Experiments on the Nuclear Interactions of Pions and Electrons

Final Progress Report for the Dept. of Energy

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Introduction

This report is the final performance technical report for U.S. Department of Energy Grant DE-FG05-88ER40390. The period covered by this grant extended from Dec. 1, 1987 to Nov. 30, 1997. During much of the grant period Prof. Klaus Ziock, who retired in June, 1995, was a co-principal investigator. All the research discussed in this report has been treated in more detail in our annual progress reports submitted to the DOE, as well as in the publications listed at the end of the report.

The work is grouped into four categories. 1) The experiments in pion nucleus physics were primarily studies of pion absorption and scattering in light nuclei, carried out at the Los Alamos Meson Physics Facility (LAMPF). 2) The experiments on fundamental particle properties were carried out at LAMPF and at the Paul Scherrer Institute (PSI) in Switzerland. The pion-beta decay experiment is still under construction and will begin taking data in 1999. 3) The experiments in electro-nuclear physics were performed at the Stanford Linear Electron Accelerator (SLAC), at the Saclay Laboratory in France, at the LEGS facility at the Brookhaven National Laboratory, and at the Continuous Electron Beam Accelerator Facility (CEBAF) at the Jefferson Laboratory. These experiments relate mainly to the question of the role of longitudinal and transverse strength for inelastic scattering from nuclei, measurements of fundamental nuclear properties with tagged polarized photons, and to the quark structure of the nucleon and its excited states. 4) Experiments on absorption of antiprotons in heavy nuclei. were carried out by K. Ziock primarily while on a sabbatical leave in Munich, Germany.

1. Pion Nucleus Physics.

Our group conducted a long-term program at LAMPF involving the study of pion elastic and inelastic reactions on light nuclei. These studies were facilitated by a cryogenic $^3\text{He}/^4\text{He}$ target designed, operated and maintained by UVA physicists and graduate students over a period of 20 years. This target was used by UVA in several collaborations with other Universities to perform unique experiments on fundamental nuclear reactions with few-body systems.

1-1. Pion Absorption in ^3He

LAMPF Exp. 705, R. Minehart, L.C. Smith, in collaboration with Argonne, Tel Aviv, Kent State, and Northwestern Univ.

LAMPF Exp. 705 was designed to study the reactions, $^3\text{He}(\pi^+pp)p$ and $^3\text{He}(\pi^-,pn)n$, at energies spanning the $\Delta(1232)$ resonance and up to 500 MeV, close to the highest

pion energy available at LAMPF. The goal was to study the density, isospin and energy dependence of the elementary two-nucleon pion absorption mechanism, and search for possible new multi-nucleon mechanisms. Several papers have been published detailing this work.^{1,2}

For these experiments, a 1 GeV/c magnetic spectrometer was placed in coincidence with an array of time-of-flight scintillation counters to detect the (pp) and (pn) final state. Measurements both at and away from quasi-free kinematics were performed. Using the framework of the quasi-free model, spectator recoil momentum distributions were used to identify contributions from two and three-body absorption. Angular distributions of both components were obtained. At all energies measured, the two-body angular distribution closely follows the shape of pion absorption on a free deuteron. Furthermore, the energy dependence of the quasifree reaction falls off steeply above the peak of the Δ resonance, similar to the $\pi^+d \rightarrow pp$ reaction, suggesting the underlying s-wave $\Delta N \rightarrow NN$ mechanism dominates the reaction. However, at the highest pion incident energy, the number of quasideuterons estimated from the two-body yield is larger than found at the peak of the Δ resonance, where it agrees with the value expected from simple isospin coupling arguments. This was interpreted by us as possible evidence for a density effect due to a smaller deuteron in ^3He .

The overall strength of the three-body component falls off with pion bombarding energy at roughly the same slope as for the two-body component, suggesting the underlying mechanism involves excitation of the Δ . The three-body matrix element displays an angular distribution at the higher energies that deviates from phase space at forward angles. We interpreted this as a possible signature of quasi-free knockout of a proton prior to pion-absorption on the remaining nucleon pair. In a recent paper, Simicevic and Mateos 3 concluded from Legendre polynomial fits to our three-body distributions that $l_\pi=1$ coupling of the pion to the 3N system is important. Since the strongest coupling is the p-wave $\pi N \rightarrow \Delta$ vertex, this could represent the initial coupling of the pion in the 3N channel. Later experiments at somewhat lower energies by the LADS collaboration⁴ at PSI have verified the existence of such initial-state interactions in ^3He .

The angular distribution and cross-section for the $^3\text{He}(\pi^-, pn)n$ reaction deviates substantially from expectations based on the quasi-deuteron model, indicating absorption of pions on a diproton either involves a different absorption mechanism compared to the deuteron or a different partial wave composition of the $\Delta N \rightarrow NN$ mechanism. Angular momentum/parity conservation prohibit the initial s-wave pp pair from coupling to an s-wave ΔN pair. This opens up the possibility of greater sensitivity to the initial state wave function (short-range correlations) or to higher angular momentum partial waves in the subsequent rescattering of the off-shell pion.

Our data show that the asymmetry present in the quasifree (pn) angular distributions at lower energies and below the peak of the Δ persists and has the same sign above resonance and up to 500 MeV. This provides a constraint to theoretical models that explain the asymmetry as interference terms arising from the mixture of different ΔN partial waves. The overall lower magnitude of the diproton absorption cross section compared

to the deuteron is sensitive to details of the models and appears to require an accurate treatment of the overall ^3He wave function. Because of the difficulty in measuring this reaction, the data are rather scarce. We hope to pool our results from LAMPF with data taken at lower energies at TRIUMF and PSI in order to produce an energy dependent partial wave analysis of this interesting absorption channel.

1-2. Pion Absorption in ^4He

LAMPF Exp. 1126, R.C. Minehart, L.C. Smith, S. T. Thornton, R. Sealock, R. M. Marshall, D. Day, J. McCarthy, R. Lourie, in collaboration with Arizona State University, Hampton University, James Madison University, Rensselaer Polytechnic Institute.

LAMPF experiment 1126 received over 900 hours of beam time during the summer of 1990. In this experiment, which was part of our long term program to study inelastic pion reaction mechanisms on light nuclei, we measured the systematics of quasi-free pion absorption on (pn),(pp) and (nn) pairs in ^4He . The experiment was motivated by the results from previous pion absorption measurements on ^3He at 165, 350 and 500 MeV (Experiment 705)^{1,2} where a larger than expected quasideuteron cross section was observed. Similar results for ^3He have now been reported at energies around the Δ resonance by the LADS collaboration³ at PSI. According to most models, the two-nucleon mechanism is sensitive to the amount of overlap between the absorbing nucleons. The ^3He result could be interpreted in this sense as resulting from absorption on a 'compressed' deuteron. If so, one would expect to see an even stronger enhancement of quasideuteron absorption in the more tightly bound ^4He nucleus. Therefore, the present measurement was undertaken to determine whether there is a systematic binding energy dependence of the two-nucleon absorption mechanism.

Another important result expected from this measurement was an estimate of the importance of three- and fourbody pion absorption. Such processes have only recently been unambiguously identified in the helium isotopes and the dynamical origin of these reaction channels is still speculative. Models involving both sequential Δ -excitation as well as $\Delta\Delta$ excitation have been proposed, but so far the only firm predictions are that such mechanisms are expected to contribute substantially to the total absorption cross section only for pion energies above 300 MeV.

Preliminary results were first presented at the Fewbody XIII conference in Adelaide, Australia and then published⁵ as a Rapid Communications in Phys. Rev. C in August 1993. Our major findings with respect to the two-nucleon channel can be summarized as follows: 1) the angular distribution of the quasi-free two-body absorption yield agrees in detail with the free $\pi d \rightarrow pp$ reaction, supporting the quasi-deuteron interpretation of this component, 2) the two-body absorption yield scales according to the number of isospin

0 pn pairs in ^4He , which is 3.0, unlike the case for ^3He , where a 30% enhancement was measured¹.

In order to interpret this result properly we need to estimate the effects of initial state interactions or 'shadowing', pd final-state interactions (FSI) and multi-nucleon absorption channels, which are all presumably stronger in ^4He than in the more weakly bound ^3He . The effects of shadowing are clearly seen in data published by University of Maryland group⁶, who measured the $^4\text{He}(\pi^+, pp)d$ reaction in the energy range from 67-327 MeV. Their excitation function for two-nucleon absorption, normalized to the $\pi^+d \rightarrow pp$ cross section, clearly shows a reduction of the quasi-deuteron yield around the Δ resonance. This behavior is not seen in ^3He , and as discussed by Breuer et al.⁶, suggests that inelastic scattering channels prevent the pion from 'sampling' the entire volume of the ^4He nucleus at low energies. The inclusion of our data point at 500 MeV confirms the trend shown by the PSI data of increasing transparency of the nucleus towards higher pion energies.

In addition to shadowing effects, pd FSI can remove strength from the two-body channel. Breuer et al.⁶ estimated from DWIA calculations that pd FSI corrections to the two-body yield range from 1.38 to 1.62 over this energy range. The correction factors were extrapolated to 500 MeV in order to correct our LAMPF 500 MeV point. Although the corrected 2N yields are larger than the expected value of 3.0 based on the quasi-deuteron model, particularly at 500 MeV, it is possible that some of this enhancement is due to the contributions from absorption on T=1 pn pairs, rather than a nuclear density effect. On the other hand, the 2N angular distributions at 500 MeV suggest a purely quasi-deuteron interpretation. Analysis of the $^4\text{He}(\pi^+, pn)pp$ and $^4\text{He}(\pi^-, pn)nn$ data taken during our experiment should allow an estimation of the contribution from T=1 absorption.

