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Nuclear Structure and Reaction Studies at Medium Energies

Progress Report

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Preface

This document constitutes the 1988 - 1991 technical progress report for Special Research Grant DE-FG05-88ER40444.

The data, calculations, and other information presented here represent work in progress, are preliminary, and should not be quoted without the authors' permission.

Further information relating to the technical portions of this document may be obtained from Dr. G. W. Hoffmann, Department of Physics, The University of Texas at Austin, Austin, Texas 78712, telephone (512) 471-1769 or Bitnet: "HOFFMANN@UTAPHY".

Abstract

This document constitutes the (1988 - 1991) technical progress report for the ongoing medium energy nuclear physics research program supported by the U. S. Department of Energy through special Research Grant DE-FG05-88ER40444.

The experiments discussed are conducted at the Los Alamos National Laboratory's (LANL) Clinton P. Anderson Meson Physics Facility (LAMPF), the Alternating Gradient Synchrotron (AGS) facility of the Brookhaven National Laboratory (BNL), and at the Fermi National Accelerator Laboratory (FNAL).

The overall motivation for the work discussed in this document is driven by three main objectives: (1) provide hadron-nucleon and hadron-nucleus scattering data which serve to facilitate the study of effective two-body interactions, test (and possibly determine) nuclear structure, and help study reaction mechanisms and dynamics; (2) provide unique, first-of-a-kind "exploratory" hadron-nucleus scattering data in the hope that such data will lead to discovery of new phenomena and new physics; and (3) perform precision tests of fundamental interactions, such as rare decay searches, whose observation would imply fundamental new physics.

Contents

1	Introduction	6
2	Nucleon-Nucleon Experiments at LAMPF	7
2.1	EXP 928: Inclusive and Exclusive Quasielastic $\vec{p}+^2\text{H}$ Spin Observables at 647 and 800 MeV	7
2.2	EXP 1072: $p + p$ Elastic Absolute Cross Sections	11
3	Nucleon-Nucleus Experiments at LAMPF	12
3.1	Proton Elastic Scattering	12
3.1.1	EXP 955U: Polarized Proton Elastic Scattering from $^{12,13}\text{C}$ at 500 MeV	12
3.1.2	EXP 955: Polarized Proton Elastic Scattering from Polarized ^{13}C	17
3.1.3	EXP 1079: $p + A$ Precision Elastic Forward Angle Cross Sections	20
3.1.4	EXP 1119: $p + d$ Elastic Absolute Cross Sections	22
3.2	Proton Induced Inelastic Scattering and Reactions	24
3.2.1	EXP 626: Polarization Transfer for Inclusive Proton Nucleus Inelastic Scattering at 800 MeV	24
3.2.2	EXP 973: Search for Narrow Resonances in the $B = 2$ Missing Mass Spectrum from $p+^3\text{He}$ Reactions	27
3.2.3	EXP 1131: Measurement of Polarization Transfer for 800 MeV Inclusive Proton Scattering at the MRS	29
3.2.4	EXPS 1052, 1061, 1062: NTOF Calibration and (p, n) Charge Exchange Reactions at Medium Energies	31
4	Pion-Nucleus Experiments at LAMPF	34
4.1	EXP 1023: Analyzing Powers for Pion Charge Exchange on Polarized ^{13}C	34
4.2	EXP 1025: Pion Elastic/Inelastic Scattering from Polarized ^{13}C in the Energy Region of the $[3,3]$ Resonance	36
5	Experiments at Brookhaven National Laboratory	39
5.1	BNL EXP 781: Search for Radiative Transitions in the Hypernucleus $^{10}_{\Lambda}\text{B}$	39
5.2	BNL EXP 791: Search for $K_L^0 \rightarrow \mu e$, $K_L^0 \rightarrow ee$	41
6	Experiments at Fermilab	43
6.1	FNAL EXP 772: Study of the Nuclear Antiquark Sea Via $p+N \rightarrow \text{Dimuons}$	43
7	Polarized Nuclear Target Development Work	46

8	Theoretical Work	48
8.1	Spin-Flip Cross Sections for $^{13}\text{C}(\vec{p}, \vec{n})^{13}\text{N}(\text{g.s})$ at 500 MeV	48
8.2	Multiple Scattering Description of Intermediate Energy Deuteron-Nucleus Scattering	50
8.3	Coupled-Channels Dirac Equation Treatment of Large Angle $\vec{p} + ^{40}\text{Ca}$ at 500 MeV	53
8.4	Antisymmetrization Correction for Nucleon-Nucleus Elastic Scattering	57
8.5	Spin-One Kemmer-Duffin-Petiau Equation and Intermediate-Energy Deuteron-Nucleus Scattering	59
8.6	Effective Interactions for Nucleon-Nucleus Scattering Above 300 MeV	61
8.7	Analyzing Powers for $\vec{p} + ^{208}\text{Pb}$ at Large Momentum Transfers . . .	66
8.8	Comparison of Dirac and Schrödinger Descriptions of Spin Observables for Proton-Nucleus Elastic Scattering at 650 and 800 MeV . .	68
8.9	Nonrelativistic Density-Dependent Calculations for $\vec{p} + ^{13}\text{C}$	71
9	Publications (1988 - 1990)	73
9.1	Journal and Conference Proceedings in Print	73
9.2	Journal Articles Submitted for Publication	80
9.3	Abstracts	82
10	Copies of Publications (1990 - 1991)	85

1 Introduction

This document is a progress report for research projects in medium energy nuclear physics (MEP) supported by the U. S. Department of Energy's Three-Year Grant No. DE-FG05-88ER40444 with the University of Texas at Austin. University of Texas personnel associated with these projects for the 1988-1991 period (not inclusive) are G. W. Hoffmann (Professor); R. L. Ray, M. L. Barlett, and G. Pauletta (Research Scientists), J. McDonough (post-doc); D. E. Ciskowski, W. F. Kielhorn, M. J. Purcell, D. E. Read, S. D. Worm, A. R. Smith (Graduate Students), and S. Z. Mujtaba (undergraduate student). Dr. Ciskowski received his Ph.D in 1989, while W. Kielhorn and M. Purcell should receive their Ph.D's in January 1991. Dr. Pauletta left our group to take a tenured faculty position at The University of Udine in Italy. Dr. Barlett is now a staff member at the University of Texas's Applied Research Laboratory at the Balcones Research Center.

The overall motivation for our MEP research program is driven by three main objectives. The first is to provide hadron-nucleon and hadron-nucleus scattering data which serve to facilitate the study of effective two-body interactions, test (and possibly determine) nuclear structure, and help study reaction mechanisms and dynamics. We have adopted the pragmatic philosophy that experiment and theory must merge in this effort in order that significant progress be made. For this reason substantial effort has gone into providing strong theoretical support of the experimental program. Another objective of the program is to provide unique, first-of-a-kind, "exploratory" hadron-nucleus scattering data in the hope that such data will lead to discovery of new phenomena and new physics and stimulate further theoretical work. Most of the above research is associated with experiments done at the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF).

Finally, with the realization that the study of fundamental interactions has come to be regarded as forming a vital branch of research in medium energy physics, we have expanded our program to include experiments which provide stringent tests of the Minimal Standard Model (MSM) and in this way probe for physics beyond the Standard Model. Specifically our work in this area involves an experiment at the Brookhaven National Laboratory which searches for previously unobserved and "forbidden" neutral kaon decay.

Our group has authored 43 refereed journal articles, 16 published conference proceedings, and 25 abstracts during the 1988-1991 research period.

The material contained in this document summarizes the highlights of our 1988-1991 efforts with emphasis given to the more recent (1990-1991) work.

2 Nucleon-Nucleon Experiments at LAMPF

2.1 EXP 928: Inclusive and Exclusive Quasielastic $\bar{p}+^2\text{H}$ Spin Observables at 647 and 800 MeV

(M. L. Barlett, G. W. Hoffmann, L. Ray, G. Pauletta; LANL; Rutgers; UCLA; M. L. Barlett, G. W. Hoffmann, J. B. McClelland, spokesmen)

A longstanding goal of the nucleon-nucleon (NN) program at LAMPF has been to provide sufficient data to allow for an accurate determination of the $I = 0, 1$ phases up to an energy of 1 GeV (laboratory). Presently, the $I = 1$ phases are fairly well-determined, but the $I = 0$ phases are still uncertain above 500 MeV.

Over the years we have performed a number of quasielastic experiments on deuterium in order to provide quasi-free pn data to aid the phase shift solutions, particularly at small momentum transfers ($q \leq 2 \text{ fm}^{-1}$). In EXP 928 inclusive and exclusive pp and pn quasielastic data for $\bar{p}+^2\text{H}$ were taken at 647 and 800 MeV. The experiment measured analyzing powers (A_y) and spin-rotation depolarization parameters (D_{ij}). The results are discussed in detail in Ref. 1. The experiment was done at the external proton beam (EPB) area at LAMPF using a liquid deuterium target, the SCYLLA low-resolution spectrometer, and the JANUS polarimeter. A recoil particle detector system allowed exclusive measurements to be made.

