. Wohn, P. R. Graham, C. J. Benesh, A. R. Smith, D. L. Hurley, and P. J. Karol, "Electromagnetic Dissociation of

^{59}Co and ^{197}Au Targets by Relativistic ^{238}U Projectiles (submitted to *Physical Review C*).

C. J. Benesh, "QCD Evolution using Finite Element Methods" (accepted for publication in *Modern Physics Letters A*).

C. J. Benesh, J. Qiu, and J. P. Vary, " J/Ψ Production in Hadron-Nucleus Collisions" (submitted to *Physical Review D*).

R. Schiavilla, R. B. Wiringa, V. R. Pandharipande, and J. Carlson, "Effects of Delta-Isobar Degrees of Freedom on Low-Energy Electroweak Transitions in Few-Body Nuclei," *Phys. Rev. C* **45**, 2628 (1992).

J. Carlson and R. Schiavilla, "Euclidean Proton Response in Light Nuclei," *Phys. Rev. Lett.* **68**, 3682 (1992).

J. Carlson, R. Schiavilla, and V. R. Pandharipande, "Variational Monte Carlo Calculations of ^3H and ^4He with a Relativistic Hamiltonian," *Phys. Rev. C* **47**, 484 (1993).

R. Schiavilla, R. B. Wiringa, and J. Carlson, "The Coulomb Sum and Proton-Proton Correlations in Few-Body Nuclei," *Phys. Rev. Lett.* **70**, 3856 (1993).

V. R. Pandharipande, J. Carlson, S. Pieper, R. B. Wiringa, and R. Schiavilla, "Isovector Spin-Longitudinal and -Transverse Response of Nuclei" (accepted for publication in *Physical Review C*).

J. Carlson, "Electron Scattering and Euclidean Response Functions," presented at the *Elba 1993 Workshop on Electron Scattering*, Los Alamos National Laboratory document LA-UR 93-3571 (to be published).

J. Carlson and R. Schiavilla, "Monte Carlo Studies of Light Nuclei: Structure and Response," presented at the *XIII European Few-Body Conference*, Amsterdam, September 1993, Los Alamos National Laboratory document LA-UR 93-3378 (to be published).

J. Carlson and R. Schiavilla, "Inclusive Scattering and Dynamics in Light Nuclei," Los Alamos National Laboratory document LA-UR 93-3571.

J. L. Friar, " p - d Capture Reactions in Muonic Molecules," invited lecture given at the *XIII European Conference on Few-Body Problems in Physics*, Marcialina Marina, Isola d'Elba, Italy, September 1991, *Few-Body Systems, Suppl.* **6**, 304 (1992).

J. L. Friar, "New Approaches for Bound and Scattering States," convener's report at the *XIII European Conference on Few-Body Problems in Physics*, Marciana Marina, Isola d'Elba, Italy, September 1991, *Few-Body Systems*, Suppl. 6, 538 (1992).

J. L. Friar and G. L. Payne, "Proton-Deuteron Scattering and Reactions," in *Coulomb Forces in Atomic and Nuclear Three-Particle Collision Phenomena*, D. A. Micha and F. S. Levin, Eds. (Plenum, New York, 1993), (to appear).

J. L. Friar, "What Is the S' -State in ^3He and Why Is It Important?," invited talk at the *Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector*, Tempe, Arizona, March 1992, R. Alarcon and M. Butler, Eds. (World-Scientific, Singapore, 1993), p. 210.

J. L. Friar, "Three-Nucleon Calculations: Status and Prognosis," convener's report presented at the *Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector*, Tempe, Arizona, March 1992, R. Alarcon and M. Butler, Eds. (World-Scientific, Singapore, 1993), p. 230.

J. L. Friar and S. Fallieros, "Gauge Invariance and the Nonrelativistic Ward-Takahashi Identity," *Phys. Rev. C* 46, 2393 (1992).

S. Scherer, J. H. Koch, and J. L. Friar, "Systematics of Low-Energy Theorems for Pion Photo- and Electroproduction," *Nucl. Phys. A* 552, 515 (1993).

C. J. Benesh and J. L. Friar, "Electromagnetic Dissociation of Nuclei in Heavy-Ion Collisions," *Phys. Rev. C* 48, 1285 (1993).

J. L. Friar, "Three-Nucleon Forces and the Three-Nucleon Systems," lectures presented at the *Fifth Indian-Summer School on Intermediate Energy Physics*, Sázava, Czechoslovakia, September 1992, *Czech. J. Phys.* 43, 259 (1993).

J. L. Friar, G. L. Payne, V. G. J. Stoks, and J. J. de Swart, "Triton Calculations with the New Nijmegen Potentials," *Phys. Lett. B* 311, 4 (1993).

A. S. Raskin, E. L. Tomusiak, and J. L. Friar, "A Gauge-Invariant Nuclear Pion-Photoproduction Amplitude with Binding-Induced Contributions" (submitted to *Physical Review C*).

J. L. Friar and S. A. Coon, "Non-Adiabatic Contributions to Static Two-Pion-Exchange Nuclear Potentials" (submitted to *Physical Review C*).

W. R. Gibbs, M. Elghossain, and W. B. Kaufmann, "Pion Double Charge Exchange Operator," *Phys. Rev. C* **48**, 1546 (1993).

J. D. Zumbro, C. L. Morris, J. A. McGill, S. J. Seestrom, R. M. Whitton, C. M. Riedel-Edwards, A. L. Williams, M. Braunstein, M. Kohler, B. Kriss, S. Høibråten, R. J. Peterson, J. Ouyang, J. E. Wise, and W. R. Gibbs, "Inclusive Scattering of 500-MeV Pions from Carbon," *Phys. Rev. Lett.* **71**, 1796 (1993).

P. B. Siegel and W. R. Gibbs, "Pion Scattering from Spin 1/2 Nuclei," *Phys. Rev. C* **48**, 1939 (1993).

M. K. Liou, D. Lin, and B. F. Gibson, "Anatomy of the Soft-Photon Approximation in Hadron-Hadron Bremsstrahlung," *Phys. Rev. C* **47**, 973 (1993).

I. R. Afnan and B. F. Gibson, "Resonances in Λd Scattering and the Σ -Hypertriton," *Phys. Rev. C* **47**, 1000 (1993).

G. L. Payne and B. F. Gibson, "Variational Aspects of Faddeev Calculations," *Few-Body Systems* **14**, 117 (1993).

A. C. Fonseca, B. F. Gibson, and D. R. Lehman, "Approximate Ways to Treat the Nucleon-Nucleon Tensor Force in the Four-Nucleon Bound State," *Phys. Rev. C* **48**, 2528 (1993).

J. N. Ginocchio, "The Group Representation Matrix and Quantum Mechanical Scattering," in *Contemporary Mathematics*, N. Kamran and P. J. Olver, Eds. (American Mathematical Society, New York, 1993).

J. N. Ginocchio and W. C. Haxton, "The Fractional Quantum Hall Effect and the Rotation Group," in *Symmetries in Science VI: From the Rotation Group to Quantum Algebras*, Bruno Gruber, Ed. (Plenum Press, New York, 1993).

J. N. Ginocchio and A. Leviatan, "An Intrinsic State With Definite Isospin for IBM-3," in *Symmetries in Science VII: Spectrum Generating Algebras and Dynamic Symmetries in Physics*, Bruno Gruber, Ed. (Plenum Press, New York, 1993).

J. N. Ginocchio, "Double Charge Exchange and Generalized Seniority," *Nucl. Phys. A* **560**, 321 (1993).

J. N. Ginocchio, "A Test of Generalized Seniority with Pion Double Charge Exchange," *Phys. Rev. C* **48**, 1460 (1993).

J. N. Ginocchio, "The Fractional Quantum Hall Effect and the Spherical Shell Model," in *From Spectroscopy to Chaos*, D. Koltun, Ed. (World Scientific, Singapore, 1993).

C. W. Johnson, and J. N. Ginocchio, "Exact, Finite, and Hermitian Fermion-Pair-To-Boson-Mapping" submitted to *Physical Review Letters*, (1993).

T. Goldman, Fan Wang, Guang-han Wu, and Li-jian Teng, "Quark Delocalization, Color Screening and Nuclear Intermediate Range Attraction," *Phys. Rev. Lett.* **69**, 2901 (1992).

T. Goldman, "Inevitable' Dibaryons," in *Intersections between Particle and Nuclear Physics*, Tucson, Arizona, May 23-29, 1991, W. T. H. van Oers, Ed., *AIP Conf. Proc.* **243**, 562 (1992).

T. Goldman, J. Pérez-Mercader, F. Cooper, and M. M. Nieto, "Dark Matter and the Effective Value of Newton's Constant at Large Distances," in *The Vancouver Meeting: Particles and Fields '91*, D. Axen, D. Bryman, and M. Comyn, Eds. (World Scientific, Singapore, 1992), p. 999.

T. Goldman, J. Pérez-Mercader, F. Cooper, and M. M. Nieto, "The Dark Matter Problem and Quantum Gravity," *Phys. Lett. B* **281**, 219 (1992).

T. Goldman, J. A. Henderson, and A. W. Thomas, "A New Perspective on the ρ - ω Contribution to Charge-Symmetry Violation in the N - N Force," *Few-Body Systems* **12**, 123 (1992).

T. Goldman, J. A. Henderson, and A. W. Thomas, "Substructure Effect on ρ - ω Mixing in Charge-Symmetry Violation," *Mod. Phys. Lett. A* **7**, 3037 (1992).

T. Goldman, M. Nieto, and V. Sandberg, "Kaons, Quantum Mechanics and Gravity," *Mod. Phys. Lett. A* **7**, 3455 (1992).

T. Goldman et al., "Beyond Metric Gravity: Progress on PS-200" *Hyperfine Interactions* **81**, 87 (1993).

D. V. Ahluwalia, M. B. Johnson, and T. Goldman, "A Bargmann-Wightman-Wigner Type Quantum Field Theory," *Phys. Lett. B* **316**, 102 (1993).

T. Goldman, "No-Lose' Theorem for Parity-Violating Nucleon-Nucleon Scattering Experiments," invited talk at the *Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4-6, 1993, BNL-52389, p. 140.

T. Goldman, C. J. Benesh and G. J. Stephenson, "Color Magnetic Corrections to Quark Model Valence Distributions," *Phys. Rev. C* **48**, 1379 (1993).

D. V. Ahluwalia and T. Goldman, "Space Time Symmetries and Vortices in the Cosmos," *Mod. Phys. Lett. A* **8**, 2623 (1993).

D. V. Ahluwalia, T. Goldman, and M. B. Johnson, "Majorana-Like $(j,0) \oplus (0,j)$ Representation Spaces: Construction and Physical Interpretation" (to appear in *Modern Physics Letters A*, February 1994).

P. Herczeg, "The Decays $\eta \rightarrow \pi e \nu_e$ and $\eta \rightarrow \pi \mu \nu_\mu$," in *Intersections between Particle and Nuclear Physics*, AIP Conf. Proc. **243**, W. T. H. van Oers, Ed. (AIP, New York, 1992), p. 654.

P. Herczeg and R. N. Mohapatra, "Muonium to Antimuonium Conversion and the Decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ in Left-Right Symmetric Models," in *The Vancouver Meeting, Particles and Fields '91*, D. Axen, D. Bryman, and M. Comyn, Eds. (World Scientific, Singapore, 1992), Vol. 1, p. 572.

P. Herczeg, "The Neutrinos in Muon Decay," *Z. Phys. C* **56**, S129 (1992).

P. Herczeg, "Theoretical Aspects of Searches for New Interactions using Oriented Nuclei," *Hyperfine Interactions* **75**, 127 (1992).

P. Herczeg and R. N. Mohapatra, "Muonium to Antimuonium Conversion and the Decay $\mu^+ \rightarrow e^+ \bar{\nu}_e \nu_\mu$ in Left-Right Symmetric Models," *Phys. Rev. Lett.* **69**, 2475 (1992).

P. Herczeg, "Rare Decays," in *Proc. of the Third International Symposium on Weak and Electromagnetic Interactions in Nuclei (WEIN-92)*, Dubna, Russia, June 16-22, 1992, Ts. D. Vylov, Ed. (World Scientific, Singapore, 1993), p. 262.

P. Herczeg, "Beta Decay and Muon Decay Beyond the Standard Model," in *Precision Tests of the Standard Electroweak Model*, Advanced Series on Directions in High Energy Physics, Paul Langacker, Ed. (World Scientific, 1993).

P. Herczeg, "On the Question of a Tensor Interaction in $\pi \rightarrow e \nu_e \gamma$ Decay," *Phys. Rev. D* **49**, 247 (1994).

H. T. Williams and R. R. Silbar, "Automated Angular Momentum Recoupling Algebra," *J. Comp. Phys.* **99**, 299 (1992).

R. R. Silbar, "An Interactive NeXTSTEP Interface to a FORTRAN Code for Solving Coupled Differential Equations," *Comp. in Phys.* 7, 592 (1993).

R. R. Silbar and M. P. Mattis, " πN Scattering in a Large- N_C σ -Model," in Fifth International Symposium on Meson-Nucleon Scattering, Boulder, Colorado, September 1993 (to be published).

Invited Presentations

The following do not include colloquia and seminars presented either externally or internally, nor ordinary contributions to conferences and meetings.

J. Carlson, "NNN and ΛNN Forces," presented at the *Workshop on Nuclear Physics and Neutron Stars*, Urbana, Illinois, June 1992.

J. Carlson, "The Hyperon-Nucleon Interaction and Light Hypernuclei," talk presented at the Nuclear Theory Institute Program on Hypernuclear Physics, July 1992.

J. Carlson, "Correlations and Dynamics: Inclusive Scattering on Light Nuclei," talk presented at the *LAMPF Workshop on QCD and Multi-GeV Hadron Physics Opportunities*, June 1993.

J. Carlson, "Electron Scattering and Euclidean Response Functions," presented at the *Elba 1993 Workshop on Electron Scattering*.

J. Carlson and R. Schiavilla, "Monte Carlo Studies of Light Nuclei: Structure and Response," presented at the *XIII European Few-Body Conference*, Amsterdam, September 1993.

J. Carlson, "Euclidean vs. Real-Time Dynamics in Light Nuclei," in *IMACS Conference on Computational Physics*, September 1993.

J. L. Friar, "What Is the S' -State in ^3He and Why Is It Important?," invited talk presented at the *Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector*, Tempe, Arizona, March 19, 1992.

J. L. Friar, "Three-Nucleon Calculations: Status and Prognosis," convener's report presented at the *Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector*, Tempe, Arizona, March 1992.

J. L. Friar, "Three-Nucleon Forces and the Three-Nucleon Systems," three invited lectures presented at the *Fifth Indian-Summer School on Intermediate Energy Physics*, Sázcava, Czechoslovakia, September 6–11, 1992.

J. L. Friar, "The Nuclear Few-Body Problem," invited talk presented at *The Atomic/Nuclear Frontier*, session of the DAMOP Annual Meeting, Reno, Nevada, May 16, 1993.

J. L. Friar, "The Nuclear Three-Body Problem," three invited lectures presented at the *Summer School in Nuclear Physics Research*, Raleigh, North Carolina, July 21–23, 1993.

J. L. Friar, "Understanding the Triton Binding Energy: Can We Make Further Progress?," invited talk at the *Workshop on Relativity in Two- and Few-Body Nuclear Systems*, CEBAF, September 20, 1993.

B. F. Gibson, "The Trinucleons: Model Properties and Physical Observables," invited talk presented at the *13th International Conference on Few Body Problems in Physics*, Adelaide, Australia, January 1992.

B. F. Gibson, "Final State Interactions in the Electromagnetic Disintegration of ^3He ," invited talk at the *Workshop on Electronuclear Physics with Internal Targets and the BLAST Detector*, Tempe, Arizona, March 1992.

B. F. Gibson and I. R. Afnan, "Resonances in the ΣNN System," invited talk at the *Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Energies*, Brookhaven National Laboratory, March 1993).

B. F. Gibson, "Nuclear Aspects of Few-Baryon Systems," invited talk at the *14th European Conference on Few-Body Problems in Physics*, Amsterdam, August 1993.

B. F. Gibson, "Few-Body Hypernuclear Constraints," invited talk at the *U.S./Japan Seminar on the Hyperon-Nucleon Interaction*, Maui, Hawaii, October 1993.