We have also seen kinematic signatures in the data which may shed light on the origin of the three- and four-body pion absorption channels observed. These studies have used comparisons with computer models which simulate pion absorption on quasi-free triton or ^3He clusters within the ^4He nucleus, and includes effects of soft final-state interactions between the various pairs of final-state particles. Our (pp) coincidence data show indirect evidence for pd FSI, although our missing mass resolution does not allow us to separate bound deuterons from unbound pn pairs in the unobserved final state. Therefore, we have examined the (pd) and (dp) coincidence data for signatures of FSI. So far we have identified the quasifree $\pi^+t \rightarrow p+d$ reaction using our models to fit missing momentum distributions of the spectator proton. The angular distribution agrees in shape and magnitude with the free process. Also angular distributions for the three-body breakup of ^4He that follow ppd phase space have been measured. These data can be used to estimate the contribution from three-body processes to the (pp) coincidence data and if possible independently estimate the FSI correction factor.

Finally, this experiment provided the first opportunity to observe the effects of 4N absorption at high pion energies where the "double- Δ " mechanism was predicted to produce a large cross section. Although our experiment was centered at two-body kinematics, an enhanced 4N absorption arising from multiple Δ excitation would have produced substantial and unambiguous backgrounds which were not observed. Hence we

were able to supply an upper limit to the contribution from 4N processes in the form of an effective cross section. Later experiments at somewhat lower energies by the LADS collaboration at PSI confirmed that 4N absorption is a minor component of the total pion absorption cross section in ^4He .

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1-3. Pion charge exchange in ^3He

LAMPF Exp. 920, M.L. Dowell, S. Gilad, E. Piasetsky, H.W. Baer, E.J. Beise, J.D. Bowman, G.W. Dodson, S. Hoibraten, F. Irom, J. Knudson, G.S. Kyle, M.J. Leitch, L.D. Pham, R.P. Redwine, S.H. Rokni, L.C. Smith, D.R. Tieger, S.A. Wood.

Final analysis of data from this experiment was completed and published¹ in Physics Letters B. Differential cross sections for the $^3\text{He}(\pi^\pm, \pi^0)$ and $^3\text{He}(\pi^\pm, \pi^0 p)$ reactions were measured using the LAMPF π^0 spectrometer and an array of plastic scintillation counters. The experiment was intended to investigate the relative significance of single-nucleon and

multi-nucleon processes in pion-nucleus interactions with a simple nuclear system. It has been suggested that contributions from multiple scattering channels are truncated by pion absorption in the case of charged pion scattering. On the other hand, for the single charge exchange process, coupling to the absorption channel may be reduced due to the isovector nature of the charge exchange interaction. This could lead to an enhancement of the multiple scattering contribution to the single charge exchange channel compared to that for the charged pion scattering channel.

The charged and neutral pion scattering channels were compared using single arm data from this experiment. An excess observed in the charge exchange spectra at large energy transfers (low π^0 energies) is evidence of an enhanced contribution from more complex processes to the charge exchange channel. The energy spectra from the $^3\text{He}(\pi^+, \pi^0 p)$ and $^3\text{He}(\pi^+, \pi^+ p)$ reactions were compared with (and rescaled to) their corresponding energy spectra from single-arm measurements. The peaks in the coincidence data are primarily due to single arm knockout. Therefore, the enhancement of the relative magnitude of the single-arm spectra over the coincidence spectra at low outgoing pion energies is evidence of multiple scattering contributions to the single-arm measurements. Moreover, the additional relative enhancement of the doubly differential cross section for the charge exchange reaction over the inelastic scattering cross section at low outgoing pion kinetic energies supports the hypothesis of a weaker coupling to the absorption channel for the charge exchange process.

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1-4. $\pi^+ + d \rightarrow 2p$.

LAMPF EXP., R. Minehart and Barry Ritchie, Spokesmen

Pion absorption on two nucleons is one of the fundamental nuclear reactions involving pions. At LAMPF we did a series of experiments^{1,2} to measure the cross section for the reaction, $\pi^+ + d \rightarrow p + p$, with high precision over the entire energy range accessible there. The last of these experiments took place during August and September of 1988, when we used very low energy incident pions (5 - 20 MeV), in LAMPF experiment 1085.

In the π -d center of mass system, the emerging protons share the total energy equally. In the laboratory both have energies of the order of 80 to 100 MeV, so that they are conveniently detected in total absorption scintillation counters. When the energies of the

two detected protons are combined, the reaction is easily separated from the background arising from pion absorption in carbon. At the low energies used for Exp. 1085, the intensity of the incident beam was low enough to count the particles with scintillation counters. Consequently, we used a deuterated scintillator (approximately CD) as an active target, which permitted us to measure the beam flux accurately. However, the beam consisted of a mixture of positrons, muons and pions, and simple counting of the incident particles was insufficient to determine the pion flux. The measurement of the beam composition was the most difficult part of the experiment.

The fraction of pions in the beam was enhanced by using an electrostatic separator to deflect positrons and muons away from the target. However, the finite beam phase space prevented perfect separation of the three components. In general, we were able to obtain a beam with 50-70% pions, with the remainder primarily being muons. The residual positrons were easy to identify on the basis of their low energy loss in the target. The problem then was reduced to separation of pions and muons. At some energies it was possible to identify the particles in the momentum analyzed beam by inferring their velocities from their time-of-flight between the production target and the experimental reaction target. At some energies this time could be obtained by comparing the time of the pion signal in the experimental target to an accelerator RF reference pulse. Since the RF period was 5 ns, this method required that the times-of-flight of the beam pions and muons not differ by a multiple of 5 ns, within an experimental resolution of about 1 ns. At energies where this method was useless, we were able to separate pions from muons by comparing the pulse heights in the target scintillator and in a second scintillator placed after the target.

Preliminary results were reported at the Baltimore meeting of the American Physical Society in May, 1989, and a letter³ was published in *Phys. Rev. Letters* in 1991. A detailed article⁴ was published in *Phys. Rev. C* in 1993. The principle results of our measurement were that the P-wave component of the absorption remains significant down to the lowest measured energies, about 4 MeV, and that the cross section is in good agreement with the recent measurements of the pion production reaction, $n+p \rightarrow d + \pi^0$, which is related by time reversal and isotopic spin rotation. Some discrepancies with theoretical models are noted in the paper.

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1-5. The reaction $\pi^+p \rightarrow \pi^+\pi^0p$ near threshold

LAMPF Exp. 1179, R. Minehart, R. Marshall, and L.C. Smith in collaboration with D. Pocanic (spokesman) et al., and LAMPF and Stanford.

Threshold pion production by pions on protons has been studied for a long time in hopes of extracting information on the $\pi - \pi$ interaction. An important development in these studies followed the success of PCAC and current algebra in the derivation of low energy theorems for soft processes. This success was due to the near masslessness of the pion. The PCAC idea was applied to the emission of soft pions in the works of Weinberg¹, Schwinger², and Chang and Gursley³, who arrived at different values for the ratio of isospin 0 and 2 s-wave $\pi\pi$ scattering lengths. Olsson and Turner⁴ then showed that a single parameter ξ could be used to connect the three results. Their analysis of data, along with subsequent analyses, favored the Weinberg solution.

Other aspects of the $\pi\pi$ interaction are also of interest. For example, the pion production reactions, $N(\pi, 2\pi)$ and $A(\pi, 2\pi)$, may provide a way to study the pion dispersion relation in nuclear matter, they may be a possible precursor to critical phenomena of a pion condensate, and they may be a signature of $\Delta\Delta$ excitations in nuclei, etc.⁵⁻⁸. The channel $\pi^-p \rightarrow \pi^-\pi + n$ has been studied with relatively high statistics near threshold, in kinematically complete measurements. The π^0 production channel $\pi^-p \rightarrow \pi^-\pi^0p$ was studied by the Omicron collaboration⁹ at the CERN-SC. Prior to our experiment only nine events below $T_\pi=200$ MeV existed for the channel, $\pi^+p \rightarrow \pi^+\pi^0p$. The two π^0 production channels contain different isospin information. Our goal was to obtain an improved constraint on the $I=2$ $\pi\pi$ scattering length (using a Chew-Low extrapolation which is free of dynamic model assumptions). When combined with data available for other charge states of the pion production reaction the results would permit a more direct isospin decomposition of the $\pi\pi N$ threshold amplitudes than previously possible.

The LAMPF π^0 spectrometer was used along with eight E- Δ E scintillation detectors for protons and six E- Δ E scintillation detectors for the charged pions. The target was a specially constructed liquid hydrogen target enclosed in a vacuum chamber with many exit ports to allow the low energy charged particles to emerge in many different directions in a vertical plane that includes the target and beam. The charged particles were detected in two sizes of thick scintillation telescopes, referred to as "pion" and "proton" counters. The detectors all lay more or less in a vertical plane that included the beam axis. Each of the proton counters covered a solid angle of 10 msr and stopped protons of energies up to 180 MeV. The pion detectors were much larger (15 cm x 15 cm at the base), subtending a solid angle of 90 msr, and stopped pions with energies up to 90 MeV. The energy threshold for the charged particle detectors was about 25 MeV for protons and 15 MeV for pions.

The experiment was first run at the end of the summer of 1991. Part of the scheduled run time was lost due to a decision by the laboratory to turn off the accelerator earlier than planned. Measurements were, however, extended to energies below 260 MeV where a target-full background source was found, rendering the inclusive measurements uncertain near threshold. On the other hand, the exclusive channels $\pi^0\text{-}\pi^0$ and $\pi^0\text{-}p$ were free of this problem.