The exclusive data were compared with previous, free NN scattering data and with phase shift predictions² and were found to be in very good agreement with each. The inclusive data, shown in Figs. 1-3, are well described by a simple isospin weighting model. This model assumes that the inclusive quasielastic spin-dependent differential cross sections are proportional to the sum of the exclusive pp and pn quasielastic spin-dependent differential cross sections. From this it follows that the inclusive quasielastic spin observable X_I can be expressed as

$$X_I = \frac{\sigma_{pp}^{ex}}{\sigma_{pp}^{ex} + \sigma_{pn}^{ex}} X_{pp}^{ex} + \frac{\sigma_{pn}^{ex}}{\sigma_{pp}^{ex} + \sigma_{pn}^{ex}} X_{pn}^{ex}, \quad (1)$$

where $\sigma_{pp}^{ex}(\sigma_{pn}^{ex})$ is the exclusive pp (pn) differential cross section at the appropriate angle and $X_{pp}^{ex}(X_{pn}^{ex})$ is the exclusive quasielastic pp (pn) spin observable corresponding to X_I . One can see that if X_I , X_{pp}^{ex} , and $\sigma_{pp}^{ex}/\sigma_{pn}^{ex}$ are known, then X_{pn}^{ex} may be calculated. The model was tested by using the above equation together with SP87 NN observables² to predict the $\bar{p}+^2\text{H}$ inclusive quasielastic analyzing power and D_{ij} . The results are shown in Figs. 1-3 by the solid curves which are seen to be in very good agreement with the data.

Based on this success the model was then used to extract exclusive pn D_{ij} observables from the inclusive data. The results at 800 and 647 MeV are shown in Figs. 4 and 5, respectively, in comparison with previous data at 800 MeV at forward angles (crosses) and with SP87 phase shift predictions (solid curves).² These pn

observables are consistent with previous data but differ quantitatively from the phase shift predictions, particularly D_{NN} and D_{LS} . At 647 MeV the phase shift analysis² reproduces the overall magnitudes of the deduced observables. These results lend support to the belief that the $I = 0$ NN phases above 500 MeV need improvement.

In addition to providing new data and testing the quasielastic method this work shows that the isospin weighting model provides an expedient means for studying pn elastic scattering in that only one-arm, inclusive quasielastic measurements are needed in order to extract pn observables. Such work is vital to the NN program as long as an insufficient amount of free pn data exist.

References

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Figure Captions

Figure 1. The 800 and 647 MeV inclusive analyzing power for $\bar{p}+^2\text{H}$. The curves are from the isospin weighting model.

Figure 2. The 800 MeV inclusive spin-rotation-depolarization parameters for $\bar{p}+^2\text{H}$. The curves are from the isospin weighting model.

Figure 3. Same as Fig. 2 except 647 MeV.

Figure 4. The 800 MeV exclusive (pn) spin-rotation-depolarization parameters deduced using the isospin weighting model are compared with previous data (crosses) and predictions of phase shift analysis.

Figure 5. Same as Fig. 4 except 647 MeV.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

2.2 EXP 1072: $p + p$ Elastic Absolute Cross Sections

(M. L. Barlett; LANL; UCLA; Rice; Rutgers; Texas A&M;
M. McNaughton, spokesman)

One objective of the nucleon-nucleon program at LAMPF is to provide a complete set of elastic data for the $p + p$ and $n + p$ systems between laboratory energies 500 - 800 MeV. The goal is that these data be used to determine the nucleon-nucleon (NN) phase shifts through careful phase-shift analysis.

Over the past 15 years most of the experimental effort for $p + p$ has gone into "spin-observable" measurements, and little attention has been given to providing the best possible cross section data. The typical quoted errors for the "best" $p + p$ cross sections are $\pm (5-10)\%$. However, it is bilinear combinations of the scattering amplitudes which are equal to products of spin-observables and the differential cross sections that are fit in the phase shift analyses. An example is the expression for the spin-depolarization parameter D_{NN} :

$$\frac{d\sigma}{d\Omega}(\theta) D_{NN}(\theta) = \frac{1}{2} [|a|^2 + |b|^2 - |c|^2 - |d|^2 + |e|^2 + |f|^2], \quad (2)$$

where a, b, c, d, e, f are the $p + p$ scattering amplitudes as defined by Bystricky and Lehar¹. Thus, knowledge of the $p + p$ amplitudes may be limited by the accuracy of the available cross section data and not that of the spin-observable data. The elastic cross section data also provide important constraints on inelasticities through the reaction cross section. Additionally, more accurate $p + p$ cross section data are desirable because many intermediate energy proton-nucleus experiments have established absolute normalizations with respect to measured $p + p$ elastic differential cross sections.

Driven by the above motivation, the experiment measured absolute differential cross sections over the center-of-momentum angular range $15^\circ - 90^\circ$ at incident laboratory energies 500, 580, 650, 733, and 800 MeV. A novel beam counting technique was developed to count beam particles individually with the 5 ns LAMPF accelerator microstructure.² The final state protons were detected in coincidence, with position and angle information recorded for both protons. Redundant sets of wire chambers (a total of 10 XY pairs) and four banks of scintillators provided overall detector efficiency greater than 99%. Data analysis is still underway, but preliminary results indicate that the differential cross sections are determined to $\pm 1\%$.

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3 Nucleon-Nucleus Experiments at LAMPF

3.1 Proton Elastic Scattering

3.1.1 EXP 955U: Polarized Proton Elastic Scattering from $^{12,13}\text{C}$ at 500 MeV

(G. W. Hoffmann, M. L. Barlett, D. Ciskowski, G. Pauletta, M. Purcell,
L. Ray; LANL; Minnesota; ASU; OSU;
G. W. Hoffmann, M. L. Barlett, spokesmen)

For more than a decade, experiments with proton beams have provided a variety of data which have been used to test models of nucleon + nucleus elastic scattering at intermediate energies. Analyzing powers, A_y , and spin-rotation-depolarization observables, D_{ij} , measured with polarized beams have been particularly useful in guiding theoretical development. Even today, the study of spin dependence in the scattering process continues to be an important part of medium energy nuclear physics research. Indeed, during the last few years much work has gone into development of polarized nuclear targets for use in scattering experiments. The intent is clearly to introduce a new degree of freedom, that of target polarization, into the scattering problem. For example, the first phase of EXP 955, $\vec{p} + ^{13}\text{C}$ at 497.5 MeV has provided A_{pion} and A_{nn} data. In order to analyze these new data, it is necessary to measure the other scattering observables from both the ^{12}C core and ^{13}C at the same energy. The $\vec{p} + ^{12}\text{C}$ data enable determination of phenomenological representations of the twelve nucleon "core" scattering amplitudes and distorted waves that are required in distorted wave Born approximation (DWBA) calculations for $\vec{p} + ^{13}\text{C}$ elastic scattering. The measured ratio of the ^{13}C to ^{12}C differential cross sections can be used to constrain models of the ^{13}C valence neutron wave function.

A complete set of $\vec{p} + ^{12}\text{C}$ elastic scattering measurements is interesting for other reasons. Such data provide a means for testing certain aspects of relativistic and nonrelativistic models of the scattering process, as well as for studying medium effects, nuclear structure models, and multistep processes. They also allow empirical determination of important components of the nucleon-nucleon (NN) effective interaction. Similar comments apply for $\vec{p} + ^{13}\text{C}$. The $\vec{p} + ^{13}\text{C}$ $d\sigma/d\Omega$ and A_y data also serve as benchmarks for the more difficult $\vec{p} + ^{13}\text{C}$ experiment. Studies of D_{NN} focus attention on important $\Delta J = 1$ contributions to the $\vec{p} + ^{13}\text{C}$ elastic scattering amplitude. When these transitions occur, D_{NN} becomes less than unity, and the spin-flip probability, given by $(1/2)(1 - D_{NN})$, is non-zero.

The data¹ were taken at LAMPF with the high resolution spectrometer (HRS) and its focal plane polarimeter (FPP). The data (and curves to be discussed) are shown in Figs. 1-3. Except at the largest angles, statistical errors are typically $\pm 1\%$ for the cross sections $\pm (0.01 - 0.02)$ for A_y , and $\pm (0.03 - 0.05)$ for D_{ij} . For

the $d\sigma/d\Omega$ and A_y data the systematic errors are small $\leq \pm 2\%$; for the D_{ij} data, the systematic uncertainties in D_{SL} and D_{SS} are $\leq \pm 0.02$, while those for D_{NN} are $\leq \pm 0.04$. The $^{13}\text{C}/^{12}\text{C}$ differential cross section ratios versus momentum transfer are plotted in Fig. 4, along with curves to be discussed.