B. F. Gibson, "Three-Nucleon Results," invited talk at the *Workshop on the Three Nucleon Force*, Adelaide, Australia, November 1993.

B. F. Gibson, "Coupled-Channel Effects in Hypernuclear Interactions," presentation at collaboration meeting on *Research Opportunities in the Strangeness Sector*, Brookhaven National Laboratory, December 1993.

J. N. Ginocchio, "The Beauty of the Fractional Quantum Hall Effect," invited talk at *The Beauty of Physics*, University of Pennsylvania, Philadelphia, Pennsylvania, January 21–22, 1993.

J. N. Ginocchio, "Testing Generalized Seniority and the Interacting Boson Model with Double Charge Exchange," in the *Workshop on Algebraic*

Techniques for Quantal Systems, University of Pennsylvania, Philadelphia, Pennsylvania, January 23, 1993.

J. N. Ginocchio, "The Fractional Quantum Hall Effect and the Spherical Shell Model," invited talk at the *Washington Meeting of the American Physical Society*, April 12–16, 1993.

J. N. Ginocchio, "The Fractional Quantum Hall Effect and the Spherical Shell Model," invited talk at *From Spectroscopy to Chaos*, Rochester, New York, April 17, 1993.

J. N. Ginocchio, "The Fractional Quantum Hall Effect and the Spherical Shell Model," invited talk at the *Symposium on Fluctuations, Chaos, and Symmetries*, Max-Planck Institute for Nuclear Physics, Heidelberg, Germany, October 7–9, 1993.

T. Goldman, "Beyond Metric Gravity: Status Report on PS-200 Measurement of the Acceleration of Gravity for AntiProtons," invited talk at the *Workshop on Traps for Radioactive Ions and Antimatter*, TRIUMF, Canada, February 25–27, 1993.

T. Goldman, "No-Lose' Theorem for Parity-Violating NN Scattering Experiments," invited talk at the *Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4–6, 1993.

P. Herczeg, "Rare Decays," at the *Third International Symposium on Weak and Electromagnetic Interactions in Nuclei (WEIN-92)*, Dubna, Russia, June 16–22, 1992.

P. Herczeg, "Rare Decays of Muons, Pions and Kaons," at the *Workshop on Hadrons and Physics Beyond the Standard Model*, Santa Fe, New Mexico, July 27–August 14, 1992.

P. Herczeg, "Searches for Physics Beyond the Standard Model using the Neutron—An Overview of the Theory," at the *Workshop on Neutrons—Their Use for Nuclear Physics and Fundamental Symmetry Tests*, held in conjunction with the *Meeting of the Division of Nuclear Physics of the APS*, Santa Fe, New Mexico, October 14–17, 1992.

P. Herczeg, "Eta Decays and New Interactions," at the *Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4–6, 1993.

P. Herczeg, "Beta Decay Beyond the Standard Model," at the *Workshop on Symmetry Tests in Semileptonic and Leptonic Weak Interactions*, Louvain-la-Neuve, Belgium, June 2-4, 1993.

R. R. Silbar and M. P. Mattis, " πN Scattering in a Large- N_C σ -Model," presented at the *Fifth International Symposium on Meson-Nucleon Scattering*, Boulder, Colorado, September 1993.

LAMPF Publications

LAMPF PUBLICATIONS

1992

H. E. Ahn, "Part I: Angular Distribution Measurement of Beam-Foil Muonium, Part II: Muon Injection Simulation for a New Muon $g-2$ Experiment," Ph.D. thesis, Los Alamos National Laboratory report LA-12380-T (1992).

D. E. Alexandreas, "A Search for 100-TeV Gamma-Ray Emission from the X-Ray Binary Pulsar 4U 0115+63 Using the CYGNUS Extensive Air-Shower Array," Ph.D. thesis, Los Alamos National Laboratory report LA-12427-T (December 1992).

D. E. Alexandreas, R. C. Allen, S. D. Biller, R. S. Delay, G. M. Dion, X.-Q. Lu, P. R. Vishwanath, G. B. Yodh, D. Berley, C. Y. Chang, B. L. Dingus, J. A. Goodman, T. J. Haines, S. Gupta, D. A. Krakauer, M. J. Stark, R. L. Talaga, R. L. Burman, K. Butterfield, R. Cady, C. M. Hoffman, J. Lloyd-Evans, D. E. Nagle, M. E. Potter, V. D. Sandberg, C. Sinnis, S. Stanislaus, T. N. Thompson, C. A. Wilkinson, W. Zhang, and R. W. Ellsworth, "The CYGNUS Extensive Air-Shower Experiment," *Nucl. Instrum. Methods A* **311**, 350 (1992).

R. C. Allen, R. L. Burman, D. R. Cady, C. Y. Chang, R. S. DeLay, R. W. Ellsworth, S. Gupta, J. A. Goodman, T. J. Haines, D. A. Krakauer, J. Lloyd-Evans, X.-Q. Lu, D. E. Nagle, M. E. Potter, V. D. Sandberg, A. J. Sena, R. L. Talaga, T. N. Thompson, and G. B. Yodh, "Use of Neutrino Detector for Muon Identification by the CYGNUS Air-Shower Array," *Nucl. Instrum. Methods A* **311**, 368 (1992).

G. Anderson, I. Cohen, B. Homann, D. Smith, W. Strossman, G. J. VanDalen, L. S. Weaver, D. Evans, W. Vernon, A. Band, R. L. Burman, T. Chang, F. Federspiel, W. Foreman, S. Gomulka, G. Hart, T. Kozlowski, W. C. Louis, J. Margulies, A. Nuanes, V. Sandberg, T. N. Thompson, D. H. White, and D. Whitehouse, "Data Acquisition System for the Large Scintillating Neutrino Detector at Los Alamos," Los Alamos National Laboratory document LA-UR-92-3150 (submitted to the *Conference on Computing in High Energy Physics 1992*, September 21-25, 1992, Annecy, France).

J. M. Applegate, B. G. Ritchie, J. Beck, T. D. Averett, C. L. Morris, J. A. McGill, R. J. Peterson, C. Kormanyos, D. S. Oakley, C. F. Moore, M. Snell,

and H. J. Ward, "Measurement of the Isospin Mixing of the 1^+ Doublet in ^{12}C with 50-MeV $\pi^\pm$ Scattering," Los Alamos National Laboratory document LA-UR-92-3269 (submitted to *Physical Review C*, September 1992).

Joffa Michele Applegate, "A Study of Isospin Symmetry Breaking in ^{12}C with 50-MeV Pions," Ph.D. thesis, University of Arizona, Los Alamos National Laboratory report LA-12487-T (November 1992).

M. S. Atiya, I-H. Chiang, J. S. Frank, J. S. Haggerty, M. M. Ito, T. F. Kycia, K. K. Li, L. S. Littenberg, A. J. Stevens, A. Sambamurti, R. C. Strand, W. C. Louis, D. S. Akerib, D. R. Marlow, P. D. Meyers, M. A. Selen, F. C. Schoemaker, A. J. S. Smith, E. W. Blackmore, D. A. Bryman, L. Felawka, P. Kitching, A. Konaka, Y. Kuno, J. A. Macdonald, T. Numao, P. Padley, J-M. Poutissou, R. Poutissou, J. Roy, and A. S. Turcot, "Search for the Decay $\pi^0 \rightarrow \gamma + X$," *Phys. Rev. Lett.* **69**, 733 (1992).

N. Auerbach, J. D. Bowman, and A. C. Hayes, "The Doorway State Approximation and Sign Correlations in Parity Nonconservation in Compound Neutron Resonances," *Phys. Rev. C* **46**, 2582 (1992).

J. Bartel, M. B. Johnson, M. Singham, and W. Stocker, "Pion Inelastic Scattering and the Neutron Density in ^{152}Sm ," *Phys. Lett.* **296B**, 5 (1992).

D. P. Beatty, R. Gilman, Q. Sun, H. T. Fortune, A. L. Williams, D. Smith, P. Hui, S. Loe, M. A. Landau, J. M. O'Donnell, M. Rawool-Sullivan, J. Urbina, and D. L. Watson, "Pion Double Charge Exchange on ^{16}O above the $\Delta(1232)$ Resonance" (submitted to *Physical Review C*, October 1992).

J. D. Bowman, G. T. Garvey, C. R. Gould, A. C. Hayes, and M. B. Johnson, "Parity Violation in the Compound Nucleus: The Role of Distant States," *Phys. Rev. Lett.* **68**, 780 (1992).

J. N. Bradbury, "Physics with Muons at LAMPF," Los Alamos National Laboratory document LA-UR-92-1908 (submitted to the *III International Symposium on Weak and Electromagnetic Interactions in Nuclei*, Dubna, Russia, June 16-22, 1992).

M. L. Brooks, B. Bassalleck, B. D. Dieterle, R. A. Reeder, D. M. Lee, J. A. McGill, M. E. Schillaci, R. A. Ristinen, and W. R. Smythe, "Neutron Induced Pion Production on C, Al, Cu, and W at 200-600 MeV," *Phys. Rev. C* **45**, 2343 (1992).

R. L. Burman, R. C. Allen, T. J. Bowles, R. D. Carlini, H. H. Chen, D. Cochran, P. J. Doe, J. S. Frank, R. Hausammann, D. A. Krakauer, W. P. Lee, X-Q. Lu, H. J. Mahler, E. Piasetzky, M. E. Potter, V. D. Sandberg, R. L. Talaga, and K. C. Wang, "Experimental Study of Neutrino

Properties," in *The Vancouver Meeting—Particles and Fields '91*, Vancouver British Columbia, Canada, August 18–22, 1991, David Axen, Douglas Bryman, and Martin Comyn, Eds. (World Scientific, Singapore, 1992), p. 946.

R. L. Burman and M. B. Johnson, "The Relevance of the Los Alamos Meson Physics Facility (LAMPF) to National Goals," a White Paper, Los Alamos National Laboratory document LA-UR-92-1467 (April 1992).

M. E. Clay, "What are Good Operators and Why are they Needed?," Los Alamos National Laboratory document LA-UR-92-899 (submitted to *Proc. of the European Particle Accelerator Conference*, Berlin, Germany, March 24–28, 1992).

S. Cohen, "Accelerator-Control-System Interface for Intelligent Power Supplies" (submitted to *Proc. of the 1992 3rd IEEE Workshop on Computers in Power*, Berkeley, California, August 9–11, 1992).

R. A. DeHaven, C. L. Morris, R. W. Johnson, J. L. Davis, and J. M. O'Donnell, "SCRUNCHER Phase and Amplitude Control" (submitted to *Proc. of the 1992 Linear Accelerator Conference*, Ottawa, Canada, August 23–28, 1992).

P. P. J. Delheij, D. Alde, J. D. Bowman, B. Crawford, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, A. Masaïke, Y. Masuda, G. E. Mitchell, S. Patterson, S. Penttilä, Yu. Popov, H. Postma, N. R. Roberson, S. J. Seestrom, E. Sharapov, H. Shimizu, Yi-Fen Yen, S. H. Yoo, and V. W. Yuan, "P and T Invariance in Neutron Reactions at Los Alamos," in *Proc. of the 10th International Symposium on High-Energy Spin Physics*, Nagoya, Japan, November 9–14, 1992, T. Hasegawa, N. Horikawa, A. Masaïke, and S. Sawada, Eds. (University Academy Press, Tokyo, 1993), p. 735.

W. R. Ditzler, D. Hill, J. Hoftiezer, K. F. Johnson, D. Lopiano, T. Shima, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, R. Wagner, A. Yokosawa, G. R. Burleson, J. A. Faucett, C. A. Fontenla, R. W. Garnett, C. Luchini, M. W. Rawool-Sullivan, T. S. Bhatia, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, R. Damjanovich, J. J. Jarmer, J. Vaninetti, R. H. Jeppesen, and G. E. Tripard, "Neutron-Proton Elastic Scattering Spin-Spin Correlation Parameter Measurements between 500 and 800 MeV: I. C_{SL} and C_{LL} at Backward c.m. Angles," *Phys. Rev. D* **46**, 2792 (1992).

M. Düren, Z. Meroz, M. Veltri, Kirsten Zapfe, H. Mairon, M. Metzger, B. Povh, K. Rith, E. Steffens, F. Stock, D. Toporkov, F. Zetsche, T.-A. Shibata, D. Fick, W. Korsch, G. Graw, W. Haeberli, and G. T. Garvey, "Test of a

Polarized Hydrogen Gas Target Based on the Storage Cell Technique," *Nucl. Instrum. Methods A* **322**, 13 (1992).

F. J. Federspiel, "Measuring the Strange Quark Contribution to the Spin of the Proton through np Elastic Scattering," in *Proc. of the Seventh Lake Louise Winter Institute on Symmetry and Spin in the Standard Model*, Lake Louise, Canada, February 23–29, 1992, B. A. Campbell, L. G. Greeniaus, A. N. Kamal, and F. C. Khanna, Eds. (World Scientific, Singapore, 1992), p. 330.

F. J. Federspiel, "The Proton Compton Effect: Recent Measurements of the Electric and Magnetic Polarizations of the Proton," Los Alamos National Laboratory document LA-UR-92-1736 (submitted to the *Hadron Structure Workshop*, Brookhaven, New York, May 28–29, 1992).

C. M. Frankle, C. D. Bowman, J. D. Bowman, S. J. Seestrom, E. I. Sharapov, Yu. P. Popov, and N. R. Roberson, "Neutron Spectroscopy on ^{113}Cd : The p-wave Levels," *Phys. Rev. C* **45**, 2143 (1992).

C. M. Frankle, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. R. Gould, D. G. Haase, J. N. Knudson, G. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan, and X. Z. Zhu, "Parity Nonconservation for Neutron Resonances in ^{232}Th ," *Phys. Rev. C* **46**, 778 (1992).

C. M. Frankle, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. R. Gould, D. G. Haase, J. N. Knudson, G. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, V. W. Yuan, and X. Z. Zhu, "Parity Nonconservation for the 0.88-eV Neutron Resonance in ^{81}Br ," *Phys. Rev. C* **46**, 1542 (1992).

G. T. Garvey, "Recent Developments in Neutrino Physics," *Nucl. Phys. A* **546**, 369c (1992).

G. Garvey, E. Kolbe, K. Langanke, and S. Krewald, "Strange Quark Contributions to Neutrino-Induced Quasielastic Scattering," *Phys. Lett.* **280B**, 249 (1992).

G. Glass, T. S. Bhatia, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, W. B. Tippens, D. B. Barlow, J. J. Jarmer, J. E. Simmons, R. H. Jeppesen, and G. E. Tripard, "Measurement of Spin-Correlation Parameters A_{LL} and A_{SL} in p - p Elastic Scattering from 500 to 800 MeV," *Phys. Rev. C* **45**, 35 (1992).

T. Goldman, M. M. Nieto, and V. D. Sandberg, "Kaons, Quantum Mechanics, and Gravity," *Mod. Phys. Lett. A* **7**, 3455 (1992).

A. Green, K. W. Jones, W. Unkelbach, J. Wambach, F. T. Baker, B. Storm, L. Bimbot, X. Y. Chen, C. Djalali, A. Sethi, D. Beatty, V. R. Cupps, G. Edwards, R. W. Ferguson, C. Glashausser, and G. Kumbartzki, "The Spin-Longitudinal/Spin-Transfer Response of ^{40}Ca to 500-MeV Protons at Low Momentum Transfer," Los Alamos National Laboratory document LA-UR-92-1547 (submitted to *Physical Review Letters*, April 1992).

E. Gülmez, D. L. Adams, S. Beedoe, M. Bleszynski, J. Bystricky, V. Ghazikhanian, G. Igo, T. Jaroszewicz, A. G. Ling, M. Nasser, M. W. McNaughton, S. Penttilä, G. Glass, G. Kahrmanis, W. F. Kielhorn, K. H. McNaughton, P. J. Riley, S. Sen, and D. Wolf, "Elastic Scattering of N , L , and S -Type Polarized 794-MeV Protons from an ND_3 Target Polarized in the S - L Plane," *Phys. Rev. C* **45**, 22 (1992).

D. G. Haase, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, C. R. Gould, J. N. Knudson, J. E. Koster, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, S. H. Yoo, and V. W. Yuan, "Analysis of Depolarization of Neutrons in Ferromagnetic ^{165}Ho by Means of Enhanced Nuclear Parity Violation ^{139}La ," *Phys. Rev. B* **46**, 11290 (1992).