The experiment was run again in the summer of 1992, after building a new liquid-hydrogen target vessel designed to improve the π^0 detection efficiency. Although the accelerator operating efficiency was not as high as we had hoped, we got about 700 events at 260 MeV and of the order of 100 events at each of the energies, 190, 200, 220, and 240 MeV. The extracted total cross sections with $\approx 10\%$ uncertainties cover the energy range sensitive to higher order terms in the phenomenological $\pi\pi N$ Lagrangian, and thus fill the remaining gap in the total cross section data needed for a new and definitive global soft-pion isospin amplitude analysis.

The acceptance, detection and track reconstruction efficiency of the π^0 spectrometer and the charged-particle arm were understood quantitatively at the few percent level. The full-fledged Monte Carlo simulation of the reaction in realistic geometry was performed using GEANT codes in order to cross-check the standard LAMPF π^0 spectrometer computer codes, giving satisfactory agreement. The apparatus could detect three classes of coincidence events, 1) $\pi^0 p$ coincidences, 2) $\pi^0 \pi^+$ coincidences, 3) and $\pi^+ \pi^0 p$ coincidences. The first two classes leave one particle undetected, but its mass can be calculated from the kinematics of the measured particles. The third type of reaction is very clean, but only 32 events were obtained. A global fit to the world's data on all of the isotopically connected channels gives a value of $\xi = -0.46 \pm 0.15$ after removing some apparently inconsistent old data. This value favors Weinberg's model, for which $\xi = 0$.

Analysis of the inclusive cross sections was finished in June 1993. We included our results in a global soft-pion analysis of the $\pi\pi N$ amplitudes and extracted a new soft-pion value of the $\pi\pi$ scattering lengths. These results were published in *Phys. Rev. Lett.*, **72**, and in the Ph.D. thesis of Emil Frlež. Because it closed an important gap in the body of data, and because of its far-reaching fundamental implications, this work has generated wide interest, and earned Emil Frlež the 1993 Louis Rosen Prize at LAMPF.

In the course of our measurements we have also determined the pion single charge exchange cross section at 27.7 MeV for $\theta_{CM} = 0 - 60^\circ$.

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2. Fundamental Particle Properties.

2-1. A Measurement of the $\pi^+ \rightarrow \pi^0 e^+ \nu$ Decay Rate

PSI Experiment R-89-01,

D. Počanić, D. Day, E. Frlež, R.M. Marshall, J.S. McCarthy, R.C. Minehart, B.E. Norum, L.C. Smith, T.P. Welch, B.K. Wright, K.O.H. Ziock, and collaborators from Arizona State, Dubna, Swierk, Tbilisi, PSI, Zagreb, and Zurich, Switzerland.

The pion beta decay reaction, $\pi^+ \rightarrow \pi^0 e^+ \nu$, provides the most direct and theoretically interpretable means to study weak u - d quark mixing. The calculated decay rate^{1,2} is $1/\tau_{\pi\beta} = 0.3977 \pm 0.0008 \text{ s}^{-1}$, where the theoretical uncertainty is due in about equal parts to the uncertainty in the mass difference between the charged and neutral pion and to the uncertainty in the radiative corrections. This calculation can be compared to the experiments of Depommier *et al.*³, who obtained $0.38_{-0.04}^{+0.03} \text{ s}^{-1}$ in 1968 using stopped pions, and to McFarlane *et al.*⁴ who reported $0.394 \pm 0.015 \text{ s}^{-1}$ in 1985 using pions in flight. The factor of 20 between the theoretical and experimental errors presents a strong challenge to the experimenters. Our experimental goal is to bring the precision for pion beta decay into the same range as the precision for the measurements of pure nuclear Fermi beta decay and neutron decay (0.2%), in several stages of measurement. The goal of our first experiment is to improve the accuracy from the 4% of McFarlane *et al.* to 0.5%.

The experiment being set up at the cyclotron facility of the Paul Scherrer Institute (PSI) in Villigen, Switzerland, is designed to measure the two photons from the decay of a stopped π^+ in a large acceptance (nearly 4π) detector of CsI. The experimental signature of the pion beta decay, $\pi^+ \rightarrow \pi^0 e^+ \nu$, is determined by the prompt decay, $\pi^0 \rightarrow \gamma\gamma$. The small branching ratio ($\simeq 1 \times 10^{-8}$) for the $\pi\beta$ decay and the required high measurement precision impose stringent requirements on the experimental apparatus:

The detector must be able to handle high event rates and cover a large solid angle with high efficiency for π^0 detection.

Efficient hardware suppression of background events calls for good energy and timing resolution.

At the same time the system must operate with low systematic errors and be subject to accurate calibration.

We have chosen to detect decays at rest, and to use $\pi \rightarrow e\nu$ decays for normalization. The apparatus has the following main components:

- (i) beam counters and a segmented active target to stop the pions,
- (ii) two concentric cylindrical multi-wire proportional chambers for charged particle tracking surrounding the active target,
- (iii) a segmented fast veto counter surrounding the MWPCs,
- (iv) a high resolution segmented fast shower calorimeter surrounding the active target and tracking detectors in a near-spherical geometry, and
- (v) cosmic ray veto counters around the entire apparatus.

The spatial, energy, and time resolution of the segmented shower calorimeter are essential for efficient running at high rates. The calorimeter consists of 240 truncated hexagonal and pentagonal pyramids; the shapes were chosen for optimum light collection efficiency, and the granularity to accommodate pion stop rates well in excess of 10^6 s^{-1} . The calorimeter modules are made of pure CsI (for speed) and are 22 cm thick, which is equivalent to 12 radiation lengths. The outer radius of the sphere is 48 cm. Central track detectors are needed for efficient tracking of charged particles with good double track resolution is necessary for a clean identification of the $\pi \rightarrow e\nu$ decay events.

Selective bias-free triggers capable of handling high rates are an essential requirement. We have designed fast analog hardware triggers optimized to accept nearly all non-prompt $\pi\beta$ and $\pi \rightarrow e\nu$ events contained in the calorimeter with individual shower energy exceeding the Michel endpoint (high threshold, $HT \simeq 55 \text{ MeV}$), while keeping the accidental rate to an acceptable level. The proper working of the trigger relies on fast analog summing and discrimination of the CsI module signals and an appropriate shower clustering scheme. The size of the CsI crystal modules was chosen to match approximately the characteristic lateral spreading of such showers, so that a typical shower deposits most of its energy in three crystals sharing a common vertex point. Hence, we sum over each of the vertices of the active calorimeter, using overlapping summing regions for maximum trigger efficiency. Analog summing and discrimination is performed in dedicated linear summer/discriminator modules (UVA-125) were designed and built in our laboratory by W. Stephens.

The basic energy summing regions, called clusters, sum over 9 detector modules each, which is consistent with the planned pion stop rates below 10^7 s^{-1} . Because clusters have to overlap, an individual crystal contributes energy to up to three clusters using linear pulse splitters (UVA-126) designed and built by W. Stephens. There are 60 clusters in the entire calorimeter. In order to simplify the trigger logic, the calorimeter is divided into 10 main regions called superclusters, each made up of a logical "OR" of 6 overlapping clusters centered about a pentagonal shaped detector. Each of the 10 superclusters has an associated opposing hemisphere (complement) made up of the logical "OR" of the 5 superclusters not neighboring it. Thus, for example, a $\pi\beta$ trigger would require a coincidence of a given supercluster with its complement.

The first in-beam feasibility tests were conducted in July and November 1989 at PSI, the latter just prior to the $1\frac{1}{2}$ year long shutdown of the ring accelerator. Rushed by the impending shutdown deadline, the November run was carried out with pure CsI detectors somewhat inferior to the best Bicron samples. Nevertheless, the measurements demonstrated that detecting stopped pion decays was a sound method — an $\approx 30\%$ measurement of the pion beta decay branching ratio was accomplished in about a day of beam time at the end of the run. During laboratory tests in 1989 it was determined that, contrary to previously reported results, pure CsI has a long intrinsic absorption length, $\geq 1 \text{ m}$. This led to a thorough redesign of the CsI calorimeter, making use of the significantly more favorable tower geometry. The ensuing Monte Carlo analysis of systematic uncertainties and detector design took well over a year of effort and resulted in the proposal which was

approved by the PSI BV Program Committee in January 1992.

In April 1992, a two-week beam development run in the PIE1 channel using in-beam MWPC's demonstrated that an acceptable beam could be achieved at 116 MeV/C with low muon and positron contamination without an electrostatic separator, which simplifies the measurements.

During a run in June-July, 1993, at PSI we made great progress in beam quality, detector development and testing, and in-beam evaluation of our electronics and data acquisition components. The major accomplishments of that run are listed in our progress report for that period.

During 1993 and the spring of 1994 design work was completed for the mechanical support structure for the detector system, thermal and light insulation housing, and the lead-lined plastic scintillator cosmic muon veto housing. This was a large project dependent on the support of engineers at PSI.

A very important electronics development regarding strict photomultiplier (PMT) linearity was completed by W. Stephens and Cole Smith at UVa in 1994. We had encountered a problem, sometimes called "superlinearity", or "over-linearity". This refers to a situation where large input signals at the photo-cathode produce an output signal from the anode that is larger than expected from a strictly linear response. This situation tends to occur when the size of the input signals are a little below the saturation value. At saturation the output is nearly independent of input. For our experiment we need to maintain a linear response up to the onset of the saturation region. We have found a design for the voltage divider that eliminates the superlinear problem and at the same time reduces the rate-dependent gain shift and drift to meet our tolerances of 1%.