In Figs. 1-3 the dashed curves (standard RIA-DWBA) are results from the relativistic impulse approximation (RIA) - Dirac equation model for ^{12}C and the relativistic DWBA model for ^{13}C (Ref. 2). The solid curves result from a Dirac optical model fit to the $\bar{p} + ^{12}\text{C}$ data and a $\bar{p} + ^{13}\text{C}$ relativistic DWBA calculation that uses the scattering amplitudes and distorted waves from the optical model fit. The improvement over the standard RIA-DWBA prediction is a direct consequence of using a phenomenological model which accurately reproduces the $\bar{p} + ^{12}\text{C}$ data. To observe effects due to the 13^{th} nucleon, with proton elastic scattering from an unpolarized ^{13}C target, the quantity D_{NN} and the small differences between the ^{13}C and ^{12}C observables, must be studied. The amount by which D_{NN} differs from unity is determined by a few of the $\Delta J = 1$ components of the NN effective interaction along with the valence nucleon wave function. The $^{13}\text{C}/^{12}\text{C}$ cross section ratio primarily depends upon the $\Delta J = 0$ components of the NN amplitudes and is particularly sensitive to the large, upper component of the valence nucleon wave function. In Fig. 16 of Ref. 2, a variety of RIA-DWBA D_{NN} predictions are shown for 500 MeV $\bar{p} + ^{13}\text{C}$. Two of these are compared with the new data in the upper half of Fig. 3; the standard RIA-DWBA result is indicated by the dashed curve; the solid curve also represents a RIA-DWBA result, except that the pseudovector form of the NN invariant amplitude was used, and the isoscalar three-vector current was suppressed.² The two curves shown in the lower half of the figure correspond to those in the upper half, except that the phenomenological ^{12}C distorted waves and scattering amplitudes were used instead. None of the four results fit the data very well. In Fig. 4, the $^{13}\text{C}/^{12}\text{C}$ $d\sigma/d\Omega$ ratio is compared with two model predictions. The ratio, (^{13}C relativistic DWBA $d\sigma/d\Omega$ using phenomenological distorted waves and core amplitudes)/(the Dirac phenomenological ^{12}C $d\sigma/d\Omega$) is indicated by the solid line. The dashed curve results from using the Dirac optical potential to calculate both the ^{12}C and ^{13}C cross sections, where in both cases the radii were scaled by $A^{1/3}$. The majority of the structure in the $^{13}\text{C}/^{12}\text{C}$ ratio results from the overall $A^{1/3}$ scaling of the nuclear size. The amount of sensitivity to different forms for the $^{13}\text{C} - ^{12}\text{C}$ nuclear structure difference is indicated by the small differences among the two curves and the data.

The new elastic scattering data for 500 MeV $\bar{p} + ^{12,13}\text{C}$ are described qualitatively with the microscopic RIA - Dirac equation model; quantitative fits are obtained with empirical potentials. The measured spin-flip probability does not agree in detail with any of the theoretical predictions shown here or in Ref. 2. However, the D_{NN} data are far from conclusive and more measurements of this quantity are needed, as are continued improvements in the theoretical model. Finally, the $^{13}\text{C}/^{12}\text{C}$ differential cross section ratio is fit reasonably well with the relativistic DWBA model; this ratio is sensitive to the $^{13}\text{C} - ^{12}\text{C}$ structure difference and can

be used to constrain the nuclear structure model used in analyses of $\vec{p} + {}^{13}\text{C}$ elastic scattering data.

References

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Figure Captions

Figure 1. Elastic differential cross section, analyzing power, and spin-rotation data, and results of calculations, for 500 MeV $\vec{p} + {}^{12}\text{C}$. The solid and dashed curves are Dirac optical model fits and RIA - Dirac equation model predictions, respectively.

Figure 2. Elastic differential cross section, analyzing power, and spin-rotation data, and results of calculations, for 500 MeV $\vec{p} + {}^{13}\text{C}$. The solid and dashed curves are relativistic DWBA results based on Dirac phenomenology and the RIA optical potentials for ${}^{12}\text{C}$, respectively, that were used to compute the twelve nucleon core scattering amplitude and relativistic distorted waves.

Figure 3. Data and RIA results for the spin-depolarization observable D_{NN} for 500 MeV $\vec{p} + {}^{13}\text{C}$ elastic scattering. The solid and dashed curves are the relativistic DWBA results when the pseudovector and pseudoscalar forms for the Lorentz invariant NN amplitude¹ are used, respectively. The curves in the upper (lower) half of the figure correspond to use of the RIA (Dirac phenomenological) ${}^{12}\text{C}$ optical potential to compute the core scattering amplitudes and distorted waves.

Figure 4. Ratio of ${}^{13}\text{C}$ to ${}^{12}\text{C}$ elastic differential cross sections as a function of momentum transfer. The errors in the data include statistical uncertainties only. The solid and dashed curves are relativistic DWBA and Dirac optical model results, respectively.

Figure 1

Figure 3

Figure 4

3.1.2 EXP 955: Polarized Proton Elastic Scattering from Polarized ^{13}C

(G. W. Hoffmann, M. L. Barlett, W. Kielhorn, G. Pauletta, M. Purcell,
L. Ray; LANL; NMSU; Minnesota; ASU; OSU; IBM;
G. W. Hoffmann, R. L. Ray, M. L. Barlett, J. Jarmer, spokesmen)

The medium energy proton-nucleus scattering data taken over the last 20 years for even-even target nuclei have stimulated calculations of density-dependent nucleon-nucleon (NN) effective interactions from a few MeV to ~ 1 GeV, investigations of off-shell and full-folding effects in the proton-nucleus optical potential, studies of ground state matter densities and matter transition densities for collective excitations, and development of the relativistic impulse approximation (RIA), based on the Dirac equation.

However, studies of elastic and inelastic (collective) scattering for $J^\pi=0^+$ targets are sensitive mainly to just the no-spin and no-isospin transfer components of the NN interaction and the isoscalar, one-body densities of the target. Other types of reactions can be studied to investigate the spin and/or isospin transfer components of the NN interaction and the single particle aspects of nuclear structure. These reactions include non-natural-parity inelastic excitations and charge-exchange processes. Another possibility is proton elastic scattering from polarized, odd-mass nuclear targets. We performed the first such experiment at medium energies: a measurement of the target analyzing power A_{oon} (Ref. 1) and the spin-correlation parameter A_{oonn} (Ref. 1) for $\vec{p} + ^{13}\text{C}$ at 497.5 MeV.²

The data were taken at LAMPF with the high resolution spectrometer (HRS). The target nuclei, ^{13}C and ^1H , were polarized by using the dynamic nuclear polarization (DNP) technique. A single coil provided both the ^{13}C and ^1H nuclear magnetic resonance (NMR) signals, which were used to determine the ^{13}C and ^1H polarizations for the entire target material. The hydrogen polarization of the target was also measured by using a target polarimeter which monitored $\vec{p} + \vec{p}$ elastic scattering at $\theta_{\text{c.m.}} = 46^\circ$, and relied upon the known values of $A_y = A_{\text{oon}}$ and A_{oonn} for 500 MeV $\vec{p} + \vec{p}$. The HRS was used to momentum analyze the scattered protons and generate missing mass spectra.

Data were taken between laboratory angles $12^\circ - 30^\circ$ in about $1.5^\circ - 2.0^\circ$ steps for the ^{13}C target and also for an empty target cell (to enable background corrections) and a thin, unpolarized $^{13}\text{C}_2\text{H}_6\text{O}_2$ target (the ethylene glycol was sandwiched between two thin Be foils separated by 1 mm) to allow accurate determination of the $^{13}\text{C}/^{16}\text{O}$ cross section ratios. The data from the dummy target and the thin ^{13}C target were crucial to the experiment because the ^{13}C and ^{16}O elastic peaks were not well-resolved except at the larger angles.

Small differences in the magnitudes of the beam polarization for normal and reverse directions and differences in the target polarization magnitudes for target "up" and target "down" runs were accounted for during data reduction.

The results for A_{oon} and A_{oonn} are shown in Fig. 1 along with theoretical

predictions. The errors shown account for all sources of statistical uncertainty; the measured yields dominated. Systematic errors in the beam and target polarizations are estimated to be small. Both data sets are smooth with respect to their angular distributions and display structure in the angular regions near the minima in the differential cross section (18.5° and 34.5° in the COM) as expected.

The theoretical results for A_{oovon} and A_{oonn} shown in Fig. 1 were computed in the distorted wave Born approximation (DWBA) for both the RIA model and the nonrelativistic impulse approximation (NRIA) model. For both calculations the ^{13}C wave function was assumed to be a pure $1p_{1/2}$ neutron single particle state coupled to an inert ^{12}C "core," and the scattering amplitude, corresponding to the twelve-nucleon core, was obtained from a Dirac phenomenological optical model fit to the EXP 955U 500 MeV $\vec{p} + ^{12}\text{C}$ elastic scattering data. The NN t matrices (in both the RIA and NRIA forms) in the proton-nucleus Breit frame were generated from the SP82 NN phase shift solution.