M. Halka, H. C. Bryant, C. Johnstone, B. Marchini, W. Miller, A. H. Mohagheghi, C. Y. Tang, K. B. Butterfield, D. A. Clark, S. Cohen, J. B. Donahue, P. A. M. Gram, R. W. Hamm, A. Hsu, D. W. MacArthur, E. P. MacKerrow, C. R. Quick, J. Tiee, and K. Rozsa, "Branching Ratio of the $\text{H}^-(n=2)$ Shape Resonance," *Phys. Rev. A* **46**, 6942 (1992).

H. W. Harris, R. A. DeHaven, V. E. Hart, W. M. Parsons, and J. C. Sturrock, "Engineering, Maintenance, and New Initiatives to Improve LAMPF Beam Availability and System Reliability" (submitted to *Proc. of the 1992 Linear Accelerator Conference*, Ottawa, Canada, August 23-28, 1992).

V. E. Hart, E. D. Bush, Jr., and S. A. Schilling, "Mechanical Design of the LAMPF Medium-Resolution Spectrometer and CEBAF Short-Orbit Spectrometer Magnets," (submitted to *Proc. of the 1992 Linear Accelerator Conference*, Ottawa, Canada, August 23-28, 1992).

N. M. Hintz, X. H. Yang, M. Gazzaly, S. J. Seestrom-Morris, C. L. Morris, D. C. Cook, A. M. Mack, J. S. McDonald, D. S. Oakley, C. F. Moore, M. Lynker, and J. D. Zumbro, "Determination of Neutron and Proton Multipole Matrix Elements in ^{208}Pb from π^+ and π^- Scattering at 180 MeV," *Phys. Rev. C* **45**, 601 (1992).

C. M. Hoffman (editor and compiler), "Research at LAMPF," Los Alamos National Laboratory document LA-UR-92-926 (documents of LAMPF research compiled for distribution at the DOE/NSAC review held at Argonne National Laboratory, Argonne, Illinois, February 17-18, 1992).

D. J. Horen, C. L. Morris, S. J. Greene, S. J. Seestrom, M. A. Plum, F. W. Hersman, J. R. Calarco, M. Holtrop, M. Leuschner, M. Rawool-Sullivan, R. W. Garnett, and J. D. Zumbro, "Isospin Character of the Transition to the 0.803-MeV State in ^{206}Pb from $\pi^\pm$ Scattering at 180 MeV," *Phys. Rev. C* **46**, 499 (1992).

J. J. Jarmer and S. I. Penttilä, "Polarization of Irradiated Lithium Hydride," in *Proc. of the 10th International Symposium on High-Energy Spin Physics*, Nagoya, Japan, November 9–14, 1992, T. Hasegawa, N. Horikawa, A. Masaïke, and S. Sawada, Eds. (Universal Academy Press, Tokyo, 1993), p. 363.

M. B. Johnson, "Hadron Dynamics in High-Energy Pion-Nucleus Scattering," Los Alamos National Laboratory document LA-UR-93-2108 (submitted to *Proc. of the Annual Fall Meeting of the Division of Nuclear Physics*, Santa Fe, New Mexico, October 14–17, 1992).

M. B. Johnson and D. J. Ernst, "Meson-Nucleus Dynamics," *Ann. Phys. (N.Y.)* **219**, 266 (1992).

M. K. Jones, B. G. Ritchie, R. D. Ransome, D. Clayton, K. Pujara, C. L. Morris, J. A. McGill, D. L. Watson, C. Fred Moore, I. Brown, and P. Campbell, "Energy Dependence of the Total $^{12}\text{C}(\pi^+, 2p)$ Cross Section," *Phys. Lett. B* **278**, 419 (1992).

Charles C. H. Jui, "Test Results from the MEGA Experiment: A Search for the Rare Decay of the Muon to an Electron and a Gamma Ray," Ph.D. thesis, Stanford University, Los Alamos National Laboratory report LA-12324-T (March 1992).

D. D. Koetke, R. Fisk, D. S. Koetke, R. Manweiler, T. J. Bowles, A. Brown, R. E. Brown, R. L. Burman, D. A. Clark, S. Clearwater, T. Dombeck, H. W. Kruse, D. M. Lee, B. Aas, G. Igo, C. Newsom, D. Beavis, S. Y. Fung, W. Gorn, R. T. Poe, G. J. VanDalen, B. Bassalleck, B. Dieterle, C. Gregory, R. E. Hill, J. H. Kang, C. Leavitt, L. Auerbach, S. Datta, and Y. Huang, "Muon-Neutrino Carbon Charged-Current Interaction Near the Muon Threshold," *Phys. Rev. C* **46**, 2554 (1992).

J. E. Koster, R. O. Nelson, M. E. Schillaci, S. A. Wender, D. Mayo, F. P. Brady, J. Romero, D. Krofcheck, M. Blann, P. Anthony, V. R. Brown, L. Hansen, B. Pohl, T. C. Sangster, H. Nifenecker, and J. A. Pinston, "Neutron-Proton Bremsstrahlung Experiments," Los Alamos National Laboratory document LA-UR-92-3334 (submitted to *Proc. of the International Conference on the Application of Accelerators*, Denton, Texas, November 2–5, 1992).

AIM

Association for Information and Image Management

1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

Centimeter

Inches

MANUFACTURED TO AIM STANDARDS
BY APPLIED IMAGE, INC.

3 of 3

D. A. Krakauer, R. L. Talaga, R. C. Allen, H. H. Chen, R. Hausammann, W. P. Lee, H. J. Mahler, X-Q. Lu, K. C. Wang, T. J. Bowles, R. L. Burman, R. D. Carlini, D. R. F. Cochran, P. J. Doe, J. S. Frank, E. Piasetzky, M. E. Potter, and V. D. Sandberg, "Experimental Study of Neutrino Absorption on Carbon," *Phys. Rev. C* **45**, 2450 (1992).

D. A. Krakauer, R. L. Talaga, R. C. Allen, H. H. Chen, R. Hausammann, W. P. Lee, H. J. Mahler, X-Q. Lu, K. C. Wang, T. J. Bowles, R. L. Burman, R. D. Carlini, D. R. F. Cochran, P. J. Doe, J. S. Frank, E. Piasetzky, M. E. Potter, and V. D. Sandberg, "Limit on Flavor-Changing Neutral Currents from a Measurement of Neutrino-Electron Elastic Scattering," *Phys. Rev. D* **45**, 975 (1992).

J. Langenbrunner, M. K. Jones, D. Dehnhard, C. L. Morris, and W. R. Gibbs, "Evidence for Direct Triton Knockout in the $^4\text{He}(\pi, \pi't)p$ Reaction," *Phys. Rev. Lett.* **69**, 1508 (1992).

J. L. Langenbrunner, C. L. Morris, and R. M. Whitton, "CsI-Phoswich Detector for Charged Particle Identification," *Nucl. Instrum. Methods A* **316**, 450 (1992).

D. M. Lee, "Radiation Damage Considerations at a High Luminosity Collider: The Interaction Region," Los Alamos National Laboratory document LA-UR-92-2998 (submitted to *Proc. of the 19th Workshop on Maximizing Luminosity of Hadron Colliders at 100 TeV*, Erice, Italy, November 13-19, 1991).

M. Leon, "Use of Time Information in Muon Level-Crossing Resonance Spectroscopy," *Phys. Rev. B* **46**, 6603 (1992).

M. Leon, "Theory of Muonic Molecule Formation: Survey of Progress and Open Questions," Los Alamos National Laboratory document LA-UR-92-3045 (submitted to *Proc. of the μCF -92 Workshop*, Uppsala, Sweden, June 28-July 3, 1992).

M. Leon, "Muon Physics with the Proposed Pulsed Lepton Source at LAMPF," Los Alamos National Laboratory document LA-UR-92-3046 (submitted to *Proc. of the μCF -92 Workshop*, Uppsala, Sweden, June 28-July 3, 1992).

J. McClelland (for LAMPF Users), "PILAC Users Group Report on the Physics with PILAC" (for distribution to LAMPF Users).

J. B. McClelland, T. N. Taddeucci, X. Y. Chen, W. P. Alford, R. C. Byrd, T. A. Carey, S. DeLucia, C. D. Goodman, E. Gulmez, W. Huang, B. Luther, D. G. Marchlenski, D. J. Mercer, D. L. Prout, J. Rapaport, L. J. Rybarczyk,

W. Sailor, E. Sugarbaker, Y. Wang, and C. Whitten, Jr., "Quasifree Polarization-Transfer Measurements in the ($\bar{p}, \bar{n}$) Reactions at 495 MeV," *Phys. Rev. Lett.* **69**, 582 (1992).

P. L. McGaughey, J. M. Moss, D. M. Alde, H. W. Baer, T. A. Carey, G. T. Garvey, A. Klein, M. J. Leitch, J. W. Lillberg, C. S. Mishra, J-C. Peng, C. N. Brown, W. E. Cooper, Y. B. Hsiung, M. R. Adams, R. Guo, D. M. Kaplan, R. L. McCarthy, G. Danner, M. J. Wang, M. L. Barlett, and G. W. Hoffmann, "Limit on the $\bar{d}/\bar{u}$ Asymmetry of the Nucleon Sea from Drell-Yan Production," *Phys. Rev. Lett.* **69**, 1726 (1992).

K. H. McNaughton, D. A. Ambrose, P. Coffey, K. Johnston, P. J. Riley, K. Koch, M. W. McNaughton, I. Supek, N. Tanaka, G. Glass, J. C. Hiebert, L. C. Northcliffe, A. J. Simon, D. J. Mercer, D. L. Adams, H. Spinka, R. H. Jeppesen, G. E. Tripard, and H. Woolverton, " np Elastic Spin-Transfer Measurements at 485 and 635 MeV," *Phys. Rev. C* **46**, 47 (1992).

M. W. McNaughton, I. Supek, K. H. McNaughton, K. Johnston, P. J. Riley, D. A. Ambrose, W. P. Coffey, G. Glass, J. C. Hiebert, L. C. Northcliffe, A. J. Simon, D. J. Mercer, D. L. Adams, H. Spinka, R. H. Jeppesen, G. E. Tripard, and H. Woolverton, " $^2\text{H}(p, n)2p$ Spin Transfer from 305 to 788 MeV," *Phys. Rev. C* **45**, 2564 (1992).

David James Mercer, "Measurement of Effective Analyzing Powers for the NTOF Polarimeter at LAMPF and $D_{LL}(0^\circ)$ for Gamow-Teller Reactions in p -Shell Nuclei," Ph.D. thesis, University of Colorado, Los Alamos National Laboratory report LA-12441-T (November 1992).

G. E. Mitchell, J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan and X. Zhu, "Parity Nonconservation for Neutron Resonances," in *From Spectroscopic to Chaotic Features of Nuclear Systems*, D. Seeliger, Ed. (World Scientific, Singapore, 1992), p. 17.

J. O'Donnell, R. Lomax, B. McCloud, J. McGill, C. Morris, J. Davis, R. A. DeHaven, R. Johnson, G. Tubb, J. Novak, E. Gray, B. Rusnak, J. M. Applegate, T. D. Averett, J. Beck, B. G. Ritchie, E. Haebel, D. Kiehlmann, U. Klein, M. Peiniger, P. Schafer, H. Vogel, H. Ward, and C. Fred Moore, "A Superconducting Radio-Frequency Cavity for Manipulating the Phase Space of Pion Beams at LAMPF," *Nucl. Instrum. Methods A* **317**, 445 (1992).

J. M. O'Donnell, B. J. McCloud, C. L. Morris, J. B. McClelland, B. Rusnak, H. A. Thiessen, and J. L. Langenbrunner, "Test of Superconducting Radio-Frequency Cavity Bombarded by Protons," *Nucl. Instrum. Methods A* **314**, 409 (1992).

H. Postma, C. D. Bowman J. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttilä, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan, and X. Zhu, "Parity Violation at Neutron p -wave Resonances at ^{238}U and ^{232}Th and Related Questions," *Hyperfine Interactions* **75**, 153 (1992).

David Lester Prout, "Quasielastic Scattering using the (p,n) Reaction at 795 MeV," Ph.D. thesis, University of Colorado, Los Alamos National Laboratory report LA-12360-T (1992).

R. D. Ransome, C. L. Morris, V. R. Cupps, R. W. Ferguson, J. A. McGill, D. L. Watson, J. D. Zumbro, B. G. Ritchie, J. R. Comfort, J. R. Tinsley, R. A. Loveman, S. Dawson, A. Green, P. C. Gugelot, and C. Fred Moore, "Pion Absorption in Heavy Nuclei," *Phys. Rev. C* **45**, R509 (1992).

R. D. Ransome, C. L. Morris, M. K. Jones, B. G. Ritchie, D. L. Watson, J. A. McGill, K. Pujara, D. B. Clayton, I. Brown, P. Campbell, and C. Fred Moore, "Pion Absorption in Light Nuclei," *Phys. Rev. C* **46**, 273 (1992).

M. W. Rawool-Sullivan, J. F. Amann, L. G. Atencio, R. L. Boudrie, R. Lomax, C. L. Morris, M. M. Murray, and R. M. Whitton, "A New Multiplexing Scheme for Cathode-Strip Readout Chambers," *Nucl. Instrum. Methods A* **311**, 168 (1992).

D. P. Rosenzweig, I. Halpern, M. A. Khandaker, J. F. Amann, R. L. Boudrie, D. M. Drake, K. G. R. Doss, J. Nelson, D. R. Tieger, and S. A. Woods, "A Comparison of Inclusive Inelastic Scattering of π^+ and π^- from Nuclei at 100 MeV," Los Alamos National Laboratory document LA-UR-92-2088 (submitted to *Physical Review C*, June 1992, by the University of Washington).

S. J. Seestrom, C. D. Bowman, J. D. Bowman, J. N. Knudson, R. Mortensen, S. Penttilä, J. J. Szymanski, S. Wender, S. H. Yoo, V. W. Yuan, C. M. Frankle, C. R. Gould, D. G. Haase, G. E. Mitchell, N. R. Roberson, X. Zhu, P. P. Delheij, H. Postma, E. I. Sharapov, and Yu. P. Popov, "Measurement of Parity Violation in Neutron-Nucleus Reactions," in *Intersections between Particle and Nuclear Physics*, W. T. H. van Oers, Ed. (American Institute of Physics, New York, 1992), p. 40.

M. Sharirli, J. M. Butner, J. L. Rand, R. J. Macek, S. J. McKinney, and M. L. Roush, "Probabilistic Risk Assessment for the Los Alamos Meson Physics Facility Worst-Case Design-Basis Accident" (submitted to *Proc. of the Probabilistic Safety Assessment International Topical Meeting*, Clearwater Beach, Florida, January 26-29, 1993).

M. Sharirli, J. L. Rand, M. K. Sasser, and Floyd R. Gallegos, "Limited-Scope Probabilistic Safety Analysis for the Los Alamos Meson Physics Facility (LAMPF)" (submitted to *Proc. of the Probabilistic Safety Assessment International Topical Meeting*, Clearwater Beach, Florida, January 26-29, 1993).

C. Sinnis, "MILAGRO: A Low-Energy Threshold Extensive Air Shower," Los Alamos National Laboratory document LA-UR-92-3132 (submitted to *Proc. of the Conference "Towards a Major Atmospheric Cerenkov Detector for TeV Astro/Particle Physics"*, Palaiseau, France, June 11-12, 1992, to be published by Editions Frontieres).

S. Stanislaus, V. Armijo, J. K. Black, R. D. Bolton, S. Carius, M. D. Cooper, C. Espinoza, G. Hart, G. Hogan, A. Gonzales, R. E. Mischke, L. E. Pilonen, J. Sandoval, S. Schilling, J. Sena, G. Suazo, J. Szymanski, D. A. Whitehouse, C. A. Wilkinson, R. Fisk, D. D. Koetke, R. W. Manweiler, and C. C. Jui, "Results from Beam Tests of MEGA's Low-Mass, High-Rate Cylindrical MWPCs," *Nucl. Instrum. Methods A* **323**, 198 (1992).