We are using the EMI 9822 QKB for our 3-inch PMT and EMI 9211 QKB for our 2-inch PMT. Bill Stephens has designed a high current modification of the high voltage divider recommended by EMI. This divider minimizes the super-linearity.

Another source of non-linearity are changes in the dynode material secondary properties arising from direct impact heating, and dynamic surface chemistry effects such as ion migration. These effects depend on dynode composition and occur at much smaller anode currents (1-10 μA). To understand the dynode dependent effect we evaluated two dynode materials offered by EMI, SbCs and BeCu, using the test setup described next.

Our acceptance criterion for the EMI photomultiplier tubes is that the gain shift for any PMT should vary by no more than 2 standard deviations from the mean gain shift. Establishing this distribution requires measuring the gain shift for every PMT. We used a two LED technique to measure the rate-induced gain shift. A reference LED was pulsed at 10 Hz and the gain of the PMT adjusted to produce a charge/pulse of 780 pC, corresponding to the charge expected from a 70 MeV photon from pion beta decay. A background LED was pulsed at a computer adjustable rate from 25 Hz to 18,000 Hz, with a charge/pulse approximately half that of the reference LED. (The background LED simulates the expected Michel electron background in the CsI crystals arising from muon decay). An ADC was used to digitize the PMT charge resulting from the reference LED. The process was automated with the CEBAF On-line Data Acquisition (CODA) system.

Our tests showed that these gain shifts are intrinsically related to the dynode composition and independent of PMT gain, high voltage or divider design. We found that SbCs offers much higher overall gain as well as improved gain stability compared to the BeCu dynodes, at the expense of some loss in overall linearity. However, we were able to modify the high voltage divider design to compensate somewhat for the loss in linearity. As a result of these measurements the SbCs dynodes were chosen for both the 2" and 3" PMT's.

The analog energy summing method was successfully tested in a $\pi \rightarrow e\nu$ test measurement at PSI in 1996 using a partial setup consisting of 26 CsI modules. Six overlapping clusters were defined with up to 9 detectors each, and a supercluster logical "OR" was formed. As described above, $e\nu$ -(LT) and $e\nu$ -(HT) triggers were formed.

Since our absolute acceptances involve an energy cutoff, properly stabilized gains are crucial for keeping the uncertainties low. Besides the usual sources of gain instability in the electronics and phototubes, CsI itself has a pronounced temperature coefficient of light output of about $-1.5\%/^{\circ}\text{C}$. Given the drifts in ambient temperature in the experimental hall, this would result in unacceptable shifts. Therefore the entire detector system will be housed in a temperature stabilized enclosure with temperature drifts regulated within 0.5°C . Klaus Ziock designed this system and tested it at PSI in 1996.

The main source of uncertainty of geometrical nature in the absolute acceptances $A_{e\nu}/A_{\pi\beta}$ has to do with the position and spatial spreading of the pion beam stopping distribution. Due to the cylindrical symmetry of our detector system the uncertainties can be broken down into the lateral and axial ones. Of the two, lateral uncertainties produce a larger effect on the acceptances than the axial ones. Also, since the $\pi\beta$ events require symmetrical coverage for the two photons emitted in the π^0 decay (nearly at rest), $A_{\pi\beta}$ is affected far more than $A_{e\nu}$. Both the centroid and the width of the pion stopping distribution have to be monitored and controlled dynamically. The regular active target is segmented into 9 regions. Prompt signals from each of the target segments will be counted in a scaler, and the scalers read out every 10 s. The 5 central regions receive practically the entire stopped beam, each counting at the same rate. The counting asymmetry (left-right or up-down) equals 2% for a shift of the centroid of 0.06 mm, corresponding to a 0.02% change in the integrated acceptance ratio. This is an easily measurable asymmetry given the counting statistics of 10^7 in 10 s, even after the Poisson corrections for unresolved double hits and accidental coincidences with Michel decays. Analysis of the measurement of the rms width of the distribution shows that a 2% central-peripheral asymmetry corresponds to a change in σ by 0.11 mm, or a 0.04% effect on the acceptance ratio $A_{e\nu}/A_{\pi\beta}$.

In the summer of 1997 an assembly using 1/4 of the total detector was tested successfully at PSI. This test included all the read-out electronics, as well. The remaining task is to assemble the entire detector, commission it and begin data taking.

Timetable

Due to difficulties experienced by the suppliers of pure CsI modules, the construction of the apparatus has taken longer than planned. The extra time was used for improve-

ments in detectors, readout linearity, trigger electronics, data acquisition, DSC digitizer development, etc. Particularly beneficial was development work on CsI detector surface treatment coupled to the 3-dimensional cosmic muon tomography technique developed specifically for this purpose, resulting in improved detector energy resolution, consistently over a large sample of modules. All these actions will eventually lead to shorter final commissioning time of the apparatus and will serve to improve the quality of our data and expedite "production" measurements.

The current timetable for the experiment is as follows:

1998: apparatus fully assembled by mid-year; proceed with detector shakedown and calibration; begin $\pi\beta$ measurements at low pion stop rate;

1999: ramp up to the nominal operating pion stop rate ($\sim 10^6 \text{ s}^{-1}$); "production" runs;

2000-2001: more "production" runs.

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2-2. Search for the rare decay, $\mu^+ \rightarrow e^+ + \gamma$.

LAMPF Exp.

K.O.H. Ziock and LAMPF collaborators.

The mu-e-gamma, or "MEGA", experiment was designed to reduce the limit on the branching ratio for the "forbidden" decay

$$\mu^+ \rightarrow e^+ + \gamma$$

to the lowest level achievable with current accelerator and detector technology. The observation of such a decay would signal that the generation (or family) quantum number is not strictly conserved. The previous upper limit on the branching ratio for this decay ($B < 5 \times 10^{-11}$) was set by the Crystal Box experiment performed at LAMPF. The design goal of the MEGA experiment was either to observe the decay or to reduce the upper limit on its branching ratio to

$$< 2 \times 10^{-13}$$

The experiment used a large (length = 2.9 m, i.d. = 2 m) super-conducting solenoid with a field of 1.5 T. The positive surface-muon beam from the low energy muon channel at LAMPF was stopped in a thin target in the center of the magnet volume. The γ -

rays from the forbidden decay were observed by a set of three pair spectrometers mounted concentric with the beam axis. The energy of the decay positron is measured with a set of wire chambers consisting of a large chamber concentric with the beam axis that is surrounded by a set of 7 smaller chambers. Inside the inner chamber and concentric with it were 2 sets of 87 scintillation detectors each that surrounded the beam entrance and beam exit pipes and determined the time of arrival for the decay positrons.

A significant fraction of the background events was due to radiative muon decays, i.e. muon decays that are accompanied by the emission of an inner bremsstrahlung photon. If this photon has a high energy it can lead to a spurious γ - ray trigger. Such spurious events, however, are accompanied by a low energy positron whereas the genuine events are accompanied by a high energy positron. The low energy positrons follow the magnetic field lines to the beam entrance and exit ports. Scintillation detectors, mounted where the low energy positrons leave the magnet could, therefore, be used to veto some of these spurious events, providing an "Inner Bremsstrahlung Veto", or IBV. The responsibilities of our group included the design, construction, and operation of the electron (e^+) scintillation detector, and of the inner bremsstrahlung veto.

The Electron Detector:

We built and assembled 174 new scintillation detectors to replace the previous set of detectors that we had built earlier. This was considered advisable for three reasons:

- The old scintillators showed signs of crazing that reduced their light output. This crazing was thought to have been due to a lack of care by the manufacturer. The new scintillators were machined with a diamond tool and subsequently annealed.
- The old scintillators were manufactured prior to a design change that reduced the diameter of the electron detector by several millimeters. As a consequence they were cut at angles that did not allow them to be arranged in a densest packing around the central beam pipe.
- The old detectors were mounted singly around the beam pipe which made their installation difficult and risky (breakage). The new detectors were mounted in groups of nine on stainless steel plates, which fit into a groove cut into the central beam pipe.

In the summer of 1992 the complete set of new scintillators was used in the first data run for the MEGA and RHO experiments.

The success of the experiment depended on the ability to eliminate background from the energy region occupied by the γ -ray from the two body MEGA decay. The elimination of background is greatly facilitated by reducing the width of the energy and timing peaks associated with the decay. Our photon energy resolution was studied by producing very low energy neutral pions in the capture reaction $\pi^- + p \rightarrow \pi^0 + n$ and measuring the energy of each of the photons from the decay $\pi^0 \rightarrow \gamma\gamma$. The energy distribution for a single photon after applying a cut on the opening angle for the photon pair resulted in an observed resolution of 1.5 ± 0.3 MeV, consistent with the design goals of the apparatus. To test the timing resolution for detection of an $e\gamma$ pair, we used the reaction $\mu^+ \rightarrow e^+ \gamma \nu \nu$. The resolution was 2.4 ns FWHM, also consistent with the design goals. The precision of

the apparatus in measuring the positron energy and the photon energy was also consistent with the design goals.

The data taking for this experiment came to an end when the LAMPF facility was shut down for nuclear physics.

2-3. Search for heavy neutrinos.