For the RIA-DWBA calculations the NN Lorentz invariant amplitudes were assumed to be given by the local McNeil-Ray-Wallace form. The valence neutron wave function was taken to be the $1p_{1/2}$ eigenstate of the relativistic mean field (RMF) scalar and time-like vector binding potentials for ^{12}C . The relativistic distorted waves were obtained through solution of the Dirac equation for $\vec{p} + ^{12}\text{C}$ elastic scattering by using the Dirac phenomenological optical potential. The results are indicated in the figure by the solid curves. RIA-DWBA calculations were also done in which the relativistic enhancement of the lower component of the $1p_{1/2}$ valence neutron wave function was suppressed, thus reducing its strength to the nonrelativistic limit. These results are shown by the dashed curves. Other calculations were made with a pseudovector, rather than pseudoscalar, form for the NN invariant amplitude, and with the twelve-nucleon core contribution to the isoscalar, three-vector current included. Both of these results lie between the solid and dashed curves in the figure.

For the NRIA - DWBA calculations the full NN t matrix in the proton-nucleus Breit frame was used. Direct and exchange contributions were included, and the amplitudes were taken to be functions of momentum transfer only. The NR distorted waves were generated by solving the Schrödinger equation with relativistic kinematics by using the Schrödinger equivalent potential of the Dirac phenomenological optical potential for $\vec{p} + ^{12}\text{C}$. The valence neutron wave function was assumed to be the (properly normalized) upper component of the RMF $1p_{1/2}$ eigenstate. The NRIA-DWBA predictions are shown by the dashed-dotted curves in the figure.

Each of the calculations qualitatively describes the data for both observables, although all are lacking in necessary structure in the region from 15° - 25° c.m. Compared to the discrepancies between theory and data, the differences between the two RIA - DWBA predictions are small as are the differences between the RIA- and NRIA - DWBA predictions.

The results reported here for $\vec{p} + ^{13}\text{C}$ at 500 MeV show that such experiments are difficult, but possible, and that quality data can be obtained. These new types of

scattering data are qualitatively explained by current theoretical models, but further improvements will evidently be necessary before quantitative understanding can be achieved.

References

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Figure Caption

Figure 1. Experimental data and theoretical predictions for $\vec{p} + {}^{13}\vec{\text{C}}$ target spin observables A_{000N} (upper portion) and A_{00NN} (lower portion) at 497.5 MeV. The RIA-DWBA predictions assuming the RMF (nonrelativistic) value for the valence neutron lower component wave function are indicated by the solid (dashed) curves. The NRIA-DWBA predictions are given by the dashed-dotted curves.

3.1.3 EXP 1079: $p + A$ Precision Elastic Forward Angle Cross Sections

(G. W. Hoffmann, M. L. Barlett, G. Pauletta, L. Ray, D. Read
S. Worm, A. Smith, M. Purcell, Z. Mujtaba; LANL; Texas A&M;
G. W. Hoffmann, N. Tanaka, J. F. Amann, spokesmen)

A comparison of observables predicted by scattering models which use either relativistic (RIA) or nonrelativistic (NR) dynamics indicates¹ significant differences in the magnitudes of the 500-800 MeV $p + {}^{16}\text{O}$, ${}^{40}\text{Ca}$, ${}^{208}\text{Pb}$ differential cross sections in the forward-angle, Coulomb-nuclear interference region (see Fig. 1). At 500 MeV some of the differences are 15-25%. This result is stable with regard to uncertainties in the theoretical calculations ($\pm 2-6\%$) including medium effects, and suggests that techniques be developed to perform the required experiment to test the various models. It has also been pointed out that precise cross section data in the Coulomb-nuclear region would set important constraints on relativistic models of the virtual pair process and the scalar densities of the target nucleus. Once developed, the techniques could also be used to renormalize to the level of 1% the vast quantity of $p + A$ elastic scattering data that has been taken at LAMPF over the past 15 years. Such accuracy is particularly useful for nuclear structure studies.

The first phase of EXP 1079 was the development of the techniques required for a 1% experiment. Of particular importance are accurate integrated beam flux determination (0.5%), precise polar scattering angle determination (0.001°), and accurate solid angle determination (0.1%).

We have had two development runs in which we have commissioned the new HRS Faraday cup, a high gain (xenon-ethane 600 mm Hg) ion chamber, the EXP 1072 beam counting scintillator telescope as modified for this experiment, and the new Line C inductive pickup coil (LCCM). We have been able to show that with care there is sufficient overlap in the beam intensity regions over which these devices operate that together they can redundantly determine beam current over the range from $10^4/\text{s}$ to several nA with better than 1% absolute accuracy.

We have demonstrated that the solid angle can be determined to the 0.1% level using brass slits of aperture 10% of the HRS acceptance. Slit edge scattering was demonstrated to have negligible effect on the solid angle defined by the aperture (note that medium energy protons that go through the slit material lose about 10 MeV so that they are shifted in the missing-mass spectrum generated by the HRS; nominal HRS resolution is 100 keV).

Small wire chambers, for use in the HRS scattering chamber, have been designed and are under construction. They will be used for tuning the zero-phase-space pencil beam and determining the spatial coordinates of the beam optic axis to about 50 microns, allowing a very precise determination of the absolute polar scattering angle.

We have developed the tools required to perform production runs, and will ask

for production time at the January, 1991 PAC meeting.

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Figure Caption

Figure 1. Uncertainty bands for the forward angle differential cross sections for 500 MeV $p + {}^{40}\text{Ca}$ and ${}^{208}\text{Pb}$ from the standard NRIA (shaded bands between dashed curves) and RIA (shaded bands between the solid curves), from Ref. 1.

3.1.4 EXP 1119: $p + d$ Elastic Absolute Cross Sections

(M. L. Barlett; LANL; UCLA; Rice; Rutgers; Texas A&M;
M. McNaughton, spokesman)

Since the $p + d$ system is one of the simplest many-body systems, the study of $p + d$ elastic scattering at intermediate energies may be a possible way to test some fundamental aspects of hadron - nucleus scattering models. For example, the data may be useful in determining the role played by 3-body forces in the nuclear medium. A complete set of scattering observables is desirable for the most rigorous tests. Among the possible observables that can be measured, the unpolarized differential cross sections play an essential role in determining the overall scale of the amplitudes, because bilinear combinations of the scattering amplitudes are expressed in terms of spin-observables times the unpolarized differential cross sections. Thus, the accuracy of the differential cross section data directly affects the interpretation of the spin-observable data. Particularly desirable, is quality data near 800 MeV, an energy where considerable $p + d$ spin-observable data exist¹ and an energy where some of the available cross section data² have been questioned.

The experiment,³ performed at LAMPF, took advantage of the apparatus developed for EXP 1072, the $p + p$ absolute differential cross section experiment. A liquid deuterium target was used, and data were taken at beam energies (center of target) of 641.3 MeV and 792.7 MeV. As in EXP 1072 both scattered and recoil particles were detected with a redundant detection scheme that allowed precise efficiencies to be determined. The integrated beam flux was also determined as in EXP 1072 using a 3-counter scintillator telescope in the beam upstream of the target to directly count beam particles. An elaborate electronic timing scheme plus the use of Poisson statistics made it possible to correct for more than one beam particle in any given rf micropulse.

The new data³ are shown in Fig. 1, together with the 800 MeV data of Winkelmann². Typical uncertainties in these new data are 2-3% (absolute). Using these new data we have been able to resolve the controversy concerning the older data set². The problem seems to be that the inverse of the correct Jacobian was used in transforming the data between the laboratory and the center-of-momentum coordinate system. The new data obtained in EXP 1119 should be useful for the continued theoretical study of the intermediate energy $p + d$ elastic scattering process.

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Figure Caption

Figure 1. Center-of-momentum cross sections as a function of center-of-momentum scattering angle for 641.3 and 792.7 MeV $p + d$ elastic scattering.

3.2 Proton Induced Inelastic Scattering and Reactions

3.2.1 EXP 626: Polarization Transfer for Inclusive Proton Nucleus Inelastic Scattering at 800 MeV

(M. Barlett, G. Hoffmann, J. Marshall; Rutgers; Institute for Atomic Energy, Beijing, China; LANL; C. Glashauser, J. McGill, spokesmen)

The high-excitation energy response of the nucleus to medium energy probes has been the subject of considerable interest. A fundamental question is whether the nuclear response in this region is close to that of a noninteracting gas of fermions or whether there are specific many-body effects that are important even at high-excitation energies. If a Fermi gas picture is valid and distortions and Fermi-motion effects are small, then spin-observables such as the analyzing power A_y or the polarization-transfer coefficients D_{ij} for inelastic proton scattering should be very close to the values for nucleon-nucleon (NN) scattering. Deviations from the Fermi gas predictions could result, for example, from nuclear structure effects like dynamical correlations which persist even at high-excitation energy. Another medium effect is suggested by applications of the Dirac equation to the description of nuclear structure and reactions. Calculations indicate that many of these effects are most easily seen in the behavior of spin observables in scattering experiments.