S. M. Sterbenz, D. Dehnhard, M. K. Jones, S. K. Nanda, C. E. Parman, Yi-Fen Yen, K. W. Jones, and C. L. Morris, "Inelastic Scattering of Polarized Protons from ^4He at 500 and 800 MeV," *Phys. Rev. C* **45**, 2578 (1992).

J. F. Stubbins, W. F. Sommer, and E. Farnum, "Overview of Spectral Effects for the Comparison of Neutron Irradiation Damage," Los Alamos National Laboratory document LA-UR-92-4259, December 1992.

J. C. Sturrock, S. Cohen, B. L. Weintraub, D. J. Hayden, and S. F. Archuletta, "Testing Intelligent Power Supplies for the Los Alamos National Laboratory Accelerator Complex" (submitted to the *Proc. of the 1992 3rd IEEE Workshop on Computers in Power*, Berkeley, California, August 9-11, 1992).

J. C. Sturrock, S. Cohen, B. L. Weintraub, D. J. Hayden, and S. F. Archuletta, "Testing and Interfacing Intelligent Power Supplies for the Los Alamos National Laboratory Accelerator Complex" (submitted to the *Proc. of the IEEE Nuclear Science Symposium*, Orlando, Florida, October 27-31, 1992).

G. R. Swain, "Cavity Shape Considerations for PILAC and Other High-Gradient Superconducting Linacs" (submitted to *Proc. of the 1992 Linear Accelerator Conference*, Ottawa, Canada, August 23-28, 1992).

G. R. Swain and H. S. Butler, "Linac Beam Dynamics Calculations for Low-Current Large-Emittance Beams" (submitted to *Proc. of the 1992 Linear Accelerator Conference*, Ottawa, Canada, August 23-28, 1992).

H. A. Thiessen, "PILAC Cavity Review," in *Proc. of PILAC Cavity Review*, May 15, 1992.

O. B. van Dyck, R. L. Hutson, M. E. Schillaci, and D. H. White, "Progress at LAMPF, January–December 1990," Los Alamos National Laboratory report LA-12256-PR (March 1992).

O. B. van Dyck, R. L. Hutson, M. E. Schillaci, and D. H. White, "Progress at LAMPF, January–December 1991," Los Alamos National Laboratory report LA-12437-PR (November 1992).

H. J. Ward, K. W. Johnson, G. P. Kahrmanis, D. S. Saunders, C. F. Moore, S. Mordechai, C. L. Morris, H. T. Fortune, M. A. Kagarlis, D. A. Smith, J. M. O'Donnell, and N. Auerbach, "The Double Giant Dipole Resonance in the (π^-, π^+) Reaction," *Phys. Rev. C* **45**, 2723 (1992).

H. Ward, C. F. Moore, P. S. Maloney, and J. D. Martin, "Probabilistic Neural Nets in Analysis of Magnetic Spectrometer Data," *Nucl. Instrum. Methods A* **321**, 583 (1992).

D. D. Weeks and G. B. Yodh, "Ultra High Energy Gamma Rays and Observations with CYGNUS/ MILAGRO," Los Alamos National Laboratory document LA-UR-92-1545 (submitted to *Proc. of Isolated Pulsers*, Taos, New Mexico, February 23–28, 1992).

S. Wender, S. J. Seestrom, and C. L. Morris, "A Beam Current Limiting Device," Los Alamos National Laboratory document LA-UR-92-185 (submitted to *Nuclear Instruments and Methods*, January 1992)

D. H. White, "Problems in Neutrino Electron Scattering with 1-GeV Neutrinos," Los Alamos National Laboratory document LA-UR-92-1302 (submitted to the *TRIUMF Neutrino Workshop*, Lake Louise, Alberta, Canada, February 18-21, 1992).

D. H. White, "Baryons in the Future of LAMPF" (submitted to *Proc. of Baryons '92 International Conference on the Structure of Baryons and Related Mesons*, New Haven, Connecticut, June 1–4, 1992).

D. H. White, "Neutrino-Proton Elastic Scattering" (submitted to the *Workshop on Flavour and Spin in Hadronic and Electromagnetic Interactions*, Torino, Italy, September 20–23, 1992).

R. M. Whitton, C. L. Morris, and J. L. Langenbrunner, "Resolution of BGO Scintillators for Use in the Neutral-Meson Spectrometer: Results of Measurements and Simulations," Los Alamos Technical Note (March 1992).

C. A. Wilkinson, D. H. Fitzgerald, S. C. Frankle, R. L. Hutson, and R. J. Macek, "Monte Carlo Based Formula for Estimating Penetration of Radiation Shielding at Forward Angles," Los Alamos National Laboratory document LA-UR-92-3202 (submitted to the *Proc. of the Division of Particles and Fields Conference*, Fall 1992).

R. L. Wood, L. M. Young, D. J. Aikin, W. L. Clark, R. F. DePaula, C. Gladwell, J. E. Ledford, F. A. Martinez, and J. S. Stovall, "Photocathode Electron Linac for AFEL" (submitted to *Proc. of the Twelfth International Conference on the Application of Accelerators in Research and Industry*, Denton, Texas, November 2-5, 1992).

S. A. Wood, J. L. Matthews, E. R. Kinney, P. A. M. Gram, G. A. Rebka, Jr., and D. A. Roberts, "Systematics of Inclusive Pion Double Charge Exchange in the Delta Resonance Region," *Phys. Rev. C* **46**, 1903 (1992).

X. D. Wu, S. R. Foltyn, R. E. Muenchausen, and D. W. Cooke, "Buffer Layers for High T_c Thin Films on Sapphire" (submitted to *Journal of Superconductivity*, June 1992).

X. Zhu, J. D. Bowman, C. D. Bowman, J. E. Bush, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttilä, Hans Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, and V. W. Yuan, "Parity Nonconservation for Neutron Resonances in ^{238}U ," *Phys. Rev. C* **46**, 768 (1992).

J. Zumbro, C. Morris, S. Seestrom, J. McGill, R. Whitton, C. M. Riedel-Edwards, A. Williams, M. Braunstein, M. Kohler, B. Kriss, S. Høibråten, R. Peterson, J. Ouyang, E. Wise, and W. Gibbs, "Evidence for Pion Transparency in Nuclei?" (submitted to *Physical Review Letters*, December 1992).

1993

D. V. Ahluwalia, "Quantum Measurement, Gravitation, and Locality," Los Alamos National Laboratory document LA-UR-93-2890 (submitted to *Physics Letters A*, August 1993).

D. V. Ahluwalia, "P and CP Structure of Space-Time," tentative outline of a proposed book to be submitted to Cambridge University Press, Los Alamos National Laboratory document LA-UR-93-4448 (submitted December 1993).

D. V. Ahluwalia and T. Goldman, "Space Time Symmetries and Vortices in the Cosmos," *Mod. Phys. Lett. A* **8**, 2623 (1993).

D. V. Ahluwalia, M. B. Johnson, and T. Goldman, "A Bargmann-Wightman-Wigner Type Quantum Field Theory," *Phys. Lett.* **316B**, 102 (1993).

D. V. Ahluwalia, M. B. Johnson, and T. Goldman, "Space-Time Symmetries: P and CP Violation," Los Alamos National Laboratory document LA-UR-93-4314 (submitted to the *Proc. of the III International Wigner Symposium*, Christ Church, Oxford, England, September 1993).

D. V. Ahluwalia, M. B. Johnson, and T. Goldman, " $(j,0) \oplus (0,j)$ Representation Space: Dirac-Like Construct," Los Alamos National Laboratory document LA-UR-93-4315 (submitted to the *Proc. of the XVII International School of Theoretical Physics: Standard Model and Beyond '93*, Szczyrk, Poland, September 1993).

D. V. Ahluwalia, T. Goldman, and M. B. Johnson, " $(j,0) \oplus (0,j)$ Representation Space: Majorana-Like Construct," Los Alamos National Laboratory document LA-UR-93-4316 (submitted to the *Proc. of the XVII International School of Theoretical Physics: Standard Model and Beyond '93*, Szczyrk, Poland, September 1993).

D. E. Alexandreas, G. Allen, D. Berley, S. Biller, R. L. Burman, D. R. Cady, M. Cavalli-Sforza, C. Y. Chang, D. Coyne, C. Dion, G. M. Gion, D. Dorfman, R. W. Ellsworth, S. J. Freedman, B. K. Fujikawa, J. A. Goodman, T. J. Haines, C. M. Hoffman, L. Kelley, S. Klein, D. A. Krakauer, P. W. Kwok, X.-Q. Lu, D. E. Nagle, M. Potter, V. D. Sandberg, C. Sinnis, A. Shoup, M. J. Stark, P. R. Vishwanath, D. D. Weeks, D. A. Williams, J.-P. Wu, G. B. Yodh, and W. Zhang, "Daily Search for Emission of Ultra-High-Energy Radiation from Point Sources," *Astrophys. J.* **405**, 353 (1993).

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M. L. Chen, P. Chumney, D. D. Coyne, C. Dion, G. M. Dion, D. Dorfman, R. W. Ellsworth, J. A. Goodman, T. J. Haines, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, S. C. Schaller, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. Zhang, "Search for Emission of Ultra-High-Energy Radiation from Active Galactic Nuclei," *Astrophys. J.* **418**, 832 (1993).

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfman, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for Continuous and Single Day Emission from Ultra-High-Energy Sources," in

Proc. of the International Cosmic-Ray Conference, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 353.

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Angular Resolution Studies of the CYGNUS Array Using the Shadows of the Sun and Moon," in *Proc. of the International Cosmic-Ray Conference, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 223.*

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for Ultra-High-Energy Radiation from γ -Ray Bursts," in *Proc. of the International Cosmic-Ray Conference, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 65.*

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for UHE Emission from Cygnus X-3," in *Proc. of the International Cosmic-Ray Conference, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 373.*

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for Emission of Ultra High Energy Radiation from Active Galactic Nuclei," in *Proc. of the International Cosmic-Ray Conference, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 416.*

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M.

Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for UHE Point-Source Emission over Various Time Scales," in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19–30, 1993, Vol. 1, p. 326.

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Search for Ultra-High Energy Emission from Geminga and Five Unidentified EGRET Sources," in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19–30, 1993, Vol. 1, p. 312.

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "A New Limit on the Rate-Density of Evaporating Black Holes," in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19–30, 1993, Vol. 1, p. 428.

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "Results from a Water-Cherenkov Array," in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19–30, 1993, Vol. 1, p. 243.

D. E. Alexandreas, G. E. Allen, D. Berley, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, P. Chumney, D. Coyne, C. L. Dion, G. M. Dion, D. Dorfan, R. W. Ellsworth, J. A. Goodman, T. J. Haines, M. Harmon, C. M. Hoffman, L. Kelley, S. Klein, D. E. Nagle, D. M. Schmidt, R. Schnee, C. Sinnis, A. Shoup, M. J. Stark, D. D. Weeks, D. A. Williams, J.-P. Wu, T. Yang, G. B. Yodh, and W. P. Zhang, "New Limit on the Rate-Density of Evaporating Black Holes," *Phys. Rev. Lett.* **71**, 2524 (1993).

D. E. Alexandreas, D. Berley, S. Biller, G. M. Dion, J. A. Goodman, T. J. Haines, C. M. Hoffman, E. Horch, X-Q. Lu, C. Sinnis, G. B. Yodh, and W.

Zhang, "Point Source Search Techniques in Ultra High Energy Gamma Ray Astronomy," *Nucl. Instrum. Methods A* 328, 570 (1993). Also in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 247.

R. C. Allen, H. H. Chen, P. J. Doe, R. Hausammann, W. P. Lee, X-Q. Lu, H. J. Mahler, M. E. Potter, K. C. Wang, T. J. Bowles, R. L. Burman, R. D. Carlini, D. R. F. Cochran, J. S. Frank, E. Piasetzky, V. D. Sandberg, D. A. Krakauer, and R. L. Talaga, "Study of Electron-Neutrino Electron Elastic Scattering at LAMPF," *Phys. Rev. D* 47, 11 (1993).

L. G. Atencio, C. L. Morris, and C. P. Sadler, "Reduced Multiple Scattering Using Thin Windows," Los Alamos National Laboratory document LA-UR-93-513 (submitted to *Nuclear Instruments and Methods Letters*, February 1993).

Johann Bartel, Mikkel B. Johnson, Mano Singham, and Wilhelm Stocker, "Microscopic Coupled-Channel Description of Pion Inelastic Scattering from Rotational Nuclei," Los Alamos National Laboratory document LA-UR-93-3871 (accepted by *Physical Review C*, 1994).

S. Barwick, S. Biller, R. L. Burman, M. Cavalli-Sforza, C. Y. Chang, M.-L. Chen, D. Coyne, C. L. Dion, D. Dorfan, R. W. Ellsworth, S. J. Freedman, J. A. Goodman, T. J. Haines, C. M. Hoffman, L. A. Kelley, S. Klein, R. C. Lamb, A. I. Mincer, D. E. Nagle, P. Nemethy, T. J. O'Neill, V. D. Sandberg, S. Schaller, D. M. Schmidt, A. Shoup, C. Sinnis, O. T. Tumer, D. D. Weeks, D. H. White, D. A. Williams, G. B. Yodh, and A. Zych, "Astrophysics with MILAGRO," in *Proc. of the International Cosmic-Ray Conference*, Calgary, Canada, July 19-30, 1993, Vol. 1, p. 436.

M. Beddo, G. Burleson, J. A. Faucett, S. Gardiner, G. Kyle, R. Garnett, D. Grosnick, D. Hill, K. Johnson, D. Lopiano, Y. Ohashi, T. Shima, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, G. Glass, R. Kenefick, S. Nath, L. Northcliffe, J. Jarmer, S. Penttilä, R. Jeppesen, G. Tripard, M. Devereux, and P. Kroll, "Measurement of Longitudinal Spin-Dependent Neutron-Proton Total Cross Section Difference $\Delta\sigma_L(np)$ between 500 and 800 MeV" (accepted by *Physical Review C*, 1993).

Steven Douglas Biller, "A Study of Ultra High Energy Radiation Associated with Hercules X-1," Ph.D. Thesis, UC Irvine (April 1993).

J. Birchall, A. R. Berdoz, J. D. Bowman, J. R. Campbell, C. A. Davis, N. E. Davidson, P. W. Green, A. Hamian, D. C. Healey, R. Helmer, E. Korkmaz, P. Levy, R. E. Mischke, S. A. Page, W. D. Ramsey, G. Roy, P. W. Schmor, J. Soukup, G. M. Stinson, T. J. Stocki, N. A. Titov, W. T. H. van Oers, and A. N. Zelenski, "Parity Violation in p - p Scattering," *Nucl. Phys. A* 553, 823c (1993).

E. Bjorklund, "Virtual Data," Los Alamos National Laboratory document LA-UR-93-3697 (submitted to the *International Conference on Accelerator and Large Experimental Physics Control Systems*, Berlin, Germany, October 18-22, 1993).

J. D. Bowman, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, J. J. Szymanski, J. J. Yeh, S. H. Yoo, V. W. Yuan, and X. Zhu, "Experimental Limit on Parity Violation in Nonresonant Neutron-Nucleus Scattering," *Phys. Rev. C* **48**, 1116 (1993).

J. D. Bowman, C. M. Frankle, J. N. Knudson, S. I. Penttilä, S. J. Seestrom, J. J. Szymanski, Yi-Fen Yen, S. H. Yoo, V. W. Yuan, B. Crawford, N. R. Roberson, X. Zhu, C. R. Gould, D. G. Haase, L. Lowie, G. E. Mitchell, S. Patterson, P. P. J. Delheij, Y. Popov, E. Sharapov, H. Postma, H. M. Shimizu, and Y. Matsuda, "Data on Parity Violation in the Compound Nucleus and its Interpretation," in *Proc. of the Second International Workshop on Time Reversal Invariance and Parity Violation*, Dubna, Russia, May 4-7, 1993, C. R. Gould, J. D. Bowman, and Yu. Popov, Eds. (World Scientific, Singapore, 1994), p. 8.

J. D. Bowman, G. T. Garvey, M. B. Johnson, and G. E. Mitchell, "Recent Advances in the Study of Parity Violation in the Compound Nucleus," *Annu. Rev. Nucl. Part. Sci.* **49**, 829 (1993).