PSI Exp., R. Minehart, K. Ziock, spokesmen

R. Minehart, R. Marshall, W. Stephens, B. Wright, K.O.H. Ziock, and SIN collaborators.

In this experiment we undertook to further reduce the upper limit for the branching ratio for the decay of a pion into a muon and a heavy (τ) neutrino, based on a proposal by R.E. Shrock¹. The experiment was a continuation of work that we had been doing for several years. We hoped to reduce the lower limit for the mass of any admixed neutrino, and to improve the limit on the measured branching ratio by a factor of 10. A new set of Ge detectors with a system of guard rings was used. We also used a new electronic system for signal sampling.

The final results were superior to those from our previous measurement in some mass regions, but overall we did not feel that the improvement in general was sufficient to justify a new publication.

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3. Electro-Nuclear Physics.

3-1. Transverse and Longitudinal Response Functions for several nuclei near $Q^2 = 1 \text{ (GeV/c)}^2$.

SLAC Experiment NE9, Z. Meziani, spokesman

R. Minehart, J.P. Chen, and L. Chinitz, with collaborators from U. Va., Stanford, Florida State U. and SACLAY.

Because the longitudinal cross section for inelastic electron scattering from nuclei is expected to be small outside the electron-nucleon quasi-elastic region, it has been thought that quasi-free electron-nucleon scattering models would be especially successful at predicting the longitudinal response function. Measurements⁽¹⁻³⁾ were made at Bates and SACLAY to obtain the separated longitudinal and transverse response functions for several nuclei ranging from ^4He to Fe. These experiments generally yielded transverse response functions in reasonable agreement with theory, but obtained a longitudinal response significantly less than the theoretical⁽⁴⁻⁶⁾ results. The disagreement between theory and experiment has elicited a large variety of theoretical explanations, some of them being rather exotic.

When the longitudinal response function, $R_L(Q^2, \nu)$, is integrated over the energy loss, ν , one obtains the "Coulomb sum rule". Except at low Q^2 , non-relativistic calculations predict that the result will be the electric form factor, G_E , of the proton times the number of protons in the nucleus. For ^4He at $Q^2 \approx 6 \text{ fm}^{-2}$, the sum rule is satisfied, but with increasing nucleon number, A , the longitudinal response is suppressed more and more, so that in ^{40}Ca , the data fail to saturate the sum rule by 40%. Data from SACLAY¹³ also report a failure at the 30% level for ^4He at Q^2 of 0.5 (GeV)^2 .

Among the proposed explanations, perhaps the most interesting require modification of the nucleon by the nuclear medium. This approach is illustrated by the work of Celenza *et al.*^(7,8) This method can improve the agreement between theory and experiment for the longitudinal response, but at the expense of removing the agreement for the transverse response function. Another approach⁽⁹⁻¹²⁾ has been to modify the nucleon current through an effective mass. This has had better success in bringing the theory and experiment into agreement, but the explanation of the effective mass is uncertain. A change in the effective mass can be expected to alter the intrinsic nucleon form factors in nuclear matter, but other factors may also affect the structure of the nucleon in nuclear matter. The Q^2 dependence of the structure functions is therefore an important feature, so that data at higher Q^2 was needed.

In 1987, we measured the quasi-elastic cross sections in the region of $Q^2 = 1 \text{ (GeV/c)}^2$ at SLAC using the 8 GeV/c magnetic spectrometer in the SLAC-NPAS facility. Measurements were made on ^3He , ^4He , ^{12}C , and Fe at two angles, 15° and 80° , with incident electron energies ranging from 600 MeV to 4 GeV. A minimum of two angles are needed to make the Rosenbluth separation of the cross section into its longitudinal and transverse parts. Additional measurements were not possible due to the limited time available at SLAC. To minimize the systematic errors, the measurements were all made with the SLAC 8 GeV/c spectrometer.

The analysis of the data was carried out largely by J.P. Chen and R. Minehart at U.Va., in parallel with Z.-E. Meziani at Stanford. The analysis of the iron data was published in Phys. Rev. Letters, in March, 1991. The analysis of the helium data was published in the Phys. Rev. Letters of July 6, 1992.

The main results are that on the low energy loss side of the quasi-free peak, the ratio of the reduced longitudinal and transverse response functions is approximately 1, in contrast to results at lower momentum transfer, where the ratio is 1 for ^3He but about 0.75 for ^4He . When plotted against the scaling variable, y , there appears to be a relative shift of the peak positions, with the transverse response appearing to move to relatively higher y values. This shift may be at least partly explained by the contributions at high momentum transfer from exchange currents and pion electro-production to the transverse response function. Within large uncertainties the Coulomb sum rule is satisfied by our data.

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3-2. The Response Function R_{LT} in the reaction $^{16}\text{O}(e,e'p)$.

SACLAY Experiment, R. Minehart, L. Chinitz, in collaboration with groups from CEBAF, SACLAY, and Frascati, J. Mougey, spokesman

This experiment was the basis of the Ph.D. thesis of L. Chinitz, working under the supervision of R. Minehart. He received his degree from the University of Virginia in August, 1990. The results were published in Phys. Rev. Letters, July 29, 1991. In this experiment, electrons were scattered quasi-elastically from protons in ^{16}O . The scattered electron and the proton were detected in coincidence using two magnetic spectrometers. By fixing the beam energy and the energy and angle of the scattered electron the measurements were made at constant Q^2 and at a fixed center of mass energy of the final system. The kinematics were chosen so that the momentum of the outgoing proton was perpendicular to the electron momentum transfer vector, $\vec{q}$, the so-called "perpendicular kinematic condition". The recoil proton was measured at many angles on both sides of $\vec{q}$.

The momentum of the recoil proton is essentially independent of this angle, so that final state effects are minimized, but the energy and direction of the incident nuclear proton depend strongly on it. We were able to cover an angular range corresponding to initial proton momenta from 0 to 200 MeV/c.

Our experiment was one of the first measurements to concentrate on an interference response function, the R_{LT} response function in $^{16}\text{O}(e,e'p)$. Cross sections were measured for scattering to the ground state ($1p_{1/2}$) of the residual ^{15}N nucleus as well as for scattering to the first excited state ($1p_{3/2}$). Spectral functions for each shell were found and were used to derive spectroscopic factors. Finally, the response function R_{LT} was found for each shell.

The results of this experiment are presented as the measured cross sections, the extracted effective spectral functions $S_f = \frac{d^6\sigma}{K\sigma_{ep}}$, the spectroscopic factors

$$N_\alpha \propto \int_{\Delta E_m} dE_m \int_{-\infty}^{\infty} dp_R S_f(E_m, p_R),$$

and the interference response functions $R_{LT}(Q^2, E_m, p_R, \gamma)$.

The shapes of the quantities measured are equally well reproduced by non-relativistic and relativistic calculations, indicating that, in this kinematical regime, there are no dramatic relativistic effects. The major difference between these two types of calculations is the scaling factor necessary to fit the calculations to the data. The relativistic calculation appears to account for 20% more of the missing single particle strength than does the non-relativistic calculation. Picklesimer *et al.*¹ find that, in their calculations, the relativistic calculation is in general suppressed relative to the non-relativistic one due almost entirely to the relativistic components in the distorted wave of the ejected nucleon. Relativistic components in the bound state account for only a small part of this suppression.

We also found significant differences in the scaling factor necessary to fit the cross section calculations to the data and the scaling factor necessary to fit the calculated R_{LT} response functions to the data. In both the relativistic and non-relativistic cases there appears to be more 'quenching' of the full cross section than there is of the R_{LT} response function. That this result might be related to the R_L "quenching" phenomenon by necessitating a re-normalization of the Coulomb coupling is an interesting result, that could be further investigated in experiments at Bates or CEBAF, in which all four nuclear response functions in $(e,e'p)$ are separated.

Our results for the spectroscopic factor are consistent with the depletion of single particle strength at the level of 50% seen in other nuclei with $A > 12$.

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3-3. Photo-disintegration of the deuteron

R. C. Minehart, collaborating on SLAC Exp. NE8 (Roy Holt, spokesman).

Photo-disintegration of the deuteron has long been of interest in nuclear physics because of its simplicity and its value in testing the nucleon nucleon potential. At energies above the pion production threshold, the process can be used to study the dynamics of large energy and momentum absorption by a nucleon pair. At energies comparable or larger than the nucleon rest mass, the process should be understood in terms of the nucleon sub-structure. In particular perturbative QCD predicts that the dependence on momentum transfer can be predicted by counting the number of point like structures in the reaction.

Experiment NE8 was run at SLAC in 1987-88 to measure the cross section for photon energies from 0.8 to 1.6 GeV. The Nuclear Physics Injector at SLAC was used to produce the electron beam in the range of a few GeV. A bremsstrahlung beam was made in a copper radiator upstream from a liquid deuterium target. The protons from the photo-disintegration reaction were measured in the SLAC 1.6 GeV spectrometer at center of momentum angles from 50° to 142° . At 90° the energy dependence of the cross section is consistent with the constituent quark counting rules.

The magnitude and energy dependence can also be reproduced by a meson-baryon calculation. At 143° the energy dependence is not consistent with quark rules. At the low energy end of the measurements the angular dependence of the cross section is flat, but at the higher energies there is noticeable rise in the backward direction, a feature that is found in Brodsky's perturbative QCD model. Thus it is possible that the simple behavior associated with the high energy constituent quark scaling results may begin to show up in this energy region.

The results were published in Phys. Rev. **C48**, 1864, (1993). Further experiments were proposed for CEBAF, but we did not have time to participate in them.