We have measured¹ all of the parity allowed polarization-transfer coefficients ($D_{NN}, D_{SS}, D_{LL}, D_{LS}, D_{SL}$) for inclusive 800 MeV proton scattering from ^1H , ^2H , and ^{12}C . The data were taken at laboratory scattering angles of 5° , 11° , and 20° , and cover the excitation energy range from the quasielastic region (elastic scattering from ^1H) to the delta region. These data comprise a survey of spin observables in this region which complement the earlier cross section and analyzing power data taken in EXP 642.²

The data are shown in Figs. 1-5, where they are plotted as a function of energy loss ω . The arrows marked "N" in each figure indicate the energy loss corresponding to free $p + ^1\text{H}$ scattering at each angle. The arrows marked π indicate the energy loss corresponding to an excitation of 300 MeV in the $p + ^1\text{H}$ system—enough to excite the center of the first delta resonance. The curves on the ^1H plots are unitary model predictions.³ The solid curves on the ^{12}C data in the quasielastic and dip regions are nonrelativistic slab model calculations.⁴ Relativistic plane wave impulse approximation predictions are shown as the dashed curves.⁵

The data for each observable at each angle show great similarity for the three targets. There are no dramatic differences which would provide clear evidence of strong medium effects on any observable. The differences that do exist are seldom greater than about two standard deviations and they show few systematic trends.

The theoretical curves for ^{12}C in the quasielastic region are in qualitative agreement with the data; only small differences between the relativistic and nonrelativistic calculations are specifically due to relativity. The two sets of theoretical

predictions contain different nuclear ingredients, yet the net effect of these differences is small. The remaining discrepancies that are apparent in the comparison of theory and experiment in a few regions are interesting and deserve further investigation.

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Figure Captions

Figures 1-5. Measured values of the polarization transfer observables D_{ij} for inclusive proton scattering at 800 MeV for the targets and scattering angles noted. The curves are from Refs. 3-5.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

3.2.2 EXP 973: Search for Narrow Resonances in the $B = 2$ Missing Mass Spectrum from $p+{}^3\text{He}$ Reactions

(M. L. Barlett, D. Ciskowski, G. W. Hoffmann, G. Pauletta, M. Purcell; Udine; Minnesota; LANL; Virginia; M. Gazzaly, G. Pauletta, N. Tanaka, spokesmen)

Reports of narrow ($\Gamma_{1/2} \leq 50$ MeV) structure in the $B = 2$ missing mass spectra have attracted considerable interest in the past few years.¹ Prominent among these are the $I(\text{isospin}) = 1$ structures seen in the ${}^3\text{He}(p,d)X$ reaction. Excitation functions for this reaction, measured at Saclay, have shown evidence of narrow structures at several energies and the credibility of these measurements is enhanced by agreement between these energies and resonance energies predicted by a rotation model based on a virtual $NN\pi$ bound state.² Other structures, reported to occur in a variety of reactions, appear to be well accommodated by this model.

The purpose of EXP 973 was to corroborate the Saclay results, by measuring both the differential cross section and analyzing power using the HRS at LAMPF. These were measured at a deuteron scattering angle of 22° (lab) at an incident proton momentum of 1.46 GeV/c. The data from this experiment are shown in Figs. 1-2 (from Ref. 1). In Fig. 1 differential cross section measurements from this experiment (solid dots) are compared with data from Saclay taken at 1.4 GeV/c (crosses). In Fig. 2 analyzing power data obtained in this experiment are shown both before (upper part) and after (lower part) dummy target background subtractions were made. The curves through the data are fits using sums of gaussians. The vertical lines in both figures correspond to predicted resonance energies.² The vertical arrows correspond to the energies at which possible structures were observed at Saclay. The possibility of structure is clearer in the missing mass spectra of the analyzing power. All but one of the maxima in the data correspond to resonance energies predicted in our range of missing mass. Interpretation of the data is not unambiguous due to the narrow range covered in missing mass and because of the lack of theoretical predictions for the behavior of the analyzing power near the resonances. These results do, however, provide ample incentive for more measurements with better statistics over a wider range of missing mass. Further experimental runs to accomplish this are planned.

References

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Figure Captions

Figure 1. Differential cross sections for the reaction ${}^3\text{He}(\vec{p}, d)X$ from this experiment (solid dots) are compared with Saclay data (crosses).

Figure 2. Analyzing power data from this experiment before (upper part) and after (lower part) subtracting dummy target backgrounds.

Figure 1

Figure 2

3.2.3 EXP 1131: Measurement of Polarization Transfer for 800 MeV Inclusive Proton Scattering at the MRS

(G. Hoffmann, D. Read, S. Worm, A. Smith, Z. Mujtaba; Rutgers; LANL; Georgia; Orsay; C. Glashauser, G. W. Hoffmann, K. Jones, spokesmen)

See the discussion concerning EXP 626 for the motivation for (p, p') experiments to probe the high excitation energy response of the nucleus at medium energies. EXP 626 was done with the high resolution spectrometer (HRS), and because of time limitations and intrinsic constraints from spin precession in the HRS dipoles, the data have relatively large statistical errors and have a number of gaps for various observables at different outgoing proton energies. These data do not have the statistical accuracy to distinguish small but possibly significant effects of the nuclear medium on various spin observables, and the gaps and poor statistics in the data for some observables in some energy-loss regions make it difficult to discuss trends. The fact that each data point represents a particular magnetic field setting also might contribute to small systematic errors from one setting to the next.

The design of the medium energy resolution spectrometer (MRS) at LAMPF (Fig. 1) suggests that this instrument is ideal for nuclear response measurements in the continuum. We have initiated an experimental program using the MRS, whose purpose is to both commission and test the spectrometer over a wide energy range, and yield new physics through a measurement of a complete set of polarization transfer data for ^1H , ^2H , ^{12}C , and ^{40}Ca at 20° with energy losses extending to about 600 MeV. The entire energy loss region can be spanned using 4 MRS magnetic field settings, and at 20° the quasielastic peak is particularly well-defined.

The initial shakedown run for this experiment has recently been completed. A considerably more than anticipated amount of time was devoted to installing and commissioning the newly constructed MRS focal plane polarimeter (FPP) and understanding the optics of the beam line as well as those of the MRS itself. Although in principle the MRS-FPP is essentially the same as the HRS-FPP in theory of operation, operation of the MRS-FPP system is in many ways much more complex than it is for the HRS-FPP system owing to the large momentum acceptance of the MRS (30%) compared to the HRS (2%). Thus, although it was possible to understand and operate the MRS system over a restricted region of the focal plane, the task of understanding it over the full momentum acceptance (30%) was a time-consuming and difficult task. Off-line analysis of the data taken during this run has now provided a reasonable calibration and understanding of the MRS-FPP system, and we are now in a position for production runs to begin.

Figure Caption

Figure 1. Schematic drawing of the new medium resolution spectrometer (MRS) at LAMPF.

3.2.4 EXPS 1052, 1061, 1062: NTOF Calibration and (p,n) Charge Exchange Reactions at Medium Energies

(D. Ciskowski, M. L. Barlett; LANL; OSU; Indiana; Ohio; Colorado; UCLA; T. A. Carey, J. B. McClelland, J. Shepard, E. Sugarbaker, T. Taddeucci, spokesmen)

The newly commissioned neutron time-of-flight (NTOF) facility at LAMPF consists of a beam line, swinger magnets, and neutron detectors which provide the capability for studying (p,n) charge exchange (CEX) reactions at intermediate energies. A variable length flight path up to 600-m is available together with a neutron detection system which allows measurement of neutron polarization. Details of the neutron detection system may be found in Refs. 1-4.

The study of (p,n) charge exchange at intermediate energies provides an opportunity for several new areas of investigation. Included among these are the following: (1) direct examination of the isovector components of the effective NN interaction, both spin-flip and non-spin-flip parts, (2) determination of Fermi (F) and Gamow-Teller (GT) transition form factors for nuclear structure studies, (3) searches for Fermi and GT strength in the continuum region of excitation, (4) further study of relativistic versus nonrelativistic descriptions of nuclear reactions and issues associated with these relativistic approaches such as pseudoscalar (PS) or pseudovector (PV) forms for the Lorentz invariant NN interaction, (5) direct study of the modification of the elemental two-body process $p + n \rightarrow n + p$ in the nuclear medium via quasielastic (p,n) measurements, (6) study of isovector giant resonances, and (7) study of direct $\Delta(1232 \text{ MeV})$ production in nuclei. Experiments in some of these areas have begun.

The purpose of EXP 1052 was to calibrate the neutron detection system over the full range of neutron energies available from the LAMPF accelerator using a tagged neutron beam. The differential and integral efficiencies were determined as well as position resolution and other systematic effects. The tagging was accomplished with an auxiliary proton detection arm which detected protons from elastic $n + p$ scattering using the neutron beam in area BR and a LH_2 target. Measured recoil proton angles and momenta determined the scattered neutron kinematics, thus allowing a calibration of the neutron detector array. Neutron energies from 50 to 750 MeV were measured. Integral efficiencies for the entire detector are roughly energy-independent and are about 0.09. Additional studies of differential efficiencies, cross talk systematics and other systematics have been completed.