J. David Bowman and Eduard Sharapov, "Likelihood Analysis of Parity Violation in the Compound Nucleus," Los Alamos National Laboratory document LA-UR-93-3516 (submitted to *Proc. of the Second International Workshop on Time Reversal Invariance and Parity Violation*, Dubna, Russia, May 4-7, 1993).

R. L. Burman, T. J. Bowles, R. D. Carlini, D. R. F. Cochran, P. J. Doe, J. S. Frank, M. E. Potter, V. D. Sandberg, D. A. Krakauer, R. L. Talaga, R. C. Allen, H. H. Chen, R. Hausamman, W. P. Lee, X-Q. Lu, H. J. Mahler, K. C. Wang, and E. Piasetzky, "Measurement of W - Z Interference from Neutrino-Electron Scattering," Los Alamos National Laboratory document LA-UR-93-1004 (submitted to *Proc. of the International Symposium on 30 Years of Neutral Currents*, Los Angeles, California, February 3-5, 1993).

C. M. Chen, D. J. Ernst, and M. B. Johnson, "Microscopic Approach to Pion-Nucleus Dynamics," *Phys. Rev. C* **47**, R9 (1993).

C. M. Chen, D. J. Ernst, and Mikkel B. Johnson, "High-Energy Pion-Nucleus Elastic Scattering," *Phys. Rev. C* **48**, 841 (1993).

X. Y. Chen, D. J. Mercer, D. L. Prout, J. B. McClelland, T. N. Taddeucci, T. A. Carey, R. C. Byrd, L. J. Rybarczyk, W. C. Sailor, S. DeLucia, B. Luther, D. G. Marchlinski, E. R. Sugarbaker, J. Rapaport, E. Gülmez, C. A. Whitten, C. D. Goodman, W. Huang, Y. Wang, and W. P. Alford, "Polarization Transfer in Quasifree Polarized ($\bar{p}, \bar{n}$) Reactions at 495 MeV," *Phys. Rev. C* **47**, 2159 (1993).

D. W. Cooke, M. Leon, M. A. Paciotti, B. Bennett, O. Rivera, S. F. J. Cox, C. Boekema, J. Lam, A. Morrobel-Sosa, P. Meier, T. Estle, B. Hitti, R. Lichti, E. A. Davis, J. Oostens, and E. Haller, "Muon Level-Crossing Resonance in Si:Al," Los Alamos National Laboratory document LA-UR-93-2124 (submitted to *Hyperfine Interactions*, June 1993).

D. W. Cooke, M. Leon, M. A. Paciotti, P. F. Meier, S. F. J. Cox, E. A. Davis, T. Estle, B. Hitti, R. Lichti, C. Boekema, J. Lam, A. Morrobel-Sosa, and J. Oostens, "Distinctive Field Dependence of the Longitudinal Muon Polarization for Mu in Polycrystalline Silicon," Los Alamos National Laboratory document LA-UR-93-2125 (submitted to *Hyperfine Interactions*, June 1993).

M. D. Cooper, "Rare Muon Processes," Los Alamos National Laboratory document LA-UR-93-1292 (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

M. D. Cooper, " $\mu^+ \rightarrow e^+ \gamma$," Los Alamos National Laboratory document LA-UR-93-1471 (submitted to *Proc. of the International Workshop on Low-Energy Muon Science-LEMS'93*, Santa Fe, New Mexico, April 4-8, 1993).

Marla L. Dowell, "Pion Single Charge Exchange in Three Body Nuclei at Intermediate Energies," Ph.D. Thesis, Massachusetts Institute of Technology, Los Alamos National Laboratory report LA-12691-T (submitted October 1993).

C. Frankle, D. Alde, J. D. Bowman, J. N. Knudson, S. I. Penttilä, S. J. Seestrom, Y.-F. Yen, S. H. Yoo, V. W. Yuan, C. Gould, D. G. Haase, G. E. Mitchell, S. S. Patterson, B. E. Crawford, R. N. Roberson, Y. P. Popov, E. I. Sharapov, A. Masaike, Y. Matsuda, S. Takahashi, Y. Masuda, H. M. Shimizu, P. P. J. Delheij, and H. Postma, "Parity Violation Experiments at Los Alamos," Los Alamos National Laboratory document LA-UR-93-1451 (submitted to the *Soviet Journal of Nuclear Physics*, April 1993).

C. M. Frankle, J. D. Bowman, B. Crawford, P. P. J. Delheij, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S. Patterson, S. Penttilä, Yu. Popov, N. R. Roberson, S. J. Seestrom, E. Sharapov, Yi-Fen Yen, S. H. Yoo,

V. W. Yuan, and X. Zhu, "Neutron Resonance Spectroscopy of ^{113}In and ^{115}In ," *Phys. Rev. C* **48**, 1601 (1993).

C. M. Frankle, J. D. Bowman, S. I. Penttilä, S. J. Seestrom, S. H. Yoo, V. W. Yuan, C. R. Gould, D. G. Haase, G. E. Mitchell, N. R. Roberson, Y. P. Popov, E. I. Sharapov, P. P. J. Delheij, H. Postma, and J. N. Knudson, "Measurement of Parity Violation in Compound Nuclear Resonances Using Epithermal Polarized Neutrons," *Nucl. Instrum. Methods B* **79**, 306 (1993).

S. Frankle, D. Fitzgerald, R. Hutson, R. Macek, and C. Wilkinson, "Application of a Simple Analytical Model to Estimate Effectiveness of Radiation Shielding for Neutrons," Los Alamos National Laboratory document LA-UR-93-1922 (submitted to the 1993 Particle Accelerator Conference, Washington, DC, May 17-20, 1993).

S. J. Freedman, B. K. Fujikawa, J. Napolitano, J. E. Nelson, R. McKeown, K. T. Lesko, J. B. Donahue, G. T. Garvey, V. D. Sandberg, C. Choi, A. Fazely, R. L. Imley, W. J. Metcalf, L. S. Durkin, R. W. Harper, T. Y. Ling, J. W. Mitchel, T. A. Romanowski, E. S. Smith, and M. Timko, "Limits on Neutrino Oscillations from $\bar{\nu}_e$ Appearance," *Phys. Rev. D* **47**, 811 (1993).

Emil Frlež, "Reaction $\pi N \rightarrow \pi\pi N$ near Threshold," Ph.D. Thesis, University of Virginia, Los Alamos National Laboratory report LA-12663-T (December 1993).

G. T. Garvey, "The Neutral Current Axial Vector Form Factor of the Nucleon" (submitted to the *Particles and Nuclei International Conference*, Perugia, Italy, June 28-July 2, 1993).

G. Garvey, E. Kolbe, K. Langanke, and S. Krewald, "The Role of Strange Quarks in Quasielastic Neutrino Scattering," *Phys. Rev. C* **48**, 1919 (1993).

G. T. Garvey, W. C. Louis, and D. H. White, "Determination of Proton Strange Form Factors from n - p Elastic Scattering," *Phys. Rev. C* **48**, 761 (1993).

Y. Grof, N. Auerbach, D. Benton, H. T. Fortune, K. Johnson, M. A. Kagarlis, G. Kahrimanis, S. Mordechai, C. L. Morris, J. M. O'Donnell, I. Orion, D. Saunders, D. A. Smith, H. Ward, and C. Fred Moore, "Double Giant Resonances in Pion Double Charge Exchange on ^{51}V , ^{115}In , and ^{197}Au ," *Phys. Rev. C* **47**, 1466 (1993).

E. Gülmez, A. G. Ling, C. A. Whitten Jr., M. W. McNaughton, D. L. Adams, V. R. Cupps, G. Glass, A. J. Simon, and K. H. McNaughton,

"Absolute Differential Cross-Section Measurements for $p + p \rightarrow \pi^+ + d$ Reaction at 500–800 MeV," *Nucl. Phys. A* 551, 621 (1993).

D. G. Haase, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, C. R. Gould, J. N. Knudson, J. E. Koster, G. E. Mitchell, S. Penttilä, H. Postma, N. R. Roberson, S. J. Seestrom, S. H. Yoo, and V. W. Yuan, "Bulk Magnetic Structure Studies Using Polarized Epithermal Neutrons," *Nucl. Instrum. Methods B* 79, 300 (1993).

J. Haidenbauer, K. Holinde, and M. B. Johnson, "A Coupled-Channel Potential for Nucleons and Deltas," *Phys. Rev. C* 48, 2190 (1993).

T. W. Hardek and A. Band, "Integrating Log-Ratio Position Processing for the Los Alamos Proton Storage Ring Extraction Line," Los Alamos National Laboratory document LA-UR-93-1955 (submitted to the 1993 *Particle Accelerator Conference*, Washington, DC, May 17–20, 1993).

T. W. Hardek, R. Macek, M. Plum, and T. S. Wang, "Beam Pinging, Sweeping, Shaking, and Electron/Ion Collecting at the Proton Storage Ring," Los Alamos National Laboratory document LA-UR-93-1921 (submitted to the 1993 *Particle Accelerator Conference*, Washington, DC, May 17–20, 1993).

C. M. Hoffman and W. K. McFarlane, "Measuring Pion Beta Decay with High-Energy Pion Beams," Los Alamos National Laboratory document LA-UR-93-0140 (submitted to the *Proc. of the Workshop on New Vistas in Physics with High Energy Pion Beams*, Santa Fe, New Mexico, October 14, 1992).

C. M. Hoffman, "Pions and Neutrinos as Probes of the Nucleon and Nuclear Few-Body System," Los Alamos National Laboratory document LA-UR-93-3006 (submitted to the 14th *European Conference on Few-Body Problems in Physics*, Amsterdam, The Netherlands, August 22–27, 1993).

R. L. Hutson, "Stripper-Foil Scan Studies of the First-Turn Beam Loss Mechanism in the LAMPF Proton Storage Ring (PSR)," Los Alamos National Laboratory document LA-UR-93-1867 (submitted to *Proc. of the 1993 Particle Accelerator Conference*, Washington, DC, May 17–20, 1993).

R. Hutson and R. Macek, "First-Turn Losses in the LAMPF Proton Storage Ring (PSR)," Los Alamos National Laboratory document LA-UR-93-1868 (submitted to *Proc. of the 1993 Particle Accelerator Conference*, Washington, DC, May 17–29, 1993).

W-Y. P. Hwang, G. T. Garvey, J. M. Moss, and J.-C. Peng, " $\bar{d}/\bar{u}$ Asymmetry in a Proton and Drell-Yan Processes," *Phys. Rev. D* **47**, 2697 (1993).

John Doeppers Johnson, "Search for an Eta-Nuclear Bound State in the Double Charge Exchange Reaction $^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne}(\text{DLAS})$," Ph.D. Thesis, University of Texas at Austin, Los Alamos National Laboratory report LA-12508-T (March 1993).

J. D. Johnson, G. R. Burleson, C. Edwards, M. El-Ghossain, M. A. Espy, R. Garnett, A. Hussein, K. Johnson, C. F. Moore, C. L. Morris, J. M. O'Donnell, M. Palarczyk, M. Rawool-Sullivan, H. Ward, D. Watson, C. Whitley, and A. L. Williams, "Search for an η Bound State in Pion Double Charge Exchange on ^{18}O ," *Phys. Rev. C* **47**, 2571 (1993).

M. B. Johnson, "Hadron Dynamics in High-Energy Pion-Nucleus Scattering," Los Alamos National Laboratory document LA-UR-93-2108 (submitted to *Proc. of the Annual Fall Meeting of the Division of Nuclear Physics*, October 14-17, 1992).

M. B. Johnson, "Dynamics of Pion-Nucleus Systems," Los Alamos National Laboratory document LA-UR-93-1692 (submitted to *Proc. of Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

M. B. Johnson and C. L. Morris, "Pion Double Charge Exchange in Nuclei," *Annu. Rev. Nucl. Part. Sci.* **43**, 165 (1993).

M. K. Jones, R. D. Ransome, V. R. Cupps, R. W. Ferguson, C. L. Morris, J. A. McGill, J. D. Zumbro, J. R. Comfort, B. G. Ritchie, J. R. Tinsley, P. C. Gugelot, and C. Fred Moore, "Pion Absorption above the $\Delta(1232)$ Resonance," *Phys. Rev. C* **48**, 2800 (1993).

M. Kh. Kankhasayev, H. Sarafian, M. B. Johnson, and Zh. B. Kurmanov, "Effect of Pion External Distortion on Low-Energy Pion Double Charge Exchange," Los Alamos National Laboratory document LA-UR-93-1691 (accepted by *Physical Review C*, 1994).

Marios A. Kagarlis, "Spin Flip Effects in Pion Nucleus Interactions," Ph.D. Thesis, University of Pennsylvania, Los Alamos National Laboratory document LA-12443-T (January 1993).

M. A. Kagarlis, Mikkel B. Johnson, and H. T. Fortune, "A Microscopic, Coupled-Channel Theory of Pion Scattering," Los Alamos National Laboratory document LA-UR-93-3872 (accepted by *Annals of Physics*, 1994).

J. Langenbrunner, M. B. Barakat, E. V. Hungerford III, C. T. Pillai, N. Tanaka, H. A. Thiessen, L. J. Rybarcyk, K. W. Jones, D. B. Barlow, J. B. McClelland, D. C. Dressman, S. C. Piltch, D. N. Mihaildis, J. B. Donahue, C. L. Morris, and R. D. Werbeck, "Pion Production at Small Angles," *Nucl. Instrum. Methods A* **325**, 187 (1993).

M. Leon, Editor, *Proceedings of the International Workshop on Low-Energy Muon Science-LEMS'93*, Santa Fe, New Mexico, April 4-8, 1993, Los Alamos National Laboratory report LA-12698-C (1994).

M. Leon, "Older Muons are Wiser: Using Time Information in μ LCR Spectroscopy," Los Alamos National Laboratory document LA-UR-93-2556 (submitted to *Proc. of the International Conference on Muon Spin Rotation/Relaxation/Resonance (μ SR)*, Wailea, Maui, Hawaii, June 7-11, 1993).

M. Leon, "Three-Body Molecular Formation in Muon-Catalyzed *d-t* Fusion: The Classical Trajectory Model" (submitted to *Physical Review A*, September 1993).

M. Leon and M. A. Paciotti, "Muon Opportunities at the Proposed Pulsed Lepton Source and Spallation Neutron Source," Los Alamos National Laboratory document LA-UR-93-2554 (submitted to *Proc. of the International Conference on Muon Spin Rotation/Relaxation/Resonance (μ SR)*, Wailea, Maui, Hawaii, June 7-11, 1993).

R. J. Macek and the extended PSR Development Team, "Machine Studies at the Los Alamos Proton Storage Ring," Los Alamos National Laboratory document LA-UR-93-2941 (submitted to the *ICANS XII Workshop*, Session C-2, The Cosener's House, Abingdon, United Kingdom, May 24-28, 1993).

R. J. Macek, D. H. Fitzgerald, M. V. Hoehn, R. D. Ryder, and R. L. York, "Status of the PSR Improvement Program," Los Alamos National Laboratory document LA-UR-93-1866 (submitted to *Proc. of the 1993 Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

R. J. Macek and H. A. Thiessen, Eds., *Proceedings of the Workshop on Accelerators for Future Spallation Neutron Sources: Volume I—Summary Reports; Volume II—Presentations*, Santa Fe, New Mexico, February 16-20, 1993, Los Alamos National Laboratory document LA-UR-93-1356 (April 1993).

Yasuhiro Masuda, "T-Violating Neutron Spin Rotation Asymmetry," Los Alamos National Laboratory document LA-UR-93-2644 (submitted to the *International Workshop on Time Reversal Invariance and Parity Violation in Neutron Reaction*, Dubna, Russia, May 4-7, 1993).

Scott K. Matthews, "Elastic Scattering of Pions from Tritium and ^3He in the Backward Hemisphere, in the Region of the $\Delta_{33}(1232)$ Resonance," Ph.D. Thesis, George Washington University, Los Alamos National Laboratory report LA-12651-T (November 1993).

J. B. McClelland, "Quasifree ($\bar{p}, \bar{n}$) Reactions and Enhancement of Pionic Processes," Los Alamos National Laboratory document LA-UR-93-1503 (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

John McClelland, Ed Arthur, Torben Brun, Wayne Cooke, George Lawrence, Paul Lisowski, Walt Sommer, Arch Thiessen, Hywel White, Jerry Wilhelmy, Peter Barnes, Richard Woods, and Andre Michaudon, "Technical Assessment of Possible Applications of the LAMPF Accelerator Complex Beyond LANSCE II," Los Alamos National Laboratory document LA-UR-93-3996, for internal distribution only (October 1993).