3-4. Measurements of the Nucleon Spin Structure at SLAC

R. Minehart, L.C. Smith, Todd Averett, with the E143 Collaboration (Virginia, SLAC, American U., Wisconsin, Basel, CEBAF, Harvard, Livermore, Massachusetts, Michigan, Ohio U., U. Pa., Rochester, Saclay, Stanford, Tel Aviv)

This experiment was designed to measure the spin structure functions, $g_1(x, Q^2)$ and $g_2(x, Q^2)$, for the proton and the deuteron. The parameter Q^2 is the absolute value of the electron four-momentum transfer. It is expected from the parton model that at large Q^2 the structure functions will depend only on the Bjorken scaling parameter $x = \frac{Q^2}{2M\nu}$, where M is the nucleon mass and ν is the energy of the virtual photon coupling the electron to the nucleon. In the scaling region, i.e. large Q^2 and large ν , the structure functions, g_1 and g_2 , can be related to the helicity distributions for the partons in the nucleon. Previous

measurements of the spin asymmetry on the proton have been carried out at SLAC and CERN. While a variety of models tend to be in agreement with the experiments in the range of $0.1 < x < 0.7$, the experimental uncertainties are too large to distinguish between the models. In the range $0.01 < x < 0.1$, the EMC³ results lie below the predictions of all the models.

Of particular interest to us was the Bjorken² sum rule, with QCD corrections, which was derived on very general grounds, so that its violation would be difficult to explain within the standard model. A test of the Bjorken sum rule requires measurements of structure functions for both the proton and the neutron. Ellis and Jaffe derived independent sum rules for the proton and the neutron. These, however, are somewhat model dependent.

The data were taken in End Station A at SLAC between Nov., 1993 and Feb., 1994. Longitudinally polarized electrons with energies of 9.0, 16.1 and 29.1 GeV were incident on polarized targets consisting of frozen ammonia (NH₃ and ND₃) pellets. Scattered electrons were detected in two independent magnetic spectrometers operating in parallel, but not in coincidence.

A laser system incorporating a strained GaAs crystal was used to provide an electron beam with polarizations of the order of 80%. The polarization of the beam was measured with two independent Moller spectrometers upstream from the scattering target.

The targets were built at the University of Virginia under the direction of Don Crabb. Pre-radiated frozen pellets of ammonia (NH₃) and deuterated ammonia (ND₃) were immersed in a liquid ⁴He bath, which was pumped to a temperature of 1K. A uniform 5T magnetic field was provided by a pair of super-conducting Helmholtz coils. The protons and the deuterons in the ammonia were then dynamically polarized by application of a 140 GHz RF field. The NH₃ and the ND₃ targets, along with an empty target and a carbon target, were attached to a common insert for the cryostat. The insert could be moved up and down remotely so that any of the four targets could be placed in the beam. This system had one disadvantage, the deuteron target, located at the top of the post, tended to shield the proton target from the source of RF power. Consequently, the proton polarization was somewhat less than could otherwise have been obtained. During the data taking, an average proton polarization of the order of 60% and an average deuteron polarization of 30% was attained. The components of the cryostat were designed with entrance and exit windows that permitted the direction of the target polarization (which was along the axis of the Helmholtz coils) to be oriented either longitudinally or transversely to the beam, simply by rotating the entire target assembly by 90° around a vertical axis.

Scattered electrons were detected in two vertical bend, non-focusing, large momentum acceptance spectrometers, with fixed central angles in the horizontal scattering plane of 4.5° and -7° with respect to the beam. The inelastic scattering data extend over the kinematic range $0.03 \leq x \leq 0.76$ and $1.25 < Q^2 < 9.7$ (GeV/c)², for invariant masses above the resonance region, $W > 2$ GeV/c. Because the beam intensity was limited by the amount of beam heating permitted for the target, the use of two spectrometers increased the data rate almost up to the maximum that could be handled by the data acquisition

system. It was possible to accept up to four events per beam pulse (width=1 μ sec). By using spectrometers at two different angles, data were obtained at two different values of Q^2 for each x value over most of the allowed kinematical region. This allowed us to check for Q^2 dependence in the structure functions.

Measurements with both longitudinally and transversely polarized nucleons permitted two independent spin asymmetries to be determined. One of our goals was to extract both g_1 and g_2 for the proton with a minimum of model dependent assumptions. The ratios involve the difference of measurements with opposite beam-target alignments divided by the sum, so that systematic errors related to acceptance uncertainties cancel. These asymmetries also depend on the unpolarized structure function, F_1 , which we took from previous experiments. As functions of x our data were not obtained at a constant value of Q^2 . To test for x scaling, it was necessary to extrapolate the measurements to a common Q^2 , introducing some additional slight model dependence.

The first result from the experiment was the determination of g_1^p/F_1^p for the proton over the range $0.027 < x < 0.8$ and $1 < Q^2 < 10(\text{GeV}/c)^2$. Results of this analysis were published⁴ in the Phys. Rev. Letters. Using somewhat model dependent methods to extrapolate the measurements into the unmeasured regions of x , we obtained the integral for $Q^2=3(\text{GeV})^2$,

$$\Gamma_1^p = \int_0^1 g_1^p(x) dx = 0.127 \pm 0.004(\text{stat}) \pm 0.010(\text{syst})$$

This is in good agreement with the value obtained from SMC measurements⁵ of $\Gamma_1^p = 0.122 \pm 0.011 \pm 0.011$ obtained at $Q^2=3(\text{GeV})^2$. The result is more than two standard deviations below the prediction of the Ellis and Jaffe sum rule¹, $\Gamma_1^p = 0.160 \pm 0.006$, evaluated with QCD corrections and with $\alpha_s = 0.35 \pm 0.05$ at $Q^2=3(\text{GeV})^2$ predicted by Ellis and Jaffe¹. Combining our results for the proton with the neutron results for Γ_1^n , we obtained $\Gamma_1^{p-n} = 0.149 \pm 0.014$, consistent with the prediction of the Bjorken sum rule with QCD corrections, $\Gamma_1^{p-n} = 0.171 \pm 0.008$.

A paper on the determination of g_1^d for the deuteron was also published⁶ in the Phys. Rev. Letters. With model dependent extrapolations, we obtained

$$\Gamma_1^d = \int_0^1 g_1^d dx = 0.42 \pm 0.003(\text{stat.}) \pm 0.004(\text{syst.})$$

at $Q^2=3(\text{GeV})^2$. When combined with our measurement of Γ_1^p we obtain $\Gamma_1^p - \Gamma_1^n = 0.163 \pm 0.010(\text{stat.}) \pm 0.016(\text{syst.})$, which also agrees with the Bjorken sum rule.

In another paper⁷, published in Phys. Letters, the Q^2 dependence of g_1 for the proton and deuteron were investigated. We found that the ratio g_1/F_1 was consistent with no Q^2 dependence for $Q^2 > 1(\text{GeV}/c)^2$ at fixed x . There was however a trend for the ratio to decrease at lower Q^2 . In this paper fits to world data, with and without a possible Q^2 dependence in the ratio g_1/F_1 were in agreement with the Bjorken² sum rule. We also studied the sensitivity of the extracted net quark helicity, Δq , to this possible Q^2 dependence. The results of this new analysis for the proton, $\Delta q = 0.35 \pm .09$, were

somewhat higher than reported in our first paper, $\Delta q = 0.27 \pm .10$. For the deuteron we obtained, $\Delta q = 0.35 \pm .05$, also somewhat higher than in our earlier analysis, $\Delta q = 0.30 \pm .06$. Using the Q^2 dependent or independent fits makes little difference in both cases. Our result is significantly less than the Ellis-Jaffe prediction¹ that $\Delta q \cong 0.58$, which was derived by assuming that there was no contribution of the strange quark sea to the helicity and assuming SU(3) flavor symmetry in the ground state baryon octet.

A paper reporting the results presented by Todd Averett in his Ph.D. thesis on g_2 for the proton and the deuteron was published⁸ in Phys. Rev. Letters. The asymmetry, A_2 , for both the proton and the deuteron was close to zero over the most of the range of measurement, and except for one point well below the positivity limit, $|A_2| < \sqrt{R}$, where R is the ratio of the longitudinal to transverse virtual photon absorption cross section. The proton asymmetry became slightly positive (≈ 0.1) for $x > 0.2$. At the largest value of x measured, $x \cong 0.8$ the deuteron asymmetry was positive and consistent with $\sqrt{R}$, but the statistical error is large. The structure functions g_2^p and g_2^d extracted from these data are consistent with model predictions, but the errors are too large to prefer one model over another.

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3-5. Contributions to the CEBAF CLAS detector

R. Minehart, L. C. Smith, W. Stephens

R. Minehart is a co-spokesman for six accepted proposals for the CLAS detector at CEBAF. These experiments are a major part of the N^* program at CEBAF to study exclusive reactions involving the electro-production of nucleon resonances. In addition we participated in another experiment in 1996 to study electro-production of the $\Delta(1232)$ at high Q^2 , also in Hall C. Our contributions to the construction of the CLAS detector are described in the following paragraphs.

The CLAS detector is a large acceptance detector with a toroidal magnetic field produced by six super-conducting coils. The trajectories of charged particles passing through the field are measured with wire chambers. Their velocities are determined with time-of-flight scintillation counters. Particles with angles of less than 45° relative to the beam pass into a forward calorimeter, sometimes called the "Electron-gamma-neutron" (EGN) detector to describe its three-fold purpose. The calorimeter is made from alternating layers of 1 cm thick scintillator and 2 mm thick lead sheets. There are a total of 39 scintillator layers, resulting in a detector that is approximately 14 radiation lengths thick. While it is intended primarily to measure the energy of electrons and photons, the calorimeter detects neutrons with more than 50% efficiency with moderate spatial resolution over a wide range of neutron energies.