EXP 1061 obtained the first set of CEX angular distribution data with NTOF for the reaction $^{15}\text{N}(\vec{p}, n)^{15}\text{O}(\text{g.s.})$ at 494 MeV. Because of the good energy separation (5.2 MeV) between ground and first excited states in ^{15}O , the short flight path (82-m) which was initially available provided adequate resolution for the experiment. An overall resolution of 2.7 MeV was obtained using the beam rebuncher. The target material consisted of ^{15}N enriched melamine of thickness 705 mg/cm².

Differential cross section and analyzing power data were obtained and are shown in Fig. 1 in comparison with a variety of theoretical predictions. The solid and dashed curves represent RIA-DWBA predictions assuming the PV and PS forms for the Lorentz invariant interaction,⁵ respectively. Relativistic enhancement of the lower component of the valence nucleon wave function was assumed in both calculations. The dotted curves represent NRIA-DWBA predictions.⁶ No available calculations are able to reproduce the forward angle analyzing power data. Further theoretical study of this reaction will continue.

The goal of EXP 1062 was to provide data for pure Fermi and GT (p, n) CEX transitions for the same target via the reaction $^{14}\text{C}(p, n)^{14}\text{N}(0^+, 2.31 \text{ MeV}; 1^+, 3.95 \text{ MeV})$. This was done² at 0° at 494, 644 and 795 MeV using the full 617-m flight path. The purpose was to study the isovector spin-flip ($J_{\sigma\tau}$) and non-spin-flip (J_τ) strengths of the NN effective interaction and the ratio of the two as functions of energy. Discrepancies between measured strengths and the free NN amplitude values at lower energies have led to speculation about strong (weak) density dependence in J_τ ($J_{\sigma\tau}$). The data are shown in Fig. 2 where the Fermi and GT 0° cross sections are shown in the lower and middle portions of the figure, respectively. In the upper portion the ratio, R^2 (essentially $|J_{\sigma\tau}/J_\tau|^2$) is shown. The predictions based on the free NN amplitudes are shown by the dashed lines; those based on a G-matrix calculation⁷ are given by the solid curves. The apparent large suppression of the Fermi strength at the higher energies is not understood at present.

Other (p, n) work engaged in by our group includes measurements from 80 - 795 MeV of $^7\text{Li}(p, n)^7\text{Be}(\text{g.s.} + 0.43 \text{ MeV})$ (494, 644 and 795 MeV at NTOF).³ Differential cross section angular distributions and integrated total cross sections for this reaction were obtained. Such data are needed for normalizing other CEX measurements. Also 0° Fermi and GT cross section measurements at 492 and 590 MeV for ^7Li , ^{11}B , and $^{12,13,14}\text{C}$ were made at the WNR facility at LAMPF for the purpose of studying the $J_{\sigma\tau}$ and J_τ strengths.⁴

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Figure Captions

Figure 1. Cross section and analyzing power for 494 MeV $^{15}\text{N}(p,n)^{15}\text{O}(\text{g.s.})$ measured at NTOF. The curves are explained in the text.

Figure 2. Values of (a) R^2 , (b) the 0° GT cross sections, and (c) the 0° F cross sections for $^{14}\text{C}(p,n)^{14}\text{N}$ at energies 100 - 800 MeV. The curves are explained in the text.

Figure 1

Figure 2

4 Pion-Nucleus Experiments at LAMPF

4.1 EXP 1023: Analyzing Powers for Pion Charge Exchange on Polarized ^{13}C

(M. L. Barlett, G. W. Hoffmann, M. Purcell; ASU; NMSU; LANL; Minnesota; Colorado; Maryland; J. Comfort, G. Kyle, spokesmen)

The pion-nucleon scattering amplitude has a spin-independent and a spin-orbit term. Each is complex and has isoscalar and isovector components. Models of pion-nucleus scattering generally build a theoretical description of the scattering process starting from this interaction, an assumed target nuclear density distribution, and include medium effects, etc. Of great interest is the study of the differences between the free pion-nucleon interaction and the "effective" pion-nucleon interaction experienced in the nuclear medium. An understanding of this "effective" interaction is one of the primary goals of pion-nucleus physics.

The pion-nucleus single-charge-exchange reaction (SCX) is directly sensitive to the isovector part of the effective pion-nucleon interaction. A considerable amount of SCX cross section data has been accumulated over the years, and these data are mainly sensitive to the spin-independent part of this piece of the interaction. SCX experiments with polarized nuclear targets may provide data which are useful in determining the effective isovector spin-dependent piece.

As part of a new program at LAMPF to exploit polarized nuclear targets in medium energy physics research, EXP 1023 measured analyzing powers A_y for the (π^+, π^0) SCX reaction on a polarized ^{13}C target at $T_{\pi^+} = 163$ MeV. The experiment spanned the center-of-momentum angular range $20^\circ - 60^\circ$. The measurements were made at the Low Energy Pion Channel (LEP) at LAMPF with the LAMPF π^0 spectrometer. The polarized target was essentially the same as the one used in EXP 955 apart from different target geometry. Dummy target data and the development of peak fitting techniques allowed extraction of yields to the isobaric analog state (IAS) and combined yields to the $3/2^-, 5/2^+$ doublet at 3.5 MeV.

The IAS data with theoretical curves are shown in Fig. 1 (Ref. 1). The solid curves are results of a distorted-wave impulse approximation (DWIA) calculation with a Cohen and Kurath wave function; the dashed curves are results of another DWIA calculation that used a Tiator wave function. The main difference in the results of these two calculations traces to the treatment of medium modifications to the effective pion-nucleon interaction (not to nuclear structure differences). There is reasonable qualitative agreement between experiment and theory (solid curves) in the region of the diffraction minima. The agreement is worst near 60° where a problem is evident for both cross section and analyzing power. It is possible that the ^{13}C nuclear structure input requires configurations from beyond the $1p$ shell. Theoretical work will continue to explore what new physics can be learned from

these new pion-nucleus spin-dependent data.

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Figure Caption

Figure 1. Cross sections and analyzing powers for the $^{13}\vec{\text{C}}(\pi^+, \pi^0)^{13}\text{N}(\text{IAS})$ reaction at 163 MeV. The curves are results of DWIA calculations.

4.2 EXP 1025: Pion Elastic/Inelastic Scattering from Polarized ^{13}C in the Energy Region of the [3,3] Resonance

(M. Barlett, G. Hoffmann, M. Purcell; Minnesota; NMSU; ASU; LANL; Penn; Colorado; Maryland; CSPU; G. Bursleson, D. Dehnhard, spokesmen)

The general motivation for this experiment is much the same as that for EXP 1023: to initiate an experimental program in pion-nucleus physics which utilizes polarized nuclear targets. The goal is to exploit the new spin degree of freedom of the target nucleus to study new parts of the pion-nucleon effective interaction.

EXP 1025 is a study of elastic and inelastic π^+/π^- scattering from ^{13}C at energies around the [3,3] resonance. The new observable, the analyzing power A_y , should provide data that further tests the available pion-nucleus scattering models, tests nuclear structure input used by the models, and leads to new information about π -nucleon "effective" interactions—especially the isoscalar spin-orbit piece.

The first run¹ was in summer 1989 at the Low Energy Pion Channel (LEP) at LAMPF using the Large Acceptance Spectrometer (LAS) and essentially the same polarized target as developed for EXP 955. The energy resolution of 3 MeV was adequate to resolve elastic scattering. Differential cross sections $d\sigma/d\Omega$ and A_y were measured for $T_{\pi^+/\pi^-} = 132$ MeV, $T_{\pi^+} = 226$ MeV, and $T_{\pi^-} = 231$ MeV. Surprisingly, analyzing powers significantly different from zero were seen only for the 132 MeV π^- data (see Fig. 1). The analyzing powers for the 231 MeV and 226 MeV data are almost consistent with zero over the entire angular range spanned by the data. In addition, analyzing powers were measured at momentum transfers near the second minimum of $d\sigma/d\Omega$ at several energies across the [3,3] resonance. Here again, the analyzing powers, contrary to expectations, are observed to be small (see Fig. 2).

The curves shown in Fig. 1 are results of a variety of distorted wave impulse approximation calculations.¹ The solid curves resulted from calculations employing a first-order optical potential generated from π -nucleon amplitudes and Cohen-Kurath wave functions. The results labelled Mach (long-short dashed curves) are from similar calculations but include a phenomenological ρ^2 term. The short-dashed curves are from calculations that used the same model that produced the long-short dashed curves except that the wave function of Tiator was used to generate the optical potential. This result suggests strong dependence of the analyzing power on nuclear structure.

It is interesting that none of the calculations qualitatively fit the analyzing power data for π^+/π^- at 132 MeV, especially near the second minimum in the cross section, near 100° c.m. The standard nuclear structure models also fail to reproduce the measured magnetic form factor of ^{13}C at $q \geq 1.6 \text{ fm}^{-1}$.