M. G. McKinzie, H. T. Fortune, P. Hui, R. Ivie, C. Laymon, X. Li, S. Loe, D. A. Smith, A. L. Williams, J. M. O'Donnell, S. Blanchard, G. R. Burleson, and B. Lail, "Interference Effects in Non-Analog Pion Double Charge Exchange," Los Alamos National Laboratory document LA-UR-93-3215 (submitted to *Physical Review C*, August 1993).

M. W. McNaughton, "LAMPF Beam-Line Polarimeters," Los Alamos National Laboratory document LA-UR-93-2725 (submitted to *Nuclear Instruments and Methods*, July 1993).

M. W. McNaughton, K. Johnston, D. R. Swenson, D. Tupa, R. L. York, D. A. Ambrose, W. P. Coffey, K. H. McNaughton, P. J. Riley, G. Glass, J. C. Heibert, R. H. Jeppesen, H. Spinka, I. Supek, G. E. Tripard, and H. Woolverton, " np -Elastic Analyzing Power A_{N0} and Spin Transfer K_{NN} ," *Phys. Rev. C* **48**, 256 (1993).

D. J. Mercer, T. N. Taddeucci, L. J. Rybarcyk, X. Y. Chen, D. L. Prout, R. C. Byrd, J. B. McClelland, W. C. Sailor, S. DeLucia, B. Luther, D. G. Marchlinski, E. Sugarbaker, E. Gülmez, C. A. Whitten, Jr., C. D. Goodman, and J. Rapaport, "Polarization Transfer in ($\bar{p}, \bar{n}$) Reactions at 318 and 494 MeV and the Effective Interaction," *Phys. Rev. Lett.* **71**, 684 (1993).

J. L. Merson and L. J. Rybarcyk, "Wider Availability of PARMILA and Recent Improvements to AT-6 PARMILA" (submitted to the *Computational Accelerator Physics Conference (CAP93)*, Pleasanton, California, February 22-26, 1993).

D. N. Mihailidis, N. M. Hintz, A. Sethi, M. K. Jones, L. Rybarczyk, K. Koch, and C. L. Morris, "A Position-Sensitive Proton Telescope," *Nucl. Instrum. Methods A* **333**, 469 (1993).

R. E. Mischke, "Parity Nonconservation in Proton Scattering at Higher Energies," Los Alamos National Laboratory document LA-UR-93-1511 (submitted to the *Proc. of Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

G. J. Moore, J. A. Hanlon, B. Lamartine, M. Hawley, J. C. Solem, S. Singer, J. J. Jarmer, S. Penttilä, L. O. Sillerud, and R. J. Pryputniewicz, "Mechanical Design Parameters for Detection of Nuclear Signals by Magnetic Resonance Force Microscopy," in *Proc. of the 11th VACEM Symposium*, 1993.

Shaul Mordechai and C. Fred Moore, "Double Giant Resonances," Los Alamos National Laboratory document LA-UR-93-2766 (submitted to the *International Journal of Modern Physics E*, July 1993).

Shaul Mordechai and C. Fred Moore, "New Results on Multiple Excitations of Giant Resonances," Los Alamos National Laboratory document LA-UR-93-2928 (submitted to the *Gull Lake Nuclear Physics Conference on Giant Resonances*, Gull Lake, Michigan, August 17-21, 1993).

C. L. Morris, "High-Energy Pion-Nucleus Scattering at LAMPF," Los Alamos National Laboratory document LA-UR-93-322 (submitted to *Proc. of the Workshop on New Vistas in Physics with High-Energy Pion Beams*, Santa Fe, New Mexico, October 14, 1992).

C. L. Morris, J. M. O'Donnell, and J. D. Zumbro, "Pion Scattering at Energies above the Δ Resonance," *Acta Phys. Pol. B* **24**, 1659 (1993), presented at the *Meson-Nucleus Interactions Conference*, Cracow, Poland, May 14-19, 1993.

C. L. Morris and J. D. Zumbro, "Some Outstanding Issues in Pion Scattering at Energies above the Delta Resonance," Los Alamos National Laboratory document LA-UR-93-1502 (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

B. Ni, K.-P. Arnold, F. Chmely, M. D. Cooper, M. Eckhause, P. P. Guss, C. M. Hoffman, G. E. Hogan, V. W. Hughes, J. R. Kane, S. H. Kettell, Y. Kuang, J. Markey, B. E. Matthias, R. E. Mischke, H. Orth, L. E. Piilonen, G. zu Putlitz, J. Reidy, H. R. Schaefer, R. A. Williams, and K. A. Woodle,

"Search for Spontaneous Conversion of Muonium to Antimuonium," *Phys. Rev. D* **48**, 1976 (1993).

L. C. Northcliffe, M. Jain, M. L. Evans, G. Glass, J. C. Hiebert, R. A. Kenefick, B. E. Bonner, J. E. Simmons, C. W. Bjork, and P. J. Riley, "Differential Cross Section for n - p Elastic Scattering in the Angular Region $50^\circ < Q^* < 180^\circ$ at 459 MeV," *Phys. Rev. C* **47**, 36 (1993).

M. A. Oothoudt, "Monitoring Production Target Thickness," Los Alamos National Laboratory document LA-UR-93-1778 (submitted to the 1993 *Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

M. A. Paciotti, D. W. Cooke, M. Leon, B. Bennett, C. Pillai, O. Rivera, B. Hitti, T. Estle, S. F. J. Cox, R. L. Lichti, R. R. Adams, C. D. Lamp, A. Morrobel-Sosa, O. Richter, C. Boekema, J. Lam, S. Alves, J. Oostens, and E. A. Davis, "Development of a μ LCR Facility at LAMPF," Los Alamos National Laboratory document LA-UR-93-2421 (submitted to *Hyperfine Interactions*, June 1993).

S. I. Penttilä, J. David Bowman, P. P. J. Delheij, C. M. Frankle, D. G. Haase, R. Mortensen, H. Postma, N. R. Roberson, S. J. Seestrom, and Y.-F. Yen, "Cryogenic Spin Filter for Polarizing an Epithermal Neutron Beam," in *Proc. of the Second International Workshop on Time Reversal Invariance and Parity Violation*, Dubna, Russia, May 4-7, 1993, C. R. Gould, J. D. Bowman, and Yu. Popov, Eds. (World Scientific, Singapore, 1994), p. 198.

Mike Plum, "Beam Diagnostics at High-Intensity Storage Rings," Los Alamos National Laboratory document LA-UR-93-3884 (submitted to the *Beam Instrumentation Workshop*, Santa Fe, New Mexico, October 20-23, 1993).

M. A. Plum and D. Brown, "Response of Air-Filled Ion Chambers to High-Intensity Radiation Pulses," Los Alamos National Laboratory document LA-UR-93-1912 (submitted to the 1993 *Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

R. A. Reeder, B. D. Dieterle, C. Gregory, F. Schaefer, K. Schum, W. Strossman, D. Smith, L. Christofek, K. Johnston, W. C. Louis, M. Schillaci, M. Volta, D. H. White, D. Whitehouse, M. Albert, K. Yaman, C. Athanassopoulos, L. B. Auerbach, P. Hermida, and D. Works, "Dilute Scintillators for Large-Volume Tracking Detectors," *Nucl. Instrum. Methods A* **334**, 353 (1993).

N. R. Roberson, C. D. Bowman, J. D. Bowman, P. P. J. Delheij, C. M. Frankle, C. R. Gould, D. G. Haase, J. N. Knudson, G. E. Mitchell, S.

Penttilä, H. Postma, S. J. Seestrom, J. J. Szymanski, S. H. Yoo, V. W. Yuan, and X. Zhu, "An Apparatus and Techniques for Tests of Fundamental Symmetries in Compound-Nucleus Scattering with Epithermal Neutron Beam," *Nucl. Instrum. Methods A* **323**, 549 (1993).

B. Rusnak, G. Spalek, E. Gray, J. N. DiMarco, R. DeHaven, J. Novak, P. Walstrom, J. Zumbro, H. A. Thiessen, and J. Langenbrunner, "Superconducting Multicell Cavity Development Program at Los Alamos, Los Alamos National Laboratory document LA-UR-93-1893 (submitted to *Proc. of the 1993 Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

H. Sarafian, M. B. Johnson, and E. R. Siciliano, "Medium Modification of Meson Propagation between Two Nucleons in Finite Nuclei," *Phys. Rev C* **48**, 1988 (1993).

Mikolaj Sawicki and D. V. Ahluwalia, "Parity Transformation in the Front Form," Los Alamos National Laboratory document LA-UR-93-4317 (submitted to *Physical Review Letters*, November 1993).

S. Schaller, "A LAMPF Controls Retrospective: The Good, the Bad, and 'It Seemed Like a Good Idea at the Time'," Los Alamos National Laboratory document LA-UR-93-3739 (submitted to the *International Conference on Accelerator and Large Experimental Physics Control Systems*, Berlin, Germany, October 18-22, 1993).

T. Shima, D. Hill, K. F. Johnson, H. Shimizu, H. Spinka, R. Stanek, D. Underwood, A. Yokosawa, G. Glass, J. C. Hiebert, R. A. Kenefick, S. Nath, L. C. Northcliffe, G. R. Burleson, R. W. Garnett, J. A. Faucett, M. W. Rawool-Sullivan, R. Damjanovich, J. J. Jarmer, R. H. Jeppesen, and G. E. Tripard, "Neutron-Proton Elastic Scattering Spin-Spin Correlation Parameter Measurement between 500 and 800 MeV. II. C_{SS} and C_{LS} at Forward c.m. Angles," *Phys. Rev. D* **47**, 29 (1993).

Anthony Joe Simon, "High Precision Absolute Differential Cross-Section Measurements for Proton-Proton Elastic Scattering at 491.9, 575.5, 641.6, 728.2, and 793.0 MeV," Ph.D. Thesis, Texas A&M University, Los Alamos National Laboratory document LA-12577-T (April 1993).

A. J. Simon, G. Glass, M. W. McNaughton, T. Noro, K. H. McNaughton, P. J. Riley, E. Gülmez, C. A. Whitten, V. R. Cupps, R. D. Ransome, and D. L. Adams, "Absolute pp -Elastic Cross Sections from 492 to 793 MeV," *Phys. Rev. C* **48**, 662 (1993).

D. A. Smith, H. T. Fortune, J. M. O'Donnell, J. D. Silk, B. Gluckman, R. Crittenden, N. Claytor, C. L. Morris, and J. A. McGill, "Pion Double Charge Exchange on ^{56}Fe at $T_\pi = 400$ MeV," *Phys. Rev. C* **47**, 1053 (1993).

J. P. Sullivan, J. G. Boissevain, K. Holzscheiter, B. V. Jacak, J. Simon-Gillo, W. E. Sondheim, H. van Hecke, M. W. Rawool-Sullivan, A. Gavron, D. Fox, B. Wolf, and K. L. Wolf, "Response of a Sampling Calorimeter to Low-Energy Pions, Muons, and Positrons," *Nucl. Instrum. Methods A* **324**, 441 (1993).

I. Supek, M. W. McNaughton, K. Koch, N. Tanaka, R. D. Ransome, D. A. Ambrose, K. H. McNaughton, P. J. Riley, G. Glass, J. Hiebert, L. Northcliffe, A. J. Simon, D. L. Adams, R. Jeppesen, H. Spinka, and G. Tripard, "Quick Polarization Analyzer (QPAN)," *Nucl. Instr. Methods Phys. Res. A* **324**, 19-22 (1993).

George R. Swain, "Fault-Tolerant Superconducting Linac Design for a 5-MW Neutron Spallation Source" (submitted to the *Sixth Workshop on RF Superconductivity*, CEBAF, Newport News, Virginia, October 4-8, 1993).

D. R. Swenson, E. P. MacKerrow, and H. C. Bryant, "Non-Invasive Beam Diagnostics for H^- Ion Beams Using Photodetachment by a Focused Laser Beam," (submitted to the *Beam Instrumentation Workshop*, Santa Fe, New Mexico, October 20-23, 1993).

D. R. Swenson, D. Tupa, R. L. York, M. Dulick, and O. B. van Dyck, "Polarization Diagnostics and Optical Pumping Development for OPPIS at LAMPF," Los Alamos National Laboratory document LA-UR-93-2040 (submitted to the *Polarized Ion Source Workshop*, Madison, Wisconsin, May 24-27, 1993).

H. A. Thiessen, *Proceedings of the Muon Collider Workshop*, Los Alamos, New Mexico, February 22, 1993, Los Alamos National Laboratory document LA-UR-93-866 (March 1993).

H. A. Thiessen, "Possible New Facilities for (π, K) and Other High Resolution Pion Physics," Los Alamos National Laboratory document LA-UR-93-943 (submitted to the *Proc. of Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Beam Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

H. A. Thiessen, J. Kapsales, R. K. Cooper, A. Faltens, T. F. Godlove, W. B. Herrmannsfeldt, and C. L. Olson, "Report of Independent Consultants Reviewing Integrated Test Stand (ITS) Performance and Readiness of DARHT for Construction Start," report to the DARHT Accelerator Review, DOE, July 1993.

H. Thiessen and J. Zumbro, "Future Facilities for High-Resolution (π, K) and Other Pion Reactions at 1 GeV," Los Alamos National Laboratory document LA-UR-93-1387 (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

D. R. Tieger, J. D. Zumbro, and W. W. Sapp, "Magnetic Measurement of Quadrupole and Sextupole Magnets for the MIT-Bates South Hall Ring (SHR)," Los Alamos National Laboratory document LA-UR-93-2244 (submitted to the *1993 Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

D. Tupa, M. McNaughton, D. R. Swenson, and R. L. York, "Systematic Errors from an Optically Pumped Polarized Ion Source," Los Alamos National Laboratory document LA-UR-93-883 (submitted to *Nuclear Instruments and Methods*, March 1993).

Leo A. Van Ausdeln, "A Photon Detector System for the Search for the Rare Muon $\mu \rightarrow e\gamma$," Ph.D. Thesis, Texas A&M University, Los Alamos National Laboratory report LA-12365-T (November 1993).

L. Wang, X. Yang, J. Rapaport, C. D. Goodman, C. C. Foster, Y. Wang, R. A. Lindgren, E. Sugarbaker, D. Marchlenski, S. DeLucia, B. Luther, L. Rybarcyk, T. N. Taddeucci, and B. K. Park, " $^{10}\text{B}(p,n)^{10}\text{C}$ Reaction at 186 MeV," *Phys. Rev. C* **47**, 2129 (1993).

H. Ward, J. Johnson, K. Johnson, S. Greene, Y. Grof, C. Fred Moore, S. Mordechai, C. L. Morris, J. M. O'Donnell, and C. Whitley, "Energy Dependence of Double Giant Resonances in Pion Double Charge Exchange," *Phys. Rev. Lett.* **70**, 3209 (1993).

H. J. Ward, J. D. Johnson, C. F. Moore, C. R. Whitley, J. M. Applegate, J. Beck, B. G. Ritchie, N. Auerbach, K. Koch, J. M. O'Donnell, C. L. Morris, S. Mordechai, M. Rawool-Sullivan, and D. L. Watson, "Systematics of the DIAS Cross Section at 50 MeV," *Phys. Rev. C* **47**, 687 (1993).

Zeev Weinfeld, "Reaction Mechanism and Nuclear Correlations Study by Low Energy Pion Double Charge Exchange, Ph.D. Thesis (submitted April 1993).

D. A. Whitehouse, R. Rameika, and N. Stanton, "Accelerator-Based Neutrino Oscillation Searches" (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

J. E. Wise, M. R. Braunstein, S. Høibråten, M. D. Kohler, B. J. Kriss, J. Ouyang, R. J. Peterson, J. A. McGill, C. L. Morris, S. J. Seestrom, R. M. Whitton, J. D. Zumbro, C. M. Edwards, and A. L. Williams, "Quasifree Pion Scattering at 500 MeV," *Phys. Rev. C* 48, 1840 (1993).