The U.Va. group, primarily R. Minehart, R. Sealock, and R. Marshall, took on the major responsibility for the construction and testing of a prototype version of this detector, which was tested successfully at the Brookhaven National Laboratory in the spring and summer of 1990. Results of the test were reported at the IEEE conference on Nuclear Detectors, in Washington, D.C., in Oct. 1990. The test was conducted in collaboration with a CEBAF group led by Volker Burkert, a group from the College of William and Mary (led by Herbert Funsten), K. Giovanetti and students from James Madison U., Joe Lieb from GWU, three Soviet collaborators (one from Moscow and two from Yerevan). Without any time to optimize the photo-tube voltages or to study the quality of the optical couplings, we succeeded in obtaining an energy resolution of $9\%/\sqrt{E(\text{GeV})}$. We had no time to investigate the timing resolution of the detector on-line, but off-line studies of the data showed that we had relatively poor resolution, of the order of $\sigma = 2$ nsec at best. Further studies after the run revealed that this could be attributed to the wavelength shifter, whose fluor had a decay time of approximately 10 nsec. Since that test new wavelength shifters have been developed with decay times 3-4 times faster, and we studied the response of these by substituting three into the original wavelength shifters in the proto-type detector. Following this work, it was later decided to replace the wave-length shifter readout with a fiber-optics system.

The CLAS calorimeter covers an angular region from approximately 10° to 45° relative to the beam direction. It consists of 6 independent sectors, each one occupying the space between two of the CLAS magnet coils. Each sector has a triangular cross section, approximately 5.5 m on each side. This triangular cross section is mounted at an angle of 22° to the beam. Each layer of scintillator is made of 36 strips of Bicron scintillator, 1 cm

thick, approximately 10 cm wide, and ranging in length from 15 cm to 550 cm are laid side by side. The orientation of the strips is rotated by 120° from one layer to the next, so that three successive layers form a U,V,W set. The UVW pattern is repeated thirteen times for a total of 39 layers. To read out the scintillation signal, the calorimeter is split into a front section consisting of the first 15 layers and a rear section consisting of the remaining 24 layers. The scintillation light travels to one end of a scintillator strip where it is collected by a bundle of optical fibers and conducted to a photomultiplier tube (PMT). The optical fibers from five corresponding U (or V, or W) strips in the front section are coupled to a single PMT. Similarly the fibers from eight corresponding U (or V, or W) strips are coupled to a single PMT. Thus each of the six EGN sectors requires 2x36 PMT's for the U strips, 2x36 PMT's for the V strips, and 2x36 PMT's for the W strips, resulting in a total of 216 PMT's for each of the six sectors. The intersection of one strip from a U plane, one strip from a V plane and one strip from a W plane has the shape of triangle approximately 12 cm on each side. Thus the EGN will independently locate the particle initiating a shower to approximately this accuracy (somewhat better when the shower spreads out over more than one pixel so that its centroid can be located more precisely). In the discussion below of the EGN cosmic ray tests these triangular areas are called *pixels*.

In December, 1995 we finished measuring the approximately 5600 EGN scintillator strips with lengths up to 3 m. A laser-driven gain calibration and monitoring system was built at the University of Virginia to permit simultaneous measurement of six scintillators. In this system, fiber optics were used to split the light from a nitrogen pulsed laser into 30 pulses, 29 of which were taken to spots separated by 10 cm along a scintillator, The remaining pulse was sent to a diode monitor. Each of the 29 pulses were split into six, so that six scintillators could be studied simultaneously. Because of instabilities in the laser and the fiber transmission characteristics frequent calibration was required. Therefore, we also built a device that uses a UV light mounted on a movable cart to measure the absolute attenuation of a scintillator, which, in turn, could be used to calibrate the laser system. Both of these systems were controlled by a computer coupled through an MBD to a CAMAC crate. The same computer system was used to read out the pulse heights from the photo-multiplier. We used the LAMPF 'Q' system for computer control of the data acquisition.

We found it necessary to return about 10% of the scintillators in the first four sectors for replacement, either because they did not meet dimensional specifications or the minimum acceptable attenuation length. The rejection rate for sectors 5 and 6 was much lower. Most of the actual measurements were carried out by part-time undergraduate students, paid with funds provided by CEBAF.

Six electronic "energy summers" are used for each sector, along with two additional modules to make various sums of the six output signals. William Stephens designed and built a complete set of these modules for the CLAS detector and they have performed very well.

Mr. Stephens also designed and built splitters, amplifiers and summing circuits for the CLAS Cerenkov counters. Because the signals from the Cerenkov counters consist of

only a few photo-electrons, it was necessary to amplify the signal before splitting it so that one part could go to the ADC and TDC modules and the other part could be used in a summing scheme designed to provide a signal proportional to the total energy lost by an electron passing through the Cerenkov counter. This signal is passed to a discriminator, also part of his package, and then passed on to the CLAS Fast Trigger.

In addition, Mr. Stephens provided a approximately sixty 64 channel pulse splitters for the CLAS Cerenkov counters and time-of-flight counters.

Cosmic Ray Tests of CLAS Detectors

The first CLAS detector packages to be ready for installation were the forward angle Electromagnetic Shower Calorimeters (EGN) and Time-of-Flight (TOF) counters. An important pre-installation checkout activity was a full-scale integrated test of the TOF and EGN systems using cosmic-ray minimum ionizing muons to trigger the detectors. The purpose of the test program was to provide preliminary information on the performance of various components of all six EGN modules as each was completed.

The test configuration consisted of a layer of 22 of the CLAS forward angle TOF scintillator bars placed 0.5 m below the EGN module to provide a signal in coincidence with the EGN sector to show that cosmic muons have passed through the EGN module. The purpose of this test were to evaluate the performance of both the TOF and EGN systems, while at the same time exercising and debugging the slow controls, calibration, gain monitoring, event display and reconstruction software. Since the test setup ran for many months, we were also able to evaluate the reliability and failure rate of components, such as photomultiplier tubes, signal dividers, cables, electronic modules, etc. The specific performance goals of interest to our group were:

- Provide data to estimate the *insitu* effective attenuation lengths of EGN scintillators, in order to compare with measurements at UVA and CEBAF prior to installation in the EGN.
- Evaluate UVA designed and built summing amplifiers for linearity and summing noise, and determine EGN trigger uniformity and values for summing amp input weighting resistors.
- Evaluate UVA signal splitter boards for cross-talk, reliability and ground loop noise.

We spent considerable effort on installation of the FASTBUS, CAMAC and NIM electronics in the Test Lab at CEBAF, and on preparing the TOF and EGN detectors, cable trays and cable bundles. The UVA group also made specific contributions to software development, such as graphical user interfaces for the LeCroy 2313 and 4413 discriminators as well as graphical event display and calibration tools using the PAW and Tcl/Tk packages. Custom enhancements to CODA, the CEBAF On-line Data Acquisition package, such as BOS-bank readout of the event fragments and shared memory access to BOS banks and on-line histograms, were also made.

Specific results were:

- Effective algorithms were developed to gain-match the PMT's using the known energy deposited in the scintillator strips by minimum ionizing cosmic muons. These procedures

depend on data cuts which restrict tracks to those which pass through single pixels. Plots of pixel energy versus pixel distance from PMT can be used both to extract effective attenuation lengths for each scintillator stack viewed by the PMT, and to estimate through extrapolation the unattenuated pixel energy at the PMT.

- Through an iterative process, PMT gains can be matched to better than 5% using cosmic rays. This requires only a few (< 5) cycles of data taking and high voltage adjusting. We believe that ultimately 1% *hardware* gain matching can be achieved, although this may not be necessary for uniform trigger response.

- Gain stability is good, although the test duration for each sector was not sufficient to allow an estimate of long-term gain drift.

- Effective attenuation lengths derived during the gain matching procedure were in overall agreement with estimates based on actual measurements of individual strips prior to installation in the calorimeter. attenuation length is compared with the *insitu* result.

- Trigger uniformity was good, indicating the compensation built into the UVa summing amplifier to attenuate the signals from shorter scintillator stacks worked as expected. This was determined by examining the uniformity of the pixel event distributions. The distribution of events/pixel is expected to vary across the face of the calorimeter for two reasons: the angular distribution of cosmic rays goes as $\cos^2 \theta$, and the pixel stack solid angle goes as $\cos^3 \theta$ (due to the projective geometry). This leads to a $\cos^5 \theta$ dependence which is consistent with the measured distribution.

- Another measure of trigger uniformity is the pixel energy distribution. Here the expected variation in pixel energy with pixel location is due to attenuation corrections and a $\cos \theta$ path length correction. When the *insitu* attenuation corrections, together with the path length corrections were applied, the resulting pixel energy distribution was uniform to within 1%.

- Linearity of the summing amplifier was checked by comparing the observed low-energy cutoff in the total energy sum spectrum with the summing amplifier discriminator setting. The data verified that the summing amplifier provides a good approximation to the total energy sum in the calorimeter.

Software Development

Software development by university based user groups was identified by CEBAF as indispensable to the successful and on-time completion of the CLAS calibration and commissioning. Towards this goal we created at UVa a development site for CODA and EPICS, the slow-controls packages being used at CEBAF. We installed on our group's HP 715 Unix workstation both CODA and EPICS software packages, and made network connections to a CAMAC read-out controller for CODA development and a VME input-output controller for EPICS slow-controls development. This allowed applications to be developed at UVa which could then be down-loaded to CEBAF and tested. In addition we developed software needed in the online monitoring and analysis of calibration runs and for the reconstruction of the commissioning reactions used for calibrating the EGN detectors. We performed lengthy debugging and coding of GEANT simulations of the CLAS detector, particularly

those aspects relating to EGN cosmic-ray trigger efficiency, uniformity and PMT gain monitoring.