The second phase of the experiment was recently completed on the EPICS

channel at LAMPF. Data were taken for π^+/π^- at 162 MeV over the laboratory angular range $30^\circ - 90^\circ$. The intention is to obtain some inelastic cross section and analyzing power angular distributions from the data taken during this run. The task is complicated by the disappointing 1.2 MeV overall experimental resolution that is presently achieved during the offline analysis.

Experimental and theoretical work will continue to explore what new physics can be learned from these new and interesting π -nucleus analyzing power data.

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Figure Captions

Figure 1. Cross sections and analyzing powers for 132 MeV π^+/π^- elastic scattering from $^{13}\vec{\text{C}}$ at 132 MeV. The curves are results from a variety of DWIA calculations.

Figure 2. Analyzing powers for π^- elastic scattering from $^{13}\vec{\text{C}}$ across the [3,3] resonance at momentum transfers near the second minimum of the differential cross sections.

Figure 1

Figure 2

5 Experiments at Brookhaven National Laboratory

5.1 BNL EXP 781: Search for Radiative Transitions in the Hypernucleus ${}^{10}_{\Lambda}\text{B}$

(M. L. Barlett, G. W. Hoffmann, E. C. Milner; BNL; Carnegie-Mellon; Columbia; MIT; Houston; Osaka; Vassar College; M. May and M. Deutsch, spokesmen)

The intent of BNL EXP 781 was to search for radiative transitions in the p-shell hypernucleus ${}^{10}_{\Lambda}\text{B}$ corresponding to M1 spin-flip transitions between members of the doublet formed by coupling an s-shell Λ hyperon to the (A-1) nuclear core.¹ For low-energy excitations of ${}^{10}_{\Lambda}\text{B}$ the simplest single particle configuration is $(1s)_N^4(1p)_N^5(1s)_\Lambda$. The spectrum of states associated with the (A-1) core will, in general, be split into a series of doublets due to the spin-dependent, Λ -core interaction. Hypernucleus shell-model calculations² using phenomenological ΛN spin-dependent effective interactions predict doublet M1 transition energies in the range 0.1 to 1 MeV.

The experiment was conducted at the Brookhaven National Laboratory using the low-energy separated kaon beam at the Alternating Gradient Synchrotron (AGS). The observed reaction was ${}^{10}\text{B}(K^-, \pi^- \gamma){}^{10}_{\Lambda}\text{B}$ using 800 MeV/c kaons and covering the 4 to 12 MeV Λ hyperon binding energy range in ${}^{10}_{\Lambda}\text{B}$. The reaction pions were detected with a QQDQQ spectrometer system ("Moby Dick"). Thin target (3.9 g/cm²) runs were made to experimentally identify bound states in ${}^{10}_{\Lambda}\text{B}$ and establish production cross sections. The radiative decay measurements were made using a thick target (12.3 g/cm²). Gamma-rays were detected with an assembly of six germanium detectors mounted above and below the ${}^{10}\text{B}$ target.

The γ -ray spectrum in coincidence with the ${}^{10}_{\Lambda}\text{B}$ bound state region is shown in Figs. 1 and 2. The solid line in Fig. 1 shows the expected total number of events predicted for the 2^- to 1^- ${}^{10}_{\Lambda}\text{B}$ ground state doublet transition.¹ The dashed line in this figure represents the 5% confidence limit for that transition. There are no observable peaks which approach the predicted size in this region of the bound state spectrum. Fig. 2 shows an expanded portion of the spectrum in Fig. 1, this being the predicted region for the doublet transition according to Ref. 2. A possible 2^- to 1^- (g.s.) M1 transition is therefore ruled out in this energy range. These results are in sharp disagreement with the predictions of Ref. 2.

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Figure Captions

Figure 1. The spectrum observed for $^{10}\text{B}(\text{K}^-, \pi^-\gamma)^{10}\text{B}$. The solid line indicates the expected event total predicted for the ^{10}B ground-state doublet transition. The dashed line represents the 5% confidence limit for that transition.

Figure 2. An expanded portion of Fig. 1.

Figure 1

Figure 2

5.2 BNL EXP 791: Search for $K_L^0 \rightarrow \mu e$, $K_L^0 \rightarrow ee$

(G. Hoffmann, J. McDonough; UCI; UCLA; LANL; Stanford; Temple; Texas; William and Mary; R. Cousins, W. Molzen, spokesmen)

The present description of the fundamental particles and their electroweak and strong interactions is the Minimal Standard Model (MSM). Although this model has never been shown to be wrong, because of its many arbitrary parameters, it is suspected to be incomplete. Measurements performed in recent years make it clear that this incompleteness must originate with physics at very large mass scales. Rare decay physics probes some of these higher mass scales.

In the MSM the decay $K_L^0 \rightarrow \mu e$ is forbidden by conservation of electron and muon additive quantum numbers. Its observation would be the first direct evidence of physics beyond the MSM. The decays $K_L^0 \rightarrow \mu\mu$ and $K_L^0 \rightarrow ee$ are permitted in the MSM, but are highly suppressed. $K_L^0 \rightarrow ee$ has not been seen, and observation of a branching ratio for this process that is significantly above MSM predictions would also be evidence for new physics.

BNL EXP 791 is a high sensitivity search for $K_L^0 \rightarrow \mu e$ and $K_L^0 \rightarrow ee$. The spectrometer, located on the B5 beam line of the Alternating Gradient Synchrotron facility of the Brookhaven National Laboratory, is shown schematically in Fig. 1. This spectrometer provides precise tracking with good (redundant) particle identification. Very high rate capability is achieved using custom built front-end electronics, a large parallel readout architecture, and a multi-level trigger system utilizing SLAC 3081/E emulators.

The experiment has had three production runs spanning 1988 - 1990. We joined the collaboration in 1989 and participated in the 18 week 1990 run. In 1989 our initial contribution to the experiment was the design and prototyping of an efficient, low mass, "upstream trigger hodoscope" for use between the two analyzing magnets shown in Fig. 1. After the 1990 production run we were instrumental in testing a beam dump installed in the second dipole magnet to investigate whether such a concept could be utilized for a new, factor of 10 type improvement, experiment. We assumed considerable responsibility for this plug test and the interpretation of the results. Based on the results of the plug test we are presently designing a new plug for additional tests to be made in early 1991.

The first stage (and most computer intensive) of the offline analysis of the 1990 data is now complete. This analysis involved processing all data tapes using event reconstruction algorithms. From this analysis we can already give a preliminary sensitivity of the 1990 data set for a single $K_L^0 \rightarrow \mu e$ event. The single event sensitivity is about 3×10^{-11} . When all three data sets are combined it is expected that this single event sensitivity will be about 1.5×10^{-11} (implying a final limit $\leq 4 \times 10^{-11}$ at the 90% confidence level).

In addition to providing the world's best limit on $K_L^0 \rightarrow \mu e$, the experiment has accumulated a large number of $K_L^0 \rightarrow \mu\mu$ events. It is anticipated that the

combined 1988 - 1990 runs will give a total number of about 600 events (350 from the 1990 run). This will imply knowledge of the branching ratio to about 5%.

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Figure Caption

Figure 1. Schematic drawing of the kaon beam line and detection apparatus for BNL EXP 791.

6 Experiments at Fermilab

6.1 FNAL EXP 772: Study of the Nuclear Antiquark Sea Via $p+N \rightarrow \text{Dimuons}$

(M. L. Barlett, G. W. Hoffmann; LANL; FNAL; Illinois; Northern Illinois; SUNY at Stony Brook; and Case Western Reserve; J. Moss, spokesman)

The European Muon Collaboration (EMC) was first to observe a modification of the quark distribution in nuclei compared to that in free nucleons.¹ Many explanations have been offered but, as yet, a generally accepted consensus on the origin of this effect has not emerged. For the region of fractional quark momenta $0.3 \leq x \leq 1.0$ the EMC data are most straightforwardly accounted for with Fermi motion and nuclear binding effects. The region $x \leq 0.1$ remains active both experimentally and theoretically.

An independent measure of the quark structure of nuclei is provided by continuum dimuon production in high energy hadron-nucleus collisions via the Drell-Yan (DY) process, $q+\bar{q} \rightarrow \ell^+\ell^-$. For $x_F \geq 0.2$ this process is dominated by beam quark - target antiquark annihilation and is thus sensitive to the nuclear antiquark distribution. This complements the deep inelastic lepton scattering which is sensitive to both quark and antiquark distributions in nuclei.

In FNAL EXP 772 a precise measurement of the A dependence of dimuon production induced by 800 GeV protons from targets of ^2H , C, Ca, Fe and W was made.²⁻⁴ Over 450,000 muon pairs with invariant mass $M \geq 4$ GeV were recorded. The experiment was run in the Meson East beam line at Fermilab using the beam line, spectrometer, and beam stop of FNAL EXP 605 (with modifications).³ Systematic errors were minimized by interchanging the solid targets with the ^2H target every few minutes. Total systematic errors in the data ratios are less than 2%.