X. Yang, L. Wang, J. Rapaport, C. D. Goodman, C. C. Foster, Y. Wang, W. Unkelbach, E. Sugarbaker, D. Marchlenski, S. DeLucia, B. Luther, J. Ullmann, A. G. Ling, B. K. Park, D. S. Sorenson, L. Rybarczyk, T. N. Taddeucci, C. R. Howell, and W. Tornow, "Dipole and Spin-Dipole Resonances in Charge-Exchange Reactions on ^{12}C ," *Phys. Rev. C* 48, 1158 (1993).

Yi-Fen Yen, J. D. Bowman, Y. Matsuda, S. I. Penttilä, S. Seestrom, H. M. Shimizu, R. W. Strickland, S. Takahashi, S. H. Yoo, and V. W. Yuan, "500-MHz Neutron Detector," in *Proc. of the Second International Workshop on Time Reversal Invariance and Parity Violation*, Dubna, Russia, May 4-7, 1993, C. R. Gould, J. D. Bowman, and Yu. Popov, Eds. (World Scientific, Singapore, 1994), p. 210.

Yi-Fen Yen, B. Brinkmøller, D. Dehnhard, M. A. Franey, S. M. Sterbenz, Yi-Ju Yu, Brian Berman, G. R. Burleson, K. Cranston, A. Klein, G. S. Kyle, R. Alarcon, T. Averett, J. R. Comfort, J. J. Gørgen, B. G. Ritchie, J. R. Tinsley, M. Barlett, G. W. Hoffmann, K. Johnson, C. F. Moore, M. Purcell, H. Ward, A. Williams, J. A. Faucett, S. J. Greene, J. J. Jarmer, C. L. Morris, S. I. Penttilä, N. Tanaka, J. A. McGill, H. T. Fortune, E. Insko, R. Ivie, J. M. O'Donnell, D. Smith, M. A. Khandaker, and S. Chakravarti, "Pion Elastic Scattering from Polarized ^{13}C in the Energy Region of the P_{33} Resonance," Los Alamos National Laboratory document LA-UR-94-492 (submitted to *Physical Review C*, December 1993).

R. York, D. Tupa, D. Swenson, and R. Damjanovich, "Volume H Ion Source Development at LAMPF," Los Alamos National Laboratory document LA-UR-93-1924 (submitted to the 1993 *Particle Accelerator Conference*, Washington, DC, May 17-20, 1993).

Rob L. York, Dale Tupa, David R. Swenson, Michael W. McNaughton, and Olin B. van Dyck, "Performance of the LAMPF Optically Pumped Polarized Ion Source," Los Alamos National Laboratory document LA-UR-93-2423 (submitted to the *Polarized Ion Source Workshop*, Madison, Wisconsin, May 24-27, 1993).

Mark Eldon Yuly, "Inclusive Measurements of Pion Double Charge Exchange and Inelastic Scattering on ^3He ," Ph.D. Thesis, Massachusetts Institute of Technology, Los Alamos National Laboratory document LA-12533-T (June 1993).

J. Zumbro, "Eta Production at the LAMPF P3 Channel," Los Alamos National Laboratory document LA-UR-93-1388 (submitted to *Proc. of the Workshop on Future Directions in Particle and Nuclear Physics at Multi-GeV Hadron Facilities*, Brookhaven National Laboratory, March 4-6, 1993).

J. D. Zumbro, C. L. Morris, J. A. McGill, S. J. Seestrom, R. M. Whitton, C. M. Edwards, A. L. Williams, M. R. Braunstein, M. D. Kohler, B. J. Kriss, S. Høibråten, R. J. Peterson, J. Ouyang, J. E. Wise, and W. R. Gibbs, "Inclusive Scattering of 500-MeV Pions from Carbon," Los Alamos National Laboratory document LA-UR-92-4319 (resubmitted to *Physical Review Letters*, July 1993).

Operations and Facilities Development

ACCELERATOR OPERATIONS

David Helfer

Los Alamos National Laboratory

1992

This section covers operating cycles 61 and 62. The accelerator was in operation from June 6 through October 11, 1992. Beams were provided for research use for 120 days of H^+ , 104 days of H^- , and 110 days of P^- . A summary of information on beams provided for research is given in Table I.

Table I. Beam statistics for cycles 61 and 62.				
		Cycle 61	Cycle 62	Total Average 1992
Number of experiments served*		18	35	53
H^+	scheduled beam (h)	1224	1636	2880
H^- PSR	scheduled beam(h)	864	1516	2380
H^- Line X	scheduled beam (h)	—	—	—
P^- Line X	scheduled beam (h)	1008	1591	2599
H^+	beam availability (%)	61	80	72
H^- PSR	beam availability (%)	54	78	66
H^- Line X	beam availability (%)	—	—	—
P^- Line X	beam availability (%)	59	74	67
H^+	average current (μA)	700	500	600
H^- PSR	average current (μA)	50	65	58
H^- Line X	average current (μA)	—	—	—
P^- Line X	average current (μA)	50	100	75
H^+	beam duty factor (%)	7.0	5.6	6.3
H^- PSR	beam duty factor (%)	1.0	1.0	1.0
H^- Line X	beam duty factor (%)	—	—	—
P^- Line X	beam duty factor (%)	3.0	3.0	3.0
* Does not include experiments performed at the PSR-LANSCE/WNR areas.				

The H^+ average beam current to Experimental Area A was restricted because of a vacuum leak at the A2 target box. This leak caused accelerated oxidation and erosion of the target graphite. Installation of a new target box is planned before the next operating period. Radioactive air emissions from the A6 primary beam stop area also caused limited beam current. The Laboratory has a federally mandated yearly accumulated radiation dose limit at the site boundary of 10 mrem. The EPA removed a 30% self-shielding factor from the calculations for this accumulated dose from air emissions; thus beam current was reduced to ensure emissions were lower than the 10-mrem limit. The Laboratory is working with the EPA to reinstate the shielding factor or allow direct dose measurement at the site boundary. MP-Division is also working to reduce emissions from the A-6 region.

A summary of unscheduled facility downtime during research shifts is given in Table II. Some of the outages are concurrent and some affected only one of the three beams.

Table II. Unscheduled machine downtime during shifts in 1992.						
Category	H^+		H^-		P^-	
	hours	%	hours	%	hours	%
H^+ injector systems	9.6	1.3				
H^- injector systems			26.0	3.6		
P^- injector systems					94.5	13.8
201-MHz rf systems	409.2	55.1	302.0	41.7	330.0	48.2
805-MHz rf systems	64.0	8.6	55.1	7.6	51.8	7.6
Vacuum systems	92.5	12.4	55.5	7.7	65.2	9.5
Magnets	11.6	1.6	70.6	9.7	13.6	2.0
Magnet power supplies	8.0	1.1	76.7	10.6	37.2	5.4
Interlock systems	8.6	1.2	5.0	0.7	9.4	1.4
Cooling water systems	19.7	2.7	51.5	7.1	19.6	2.9
Computer systems	0.2	0.0	3.6	0.5	18.8	2.8
Production targets	78.2	10.5	11.3	1.5	0.4	0.0
Beam diagnostics	1.1	0.2	2.2	0.3	1.1	0.2
Miscellaneous	39.3	5.3	65.3	9.0	42.4	6.2
TOTAL	742.0	100	724.8	100	684.0	100

The large increase in downtime from the 201-MHz rf systems is attributed to a high failure rate of some of the high power amplifier tubes. This higher rate may be because of a deterioration of some protective high-voltage dump circuits, as well as not having an adequate test stand to condition tubes thoroughly before installation into the amplifier chains.

Investigation into the causes is continuing and a new test stand is being constructed.

A water leak in one of the drift tube linac quadrupole magnets located within a drift tube caused the magnet ground current to exceed normal set-points, as well as water leaking into the soft vacuum system. A separate power supply was connected to this magnet and was allowed to float above ground, thus eliminating the ground path, and a separate vacuum pump was installed on the quad and drift tube. These changes allowed continued operation until the scheduled operating period was completed. The drift tube and quadrupole magnet will be replaced during the next annual maintenance period.

1993

This section covers operating cycles 63, 64, and 65. The accelerator was in operation from July 5 through October 31, 1993. Beams were provided for research use for 109 days of H^+ , 82 Days of H^- , and 80 days of P^- . A summary of information on beams provided for research is given in Table III.

Table III. Beam statistics for cycles 63, 64, and 65.					
		Cycle 63	Cycle 64	Cycle 65	Total Average 1993
Number of experiments served*		15	21	22	19
H ⁺	scheduled beam (h)	1008	886	706	2600
H ⁻ PSR	scheduled beam(h)	696	646	545	1887
H ⁻ Line X	scheduled beam (h)	696	749	532	1977
P ⁻ Line X	scheduled beam (h)	432	832	636	1900
H ⁺	beam availability (%)	82	90	88	87
H ⁻ PSR	beam availability (%)	78	77	66	74
H ⁻ Line X	beam availability (%)	78	55	48	60
P ⁻ Line X	beam availability (%)	72	78	83	78
H ⁺	average current (μA)	590	560	750	630
H ⁻ PSR	average current (μA)	47	71	66	60
H ⁻ Line X	average current (μA)	525	670	340	510
P ⁻ Line X	average current (μA)	130	210	130	160
H ⁺	beam duty factor (%)	4.8	4.8–7.1	5.6–8.1	7.1
H ⁻ PSR	beam duty factor (%)	1.0	1.0	1.0	1.0
H ⁻ Line X	beam duty factor (%)	2.9	2.9	2.9	2.9
P ⁻ Line X	beam duty factor (%)	2.3	5.8	5.8	4.8

* Does not include experiments performed at the PSR-LANSCE/WNR areas.

This year's operating period included three run cycles by extending the operating period into the 1994 fiscal year. The H^+ average beam current to Experimental Area A was again restricted because of the vacuum leak at the A-2 target box. This leak causes accelerated oxidation and erosion of the target graphite. The new target box will be installed before the next operating period.

A summary of unscheduled facility downtime during research shifts is given in Table IV. Some of the outages are concurrent and some affected only one of the three beams.

Table IV. Unscheduled machine downtime during shifts in 1993.						
Category	H^+		H^-		P^-	
	hours	%	hours	%	hours	%
H^+ injector systems	8.1	2.7				
H^- injector systems			144.4	3.9		
P^- injector systems					180.4	52.8
201-MHz rf systems	34.0	11.1	19.5	4.5	15.7	4.6
805-MHz rf systems	33.5	10.9	21.3	4.9	23.2	6.8
Vacuum systems	56.7	18.5	106.4	24.4	71.4	20.9
Magnets	19.3	6.3	7.0	1.6	12.5	3.7
Magnet power supplies	9.4	3.1	67.3	15.5	9.5	2.8
Interlock systems	2.6	0.9	14.9	3.4	5.5	1.6
Cooling water systems	24.9	8.1	32.1	7.4	17.8	5.2
Computer systems	3.0	1.0	7.1	1.6	1.2	0.4
Production targets	90.7	29.6	6.2	1.4	0.3	0.1
Beam diagnostics	4.9	1.6	4.8	1.1	4.4	1.3
Miscellaneous	19.1	6.2	4.4	1.0	42.4	6.2
TOTAL	306.2	100	435.3	100	341.9	100

The large increase in availability as compared to the last couple of operating periods is attributed to improved reliability of the 201-MHz rf amplifiers. Spare amplifier tube availability because of previous high failure rates caused operation a reduced duty factor.

Other improvements included the reworked amplifier fault detection and safe systems.

A water leak in one of the drift tube linac quadrupole magnets located within a drift tube caused the magnet ground current to exceed normal set-points as well as water leaking into the soft vacuum system. A separate power supply was connected to this magnet and was allowed to float above

ground, thus eliminating the ground path and a separate vacuum pump was installed on the quad and drift tube. These changes allowed continued operation until the scheduled operating period was completed. The drift tube and quadrupole magnet will be replaced during the next annual maintenance period.

LINAC BEAM ENERGY MEASUREMENTS

Participants

R. Johnson, L. Rybarczyk, R. Stuewe, and O. van Dyck

Institutions

Los Alamos National Laboratory

Prior to 1993 beam operation, the "Delta-T" signal processing hardware in the linac was upgraded, and the software was modified correspondingly and features were added. The new system provides a routine capability to measure the acceleration curve of a linac module over a full cycle of rf; presently under development is the capability to measure absolute beam energy by time-of-flight.

The hardware was greatly simplified and its stability and performance enhanced. The new configuration employs double-balanced mixers used in pairs to form orthogonal projections of the phase of beam-induced rf signals with respect to a reference signal tied to the accelerator rf, as sketched in Fig. 1. The two phase projection voltages are fed to the computer, which calculates relative phase from the arctangent of the ratio of the detected signals.

Fig. 1. Block diagram of beam phase measuring system ("Delta-T hardware").

The standard Delta-T method uses the time advance of the beam signal when the upstream module is energized (vs. module off). Because the modules are long and have longitudinal focusing, the time advance (Δt) of the beam measured at two downstream points can be used to calculate the beam energy and beam phase with respect to accelerating cavity rf, using knowledge of the beam dynamics in the accelerating module.

Measurement of beam energy and phase gain as the module under study is scanned through a full cycle of rf provides data rich in information on the accuracy of the linac model and is facilitated by the new electronics, which eliminates the older active phase bridges with troublesome end-of-range artifacts. Figure 2 shows a comparison of a typical measurement to a linac design code simulation.

The new system is sufficiently stable to enable absolute beam energy by time-of-flight over long distances, where the beam time pickoffs are synchronized by inserting a constant reference signal sequentially on each pickoff (the reference signal is moved to the pickoffs one at a time using a long cable). Preliminary checks indicate that the system is sufficiently stable that the electronic timing drift during the whole process is small.

Fig. 2. Measured and calculated beam phase advance (micropulse arrival time) in degrees of 805 MHz as rf phase is changed in last accelerating module (axis in degrees of 201.25 MHz).

Factors in the accuracy of the beam energy estimate include timing accuracy, number of measurement points and their distances, and kinematics. System development at the end of 1993 beam operation used all of the Delta-T time pickoffs in the linac downstream of the module under study, which for the earlier modules takes advantage of many measurement points and long distances. An example of the preliminary results obtained is given in Table I.

Table I. Beam energy by TOF. Module 18 design energy is 302.63 MeV.	
Beam Peak Current (mA)	Energy by TOF (MeV)
1	303.13
1	303.14
10	302.07
10	302.10

At 303 MeV, where about 500 m of flight path to the switchyard is available and 17 pickoffs can be used, the ultimate accuracy of the method can be ~10 keV. To maintain useful accuracy (~0.1 MeV) at higher energies, the flight path can be extended by installing additional pickoffs in the switchyard and down Line A and Line D.

This development activity has several goals. For facility tune-up, the upgrade has given increased reliability, accuracy, and ease-of-use. To provide a beam energy monitoring capability during operation, the system can be extended down Line A and Line D. And for development, the system provides a useful tool for evaluation of models of linac dynamics, for example, with higher peak currents, which may be important for the future uses of the facility.