3-6. Activities at LEGS

L. C. Smith

After completion of the LAMPF experiment the time-of-flight nucleon detector apparatus was shipped to Brookhaven National Lab for use at the Laser Electron Gamma Source (LEGS) facility. This facility uses polarized high energy gamma photons to probe beam polarization observables in breakup reactions on few-body nuclei. The detector system is part of Virginia's contribution to the LEGS collaboration.

An experiment proposed by Rensselaer Polytechnic Institute and which concluded in September, 1991, measured photo-disintegration of ^3He over a large range of photon energies up to 300 MeV. This experiment was designed to measure the isospin dependence of both two- and three-body breakup modes and to measure the angular distributions of the photon asymmetry (Σ), which is the ratio of the difference to the sum of cross sections obtained with the photon's electric vector parallel and perpendicular to the reaction plane, will be compared to a just completed photo-disintegration measurement on the deuteron. Results from that experiment showed that (Σ) is sensitive to the short range behavior of the tensor interaction in models of the nuclear force. Comparisons between ^3He and deuterium should be particularly revealing in light of the difference in binding energy. The measurement required detection of both (pp) and (pn) pairs, which was done using an array of phoswich E- Δ E detectors on one side of the beam and on the other side a similar array of the sixteen pairs of neutron detector bars provided by Virginia.

These first measurements of exclusive nuclear photo-disintegration in ^3He with linearly polarized photons were reported at the Few Body XIV conference and in Physical Review Letters. Also, our collaboration published results from the inclusive part of this measurement in Physical Review Letters¹. Comparisons of the cross section data with calculations indicate the $^3\text{He}(\vec{\gamma}, pp)$ reaction is dominated by 3N mechanisms involving meson double scattering. The measured proton momentum dependence of the photon asymmetry observable Σ is in stronger agreement with the 3N calculation than is the angular distribution of Σ .

Another LEGS experiment proposed by RPI was conducted in October and November of 1991. This measured the reaction $D(\vec{\gamma}, pn)\pi^0$ to study the deviations from the predictions of the spectator nucleon model, particularly those caused by Δ N re-scattering. The creation and propagation of the Δ in nuclei is the only way to reach the Δ N interaction. The reaction $D(\vec{\gamma}, pn)\pi^0$ is particularly well suited to this purpose since π^0 photo-production proceeds mostly through the delta channel and the requirement of a π^0 in the final state

ensures that a delta has been formed. Also, theorists are able to calculate the multiple scattering series explicitly in the two nucleon system.

We conducted two LEGS experiments in collaboration with Ohio University and Virginia Polytechnic University. The first was a study of Δ photo-production in ^{16}O using the $(\vec{\gamma}, \pi^- p)$ reaction. Here the goal was to use the spin asymmetry Σ to study medium modifications of the Δ in the nucleus. The advantage of using polarization observables for these studies is that by taking cross section ratios, sensitivity to FSI uncertainties involving the choice of optical potential or spectroscopic factors is minimized. Also, this charge channel is much more sensitive to the basic pion photo-production process in nuclei than is (γ, π^+) , since the nucleons can remain in the ground state. The second was a measurement of the cross section and photon asymmetry for the $^{16}\text{O}(\vec{\gamma}, pp)$ reaction. In this experiment, the transverse structure functions f_{11} and f_{1-1} are measured in order to provide information on the effects of short-range nucleon-nucleon correlations in nuclei and the effects of Δ -isobar excitation in the intermediate state.

Preliminary results from the $(\vec{\gamma}, \pi^- p)$ measurement were presented at the SPIN 94 conference³ and have been subsequently published⁵. The data were compared to models which involved substantially fewer approximations compared to previous versions, with complete non-local momentum-space integrations of the full Blomqvist-Laget production operator. For momentum transfers q less than 200 MeV/c, where the harmonic wave functions used in the calculations are expected to be reliable, the spin asymmetry results are in good agreement with PWIA calculations. The data show slightly better agreement when a modified Δ mass is used. At larger q , the model does not follow the trend of the data. For this region, more advanced calculations using the Δ -hole model and Woods-Saxon wave functions will be tried.

Early results of the $(\vec{\gamma}, pp(n))$ measurement were presented at the Gent workshop⁴ and a more complete analysis has been submitted for publications⁶. Missing energy distributions of the (pp) final state showed more strength at large missing energy than for the (pn) final state, a possible indication of three-body contributions to this channel. Cuts on low missing energy were used to isolate two-body cross-sections and asymmetries, and the experiment was analyzed using symmetric kinematics. A simple prediction of most factorized models (such as due to Gottfried) is that absorption on s-wave pp pairs leads to a spin asymmetry of -1 in coplanar and symmetric kinematics. Although the LEGS data clearly show a more negative asymmetry for pp absorption compared to pn absorption, it is still far from -1. Comparison have been made to calculations by the Pavia and Gent groups. These are unfactorized models that do not restrict the motion of the nucleon pair to a relative S-state. The Pavia group uses single particle H-O wave functions and treats FSI with an optical potential, while the Gent calculation uses Hartree-Fock wave functions and treats FSI with a partial wave expansion that preserves orthogonality. The Gent model more accurately describes the shape of the missing mass distributions for both pn and pp absorption. However, it does less well in accounting for the asymmetry for pn absorption, and predicts substantially more negative asymmetry for pp absorption compared to the data. The Gent group has stated that deviation from -1 can result from photoabsorption

on P and D wave relative components.

As a member of the LEGS-Spin Collaboration, Cole Smith also took part in building the Plastic-Bar array of scintillator counters for SASY, the Spin Asymmetry Detector. This detector, along with the SPHICE H-D polarized target, will be used in experiments with a polarized photon beam to measure the helicity dependent photo-production cross sections and provide information on the nucleon's spin-dependent polarizability γ , and the spin-dependent part of the asymptotic forward Compton amplitude through the Drell-Hearn-Gerasimov (DHG) sum rule. These will be the first direct measurements of $\sigma_{1/2}$ and $\sigma_{3/2}$ for either the proton or the neutron, and will be measured from pion-threshold up to 470 MeV.

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4. Absorption of antiprotons in heavy nuclei.

LEAR Exp. at CERN

R.M. Marshall, B. Wright, and K.O.H. Ziock, with collaborators from the Technische Universität München, Germany.

In collaboration with a German group headed by Profs. v. Egidy and Daniel (T.U. Munich), several inclusive antiproton induced reactions were studied, e.g. the emission of charged particles He, Li, and Be ions, as well as $\bar{p}$ -induced fission, in carbon, gold, and uranium targets. The following publications resulted from this collaboration.

1. Hoffman *et al.*, Charged Particle Spectra from Antiproton Annihilation at Rest in $A=12$ to 238 Nuclei. Nucl. Phys. A 512, (1990) 669
2. T.v.Egidy *et al.*, "Nuclear Heating and Fission Induced by Antiproton Annihilation,"
3. T.v.Egidy *et al.*, "Antiproton Induced Fission and Fragmentation," 6th International Conference on Nuclear Reaction Mechanisms.
4. P. Bauman *et al.*, "Nuclear Excitation by Antiproton Annihilation at Rest," XXX International Winter Meeting on Nuclear Physics, Bormio (Italy), 1992.
5. MACHNER *et al.*, "Fission Fragment Distribution Following Antiproton Absorption at Rest on ^{235}U ," Zeitschrift für Physik A 343, (1992) 73-77.

5. Ph.D. Theses

1. " R_{LT} Response Function for $^{16}\text{O}(e,e'p)$ ", Leigh Michael Chinitz, University of Virginia, August, 1990.
2. "Measurement of the Spin Structure Function $g_2(x, Q^2)$ for the Proton and the Deuteron", Todd Denson Averett, University of Virginia, August 1995 (unpublished).

6. Talks

1. "Nucleon Resonance Program at CEBAF", R. Minehart, U. of South Carolina, Feb. 20, 1990.
2. " π d to 2p reaction." R. C. Minehart, Univ. of Va. seminar, Feb. 1991.
3. "Nucleon Structure Program at CLAS", R. C. Minehart, Invited talk given at the CLAS Working Group Meeting, April, 1991.
4. "Nucleon Structure Program at CLAS", R. C. Minehart, Duke University Seminar, April, 1992.

7. Presentations at Meetings

1. "Measurement of the Differential Cross Section for the $^2\text{H}(\gamma, p)n$ Reaction in the GeV Region", J. Napolitano /etal, Bull. Amer. Phys. Soc., **33**, 1098 (1988).
2. "Measurements of the transverse and Longitudinal Response Functions for ^{56}Fe at Q^2 near 1 $(\text{GeV}/c)^2$ ", J.P. Chen, L. Chinitz, D. Day, K. Giovanetti, J. S. McCarthy, R.C. Minehart, O. Rondon-Aramayo, R.M. Sealock, C. Smith, S.T. Thornton, Z.E. Meziani, G. Dodge, D. Beck, B. Goyd, B.W. Fillipone, J. Jourdan, R.D. McKeown, R.G. Milner, D. Potterveld, R. Walker, C. Woodward, L.C. Dennis, K.W. Kemper, W. Lorenzon, I. Sicke, J. Morgenstern, J. Mougey, Bull. Amer. Phys. Soc., **34**, 1811 (1989).
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