Appendices

Appendix A

EXPERIMENTS RUN IN 1992-1993

Exp.	Channel	Title
267	IP	Preparation of Radioisotopes for Medicine and the Physical Sciences Using the LAMPF Isotope Production Facility
823	BR	Development of an (n,p) Reaction Capability at Area B or Beam Line D
876	BR	Spin Transfer Measurements for NP Elastic
881	NTOF	Quasifree Axial Response Functions for Pb and ^2H Using the $(\bar{p}, \bar{n})$ Reaction
969	SMC	MEGA — Search for the Rare Decay $\mu^+ \rightarrow e^+ \gamma$
978	P3	A Coincidence Measurement of Pion Double Charge Exchange: $^4\text{He}(\pi^+, \pi^- p)^3p$
1024	TOFI	Lifetime Measurements of Extremely Neutron-Rich Nuclides by Delayed Neutron Counting at TOFI
1040	NTOF	Spin Variable Measurements for the $(\bar{p}, n')$ Inclusive Reaction on Several Nuclei
1054	SMC	Ultra High Precision Measurements on Muonium Ground State: Hyperfine Structure and Muon Magnetic Moment
1062	NTOF	Study of Pure Fermi and Gamow-Teller Transitions in the $^{14}\text{C}(p,n)^{14}\text{N}$ Reaction
1066	EPICS	The Exotic Nucleus Helium-9 and Its Excited States
1079	HRS	Development of Experimental Techniques to Study Relativistic Effects in Proton-Nucleus Elastic Scattering at Forward Angles
1084	HRS	Extended Angular Range of S_{nn} Measurements in ^{40}Ca
1097	BR	Single Pion Production in np Scattering

Exp.	Channel	Title
1100	TOFI	Mass Measurements of Neutron-Rich Nuclei with $Z = 18-32$
1107	P3	Studies of Pion Double Charge Exchange Scattering at Energies above the Δ Resonance
1109	P3	Pion-Induced Fission
1124	TOFI	Measurement of Correlated Spin Asymmetries and Spin Transfer Observables in 800-MeV Proton-Deuteron Elastic Scattering Using the Medium Resolution Spectrometer with N and $\bar{S}$ Type Polarized Deuteron Targets
1137	NTOF	Measurement of $D_{LL}(0^\circ)$ for $1^+(p,n)$ Transitions in p -shell Nuclei
1139	HRS	Testing of Radiation Resistance of Read-Out Chips for Use in High-Rate Nuclear and Particle Physics Applications
1173	A6	A Proposal to Search for $\bar{\nu}_\mu - \bar{\nu}_e$ Oscillations with High Sensitivity at LAMPF
1179	LEP	Reaction $\pi^+ p \rightarrow \pi^+ \pi^0 p$ near Threshold
1184	NTOF	Measurement of Analyzing Powers for the $^{14}\text{C}(p,n)$ (IAS) Transition
1188	LANSCE	Search for Parity and Time Reversal Symmetry Violation Using Polarized Neutron-Nucleus Interactions
1190	P3	Pion-Proton Transmission Cross Section Measurements
1195	EPICS	DIAS Widths in Medium and Heavy Nuclei
1205	HRS	Precision Measurement of D_{NN} for $^{13}\text{C}(\bar{p}, \bar{p})$ at 500 MeV
1207	EPICS	The Nature of T_z States Observed in DCX on Medium-Mass Nuclei
1209	EPICS	Energy Dependence of Double Resonances in Pion DCX
1213	A6	Measurement of the Neutrino Capture Cross Section in ^{37}Cl and ^{127}I with Mu^+ Decay Neutrinos

Exp.	Channel	Title
1216	P3	${}^6\text{Li}(\pi, \pi'X)$ Coincidence Measurements near the $\Delta_{3,3}$ Resonance
1217	EPICS	Accurate Determination of the T_1 Giant Dipole State in Light $T = 1/2$ Nuclei Using Pion DCX
1218	HIRAB	Branching Ratios and High-Resolution Spectroscopy of the Doubly Excited Hydrogen Ion
1220	EPICS	Measurement of Angular Distributions $d\sigma/d\Omega$ for ${}^6\text{Li}(\pi^+, \pi^+)$ at $T_\pi = 100, 134, 164, 190,$ and 219 MeV
1226	LEP	A Study of the Pion-Nucleus Isovector Spin-Flip Mechanism at Low Energies Using ${}^{10}\text{B}$
1227	LEP	The Two-Proton Component of the Pion Absorption Reaction on Nuclei at Low Energies
1231	SMC	Laser Polarized Muonic Atoms and Spin Dependence of Nuclear Muon Capture
1235	SMC	μSR : Level-Crossing Resonance Spectroscopy
1239	LEP	Feasibility of the Direct Production of Pionic Atoms at LAMPF
1240	SMC	A Proposal to Measure the Michel Parameter ρ with the MEGA Positron Spectrometer
1245	EPICS	Pion DCX on Odd Z Nuclei, an Experiment to Clarify Apparent Shell Effects in DIAS Cross Sections
1263	EPICS	Analog Contribution to Non-Analog Double Charge Exchange
1264	EPICS	Discrepancy between the M_n/M_p for the Giant Quadrupole Resonance Deduced for Pion and Heavy-Ion Scattering
1267	P3	Elastic Scattering of π^+ and π^- from Polarized ${}^3\text{He}$ at $T_\pi = 180$ to 475 MeV
1268	LEP	$\pi^- p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance

Exp.	Channel	Title
1272	P3	Pion Single Charge Exchange on the Deuteron $\pi^-d \rightarrow \pi^0nn$: A Tune-Up Experiment for the Neutral Meson Spectrometer
1277	REF	<i>In-situ</i> Measurement of Radiation-Induced Absorption and Fluorescence of Fiber Optic Cables
1286	LEP	Report on η - γ Coincidence Measurements at LEP
1288	EPICS	Elastic Pion Scattering from ^{13}C
1289	LEP	The Spin-Flip Electric Dipole in Pion Single Charge Exchange
1290	LEP	Measurement of the Isobaric Analog and Search for Anti-Analog Transitions in Pion Single Charge Exchange on Heavy Nuclei
1292	EPICS	Systematics of Isospin Character of the First 2_1^+ and 3_1^- States in $^{90,92,94,96}\text{Zr}$
1293	BR	np Elastic Analyzing Power
1294	NTOF	Spin Decomposition of the Giant Resonance Region for the $\text{Ca}(p,n)$ and $\text{Pb}(p,n)$ Reactions at 795 MeV
1296	NTOF	A Search for Signatures of Longitudinal Correlations in the $^{12}\text{C}(p,n\pi^+)$ Reaction at 800 MeV
1303	A6	A High-Intensity He-Jet Production Source for Radioactive Beams and the Cs-PNC Experiment
1304	EPICS	Search for the Analog of the Giant Gamow- Teller Resonance in a Medium Mass Nucleus
1306	NTOF	Activation Total Cross Section for the $^7\text{Li}(p,n)^7\text{Be}(\text{g.s.} + 0.43\text{-MeV})$ Reaction
1307	HIRAB	Measurement of H^0 Excited States Produced by Foil Stripping of 800-MeV H^- Ions
1309	BR	Proposal to Measure Analyzing Power and Spin Transfer in the np Inelastic Channel as an Extension of Exp. 1293

Appendix B

NEW PROPOSALS IN 1992-1993

Exp.	Spokespersons	Title
1258	G. R. Burleson W. R. Gibbs M. Rawool-Sullivan New Mexico State Univ.	The Direct Measurement of the π -Nucleon Interaction Strength Difference between π^+ and π^0
1259	T. Kobayashi RIKEN (Japan)	Study of ^{11}N and ^{10}Li Nuclei for Understanding the Structure of ^{11}Li (and a Mirror Symmetry between ^{11}Be and ^{11}N)
1260	G. Glass Texas A&M Univ.	Search for the 'Inevitable Dibaryon' through the Reaction $^3\text{H}(\pi^+, p)X$
1262	S. Mordechai Ben-Gurion Univ. D. A. Smith Univ. of Pennsylvania	The Double Giant Dipole Resonance in Deformed Nuclei
1263	H. T. Fortune A. L. Williams Univ. of Pennsylvania	Analog Contribution to Non-Analog Double Charge Exchange
1264	D. J. Horen Oak Ridge C. L. Morris Los Alamos	Discrepancy between the M_n/M_p for the Giant Quadrupole Resonance Deduced for Pion and Heavy-Ion Scattering
1265	H. T. Fortune M. McKinzie Univ. of Pennsylvania	A Comparison of the DCX Mechanism to the GDR ² and to Other $2p$ - $2h$ States
1266	R. D. McKeown Caltech R. J. Holt K. P. Coulter Argonne	Measurement of the Asymmetry in π - ^3He Quasielastic Scattering

Exp.	Spokespersons	Title
1267	D. Dehnhard Univ. of Minnesota G. R. Burleson New Mexico State Univ. O. Häusser Tri-Univ. Meson Facility	Elastic Scattering of π^+ and π^- from Polarized ^3He at $T_\pi = 180$ MeV to 475 MeV
1268	M. E. Sadler Abilene Christian Univ.	$\pi^- p \rightarrow \pi^0 n$ Cross Sections in the Region of the Δ Resonance
1269	E. R. Kinney Univ. of Colorado G. R. Burleson New Mexico State Univ.	Precise Measurement of Isovector Transitions in ^{13}C and ^7Li Induced by Pion Single Charge Exchange
1270	J. L. Matthews MIT G. A. Rebka, Jr. Univ. of Wyoming P. A. M. Gram Los Alamos	A Study of the $^3\text{He}(\pi^-, ^3\text{H})\pi^0$ Reaction
1272	J. L. Matthews MIT M. Whitton Los Alamos	Pion Single Charge Exchange on the Deuteron ($\pi^- d \rightarrow \pi^0 nn$): A Tune-Up Experiment for the Neutral Meson Spectrometer
1273	H. T. Fortune P. P. Hui Univ. of Pennsylvania	Non-Analog Single Charge Exchange on $T = 0$ Nuclei
1274	K. Seth Northwestern Univ.	Spectroscopy of Light Exotic Nuclei by a Novel Technique
1275	K. O. Oganesyan JINR, USSR C. L. Morris Los Alamos	Study of the Reaction $\pi^+ + d \rightarrow p + p$ at Pion Energies 20–50 MeV
1279	R. J. Peterson R. A. Ristinen Univ. of Colorado	Reaction and Total Cross Sections for 300–500-MeV Pions on Nuclei
1280	K. Seth Northwestern Univ. J. Beene Oak Ridge	Deeply Bound Pionic States in Heavy Nuclei

Exp.	Spokespersons	Title
1281	S. Mordechai Ben-Gurion Univ. C. Fred Moore Univ. of Texas, Austin	Measurement of the Nuclear Isovector Monopole Resonance Using the NMS
1282	R. B. Ivie H. T. Fortune Univ. of Pennsylvania	Search for a New Reaction Mechanism in Ground State DCX on Medium-Mass Nuclei
1283	R. Gilman Rutgers Univ. M. Rawool-Sullivan L. Waters Los Alamos	The Measurement of π -Nucleus Elastic and Inclusive Cross Sections above the $\Delta_{3,3}$ Resonance
1284	E. A. Pasyuk JINR (Russia) S. J. Greene Los Alamos	Study of the Reaction $\pi^{\pm} + {}^4\text{He} \rightarrow \pi^{\mp} + 4p(n)$ at Pion Energies 60–120 MeV
1285	C. L. Morris J. D. Zumbro Los Alamos	Search for Δ^{-} Components in Nuclear Ground States
1286	A. Hussein King Fahd Univ. of Petroleum and Minerals (Saudi Arabia) S. Sterbenz Los Alamos	Measuring Neutron-Neutron Scattering Length and Effective Range Using the ${}^2\text{H}(\pi^{-}, 2n)\gamma$ Reaction
1289	D. Smith H. T. Fortune Univ. of Pennsylvania	The Spin-Flip Electric Dipole in Pion Single Charge Exchange
1290	C. L. Morris M. Rawool-Sullivan R. Whitton Los Alamos	Measurement of the Isobaric Analog and Search for Anti-Analog Transitions in Pion Single Charge Exchange on Heavy Nuclei
1291	C. L. Morris M. Rawool-Sullivan R. Whitton Los Alamos	Neutron Radii in the Calcium Isotopes and Isotones ${}^{48}\text{Ca}$, ${}^{50}\text{Ti}$, ${}^{52}\text{Cr}$, and ${}^{54}\text{Fe}$

Exp.	Spokespersons	Title
1292	D. J. Horen Oak Ridge C. L. Morris Los Alamos	Systematics of Isospin Character of the First 2^+ and 3^- States in $^{90,92,94,96}\text{Zr}$
1293	M. McNaughton Los Alamos	np Elastic Analyzing Power
1294	D. Prout E. Sugarbaker The Ohio State Univ.	Spin Decomposition of the Giant Resonance Region for the $\text{Ca}(p,n)$ and $\text{Pb}(p,n)$ Reactions at 800 MeV
1295	A. C. Hayes Chalk River Labs J. M. O'Donnell Los Alamos	Study of ^{15}B Using the $^{15}\text{N}(\pi^-, \pi^+)^{15}\text{B}$ Reaction
1296	M. Jones Los Alamos G. Edwards C. Glashausser Rutgers Univ.	A Search for Signatures of Longitudinal Correlations in the $^{12}\text{C}(p,n\pi^+)$ Reactions at 800 MeV
1297	S. Mordechai Ben-Gurion Univ. C. F. Moore Univ. of Texas, Austin	Study of a New Resonance above the DIAS in Pion DCX
1298	R. Boudrie J. Ullmann Los Alamos R. Rapaport R. Finley Ohio Univ.	A Study of the Spin and Non-Spin Isovector Monopole Resonance Using the (n,p) Reaction at 800 MeV
1299	C. L. Morris J. D. Zumbro M. Rawool-Sullivan Los Alamos	Pion Scattering to the Continuum and Pion Transparency in Nuclei
1300	B. K. Park New Mexico State Univ. D. Dehnhard Univ. of Minnesota O. Häusser Simon Fraser Univ/ TRIUMF	Measurements of Asymmetries A_y and Differential Cross Sections of Pion-Induced Single Charge Exchange on Polarized ^3He

Exp.	Spokespersons	Title
1301	E. R. Kinney Univ. of Colorado	Inclusive Pion Single Charge Exchange in ^3He and ^4He
1302	D. P. Beatty R. Gilman Rutgers Univ.	Understanding Non-Analog Pion Double Charge Exchange
1303	C. Wieman Univ. of Colorado D. Vieira Los Alamos	Parity Nonconservation Measurements of Trapped Radioisotopes — A Precise Test of the Standard Model
1304	P. P. Hui H. T. Fortune Univ. of Pennsylvania	Search for the Analog of the Giant Gamow-Teller Resonance in a Medium Mass Nucleus
1305	A. L. Williams H. T. Fortune Univ. of Pennsylvania	Pion Double Charge Exchange on ^{17}O
1306	T. N. Taddeucci J. Ullmann Los Alamos	Activation Total Cross Section for the $^7\text{Li}(p,n)^7\text{Be}(\text{g.s.}+0.43\text{-MeV})$ Reaction
1308	R. J. Peterson Univ. of Colorado	Pion Inelastic Scattering from ^{40}Ar

Appendix C
COMMITTEES

Program Advisory Committee

1992

Nucleon Physics

B. Filippone
J. Kelly
A. Miller
B. Serot
W. vanOers
S. Vigdor
S. Wallace
J. Wambach

Pion Physics

L. Bland
T. Donnelly
D. Pocanic
R. Redwine
G. Smith
J. Van Den Brand
G. Wagner
G. Walker
H. Wildenthal

Electroweak Physics

R. Brock
D. Bryman
S. Freedman
N. Isgur
J.-M. Poutissou
R. G. H. Robertson
P. Vogel

LAMPE PAC Liaison Staff — 1992

K. Jones
M. McNaughton
L. Rybaryk
O. van Dyck

R. Boudrie
S. Greene
J. Knudson
R. Werbeck

G. Garvey
M. Hoehn
M. Schillaci

1993

B. Filippone
A. Miller
B. Serot
S. Vigdor

T. Donnelly
H. Jackson
D. Pocanic
R. Redwine
G. Smith
J. Van Den Brand
G. Wagner

R. Brock
F. Calaprice
J. Donoghue
N. Isgur
J.-M. Poutissou
R. G. H. Robertson
P. Vogel

LAMPE PAC Liaison Staff — 1993

K. Jones
M. McNaughton
L. Rybaryk
O. van Dyck

R. Boudrie
S. Greene
J. Knudson
R. Werbeck

M. Schillaci
M. Zumbro

Experimental Facilities Panel

1992

F. Todd Baker, University of Georgia
Byron Dieterle, University of New Mexico
Gary Hogan, MP-4
James Knudson, MP-7
June Matthews, Massachusetts Institute of Technology
Christopher Morris, MP-10
Peter Haustein, Brookhaven National Laboratory
Barry Ritchie, Arizona State University
Gerald Hoffmann, University of Texas
Terry Taddeucci, MP-10
John Ullmann, P-17

1993

Ali Fazely, Southern University
George Glass, University of Texas
Andrew Green, Los Alamos National Laboratory
Steven Greene, Los Alamos National Laboratory
Peter Haustein, Brookhaven National Laboratory
Gerald Hoffmann, University of Texas
June Matthews, Massachusetts Institute of Technology
Michael Paciotti, Los Alamos National Laboratory
Barry Ritchie, Arizona State University
David Whitehouse, Los Alamos National Laboratory
Robert Chrien, Brookhaven National Laboratory
Ronald Ransome, Rutgers University

**DATE
FILMED**

9/12/94

END