Fig. 1 shows a composite dimuon yield spectrum for all targets revealing very clear J/ψ and ψ' peaks, the broad DY continuum from $4 \leq M \leq 9$ GeV and a partial resolution of the Υ states. Fig. 2 shows the ratios of integrated yields per nucleon for the nuclear targets relative to deuterium for the J/ψ , ψ' and Υ resonances and the DY continuum. The strong A dependence of the quarkonium resonances contrasts sharply with the A independence of the DY continuum. Fig. 3 shows the ratios of DY yield per nucleon for each target to ^2H as a function of x_t for muon pairs with positive x_F (0.26). The curves shown for $\text{Fe}/^2\text{H}$ are predictions of various models of the EMC effect. No nuclear mass dependence is found for $x_t > 0.1$ but a slight suppression at $x_t < 0.1$ (shadowing) is observed for the heavier targets. Models of the EMC effect which postulate a significant pion excess or hadron clusters are apparently ruled out. The strong mass dependence of the J/ψ , ψ' and Υ states cannot be explained by small- x shadowing or hadronic attenuation models.

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Figure Captions

Figure 1. Dimuon event distribution measured in E772.

Figure 2. Measured A-dependence of integrated yields for J/ψ , ψ' , $\Upsilon(1s)$ and Drell-Yan production.

Figure 3. Ratios of the Drell-Yan dimuon yield per nucleon for positive x_F . The curves are discussed in the text.

Figure 1

Figure 2

Figure 3

7 Polarized Nuclear Target Development Work

(G. Hoffmann, M. Barlett, M. Purcell, S. Worm, D. Read; LANL; ANL)

Because of broad interest in exploring the new physics that can be learned through use of polarized nuclear targets in medium energy scattering experiments, and as an initial step in the realization of such experiments, we have polarized ^{13}C and ^{19}F using dynamic nuclear polarization techniques (DNP).^{1,2} The ^{13}C work led to the development of the polarized target constructed at LAMPF³ and used for experiments 955, 1023, and 1025. This target was fabricated from one of the LAMPF setups originally designed to provide a polarized ^1H target for the LAMPF nucleon-nucleon program. Physically this setup (cryostat plus supporting equipment such as vacuum pumps, dewars, NMR hardware, microwave hardware, etc.) is large and considerable manpower and overhead is required in its use for $p + \text{nucleus}$ and $\pi + \text{nucleus}$ scattering experiments.

For the past 15 years the PSI group in Switzerland, headed by Prof. S. Mango, has been developing compact ^3He evaporation/ ^3He - ^4He dilution refrigerators⁴ for use with the polarized proton/deuteron experiments performed at PSI. Such compact setups would be ideal for the programs that seem to be starting up at LAMPF with polarized nuclear targets. Because of our longer term interest in performing medium energy experiments which utilize polarized nuclear targets, we have begun construction of a copy of the PSI target setup. Schematic diagrams of the cryostat, the ^3He evaporation unit, and the ^3He - ^4He dilution refrigerator unit are shown in Figs. 1-3. PSI provided us with a complete set of engineering drawings for the system. They are also consulting with us concerning this technically difficult project.

The cryostat construction is complete and approximately 50% of the ^3He evaporation unit has been made at this time. All components for the 70 GHz microwave system required for DNP (at a magnetic field of 2.5 T) have been acquired. We have also acquired most of the components required for the NMR system. The microvax-CAMAC controlled NMR system developed for EXP 955 will be updated and used for the new system. We are presently procuring the ^3He pumping system, the ^3He storage system, as well as a 2.5 T superconducting split-coil magnet for the target.

The intention is that the setup will serve to test new materials for polarization feasibility as well as serve as the actual target for experiments at LAMPF and elsewhere.

The target is designed to be service and user friendly. The sample holding device can be removed or inserted into the cryostat at 4 K. PSI experience is that the target can be installed in the time period of one day. The comparable time period for the LAMPF setup is one month. The availability of the new PSI designed target will greatly benefit future polarized nuclear target experiments at LAMPF.

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Figure Captions

Figure 1. Schematic of PSI standard cryostat with central tube for ^3He evaporation insert (Fig. 2) or dilution unit (Fig. 3).

Figure 2. Schematic of PSI ^3He evaporation unit and sample holding device.

Figure 3. Schematic of PSI ^3He - ^4He dilution refrigerator unit with corresponding sample holding device.

Figure 1

Figure 2

Figure 3

8 Theoretical Work

8.1 Spin-Flip Cross Sections for $^{13}\text{C}(\vec{p}, \vec{n})^{13}\text{N}(\text{g.s.})$ at 500 MeV

(L. Ray and J. R. Shepard (University of Colorado))

During the last few years (p, n) charge exchange (CEX) data have been taken at the Neutron Time-of-Flight (NTOF) facility at LAMPF. The first set of data obtained was for the reaction $^{15}\text{N}(\vec{p}, n)^{15}\text{O}(\text{g.s.})$ at 500 MeV. Analyses have shown that the analyzing power cannot be explained by current theoretical models.¹

Understanding this failure is made difficult by the fact that each component of the isovector NN effective interaction contributes significantly to the cross section, analyzing power, and polarization transfer (D_{ij}) observables in a mixed and complicated manner. We have developed a method for attacking this problem by utilizing certain linear combinations of the $(\vec{p}, \vec{n})$ polarization transfer observables which allows one to focus attention on the individual dynamical elements of the reaction model.² The method was illustrated with relativistic distorted wave impulse approximation³ (RDWBA) calculations for the $^{13}\text{C}(\vec{p}, \vec{n})^{13}\text{N}(\text{g.s.})$ reaction at 500 MeV. In this approach the RDWBA transition amplitude is determined by the relativistic distorted waves, the $1p_{1/2}$ valence bound state wave function, and the isovector components of the nucleon-nucleon (NN) Lorentz invariant amplitudes. Both Fermi (F) and Gamow-Teller (GT) transitions contribute. Assuming isospin invariance the transition amplitude is given by²

$$F_{\text{CEX}} = A_F + B_F \sigma_n^p + A_{GT} \sigma_n^t + B_{GT} \sigma_n^p \sigma_n^t + C_{GT} \sigma_p^p \sigma_p^t + D_{GT} \sigma_q^p \sigma_q^t, \quad (3)$$

where superscripts (p) and (t) refer to the projectile nucleon and target nucleus, respectively. The unit vectors $\hat{n}$, $\hat{p}$, and $\hat{q}$ (denoted by subscripts) correspond to directions normal to the scattering plane and perpendicular and parallel to the momentum transfer, respectively. The longitudinal and transverse spin-flip cross sections, obtained from the above amplitudes by the following:²

$$\sigma S_{FP}^L = |D_{GT}|^2, \quad \sigma S_{FP}^T = |C_{GT}|^2, \quad (4)$$

depend predominantly on just the isovector-pseudoscalar and isovector-tensor components of the Lorentz invariant interaction as shown in Figs. 1 and 2. A non-spin-flip cross section, $\sigma_0 = |A_F|^2 + |A_{GT}|^2$, is predominantly sensitive to part of the Fermi interaction at forward angles. By studying these particular cross sections, along with $d\sigma/d\Omega$, A_y , and D_{ij} , the different parts of the NN isovector effective interaction in combination with the structure of the valence nucleon wave function can be studied one at a time in an optimum fashion.

It is intended that analyses of this type will provide an important tool for diagnosing the apparent inadequacies with the theoretical description of intermediate energy (p, n) CEX from odd-mass nuclei.

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Figure Captions

Figures 1 and 2. RDWBA predictions for the transverse and longitudinal spin-flip cross sections. The solid curves (same in each respective figure) represent calculations assuming the pseudovector (PV) form for the NN interaction and a relativistic lower component, λ^{Rel} , for the valence nucleon wave function. In the upper portion the dotted and dashed curves are from calculations that assumed the PV and pseudoscalar (PS) forms, respectively, where the nonrelativistic limit for the valence nucleon lower component, λ^{NR} , was assumed. In the middle portion the dashed and dashed-dotted curves represent RDWBA calculations with the PS and tensor components of the NN interaction omitted, respectively. The dashed and dashed-dotted curves in the lower portion are similar except that the axial-vector and space-like vector components were omitted, respectively.

8.2 Multiple Scattering Description of Intermediate Energy Deuteron-Nucleus Scattering

(L. Ray)

Recent deuteron-nucleus (dA) elastic scattering data from Saturne^{1,2} have dramatized the need for theoretical models for composite projectile - nucleus scattering which are appropriate for intermediate energy, which are based on microscopic, many-body theory, and which are readily calculable. In the past, studies of dA elastic scattering have been carried out at low energies and have relied on the non-relativistic folding model derived by Watanabe.³ It is important to realize that this model is based on an *effective* Hamiltonian for the dA many-body system which uses nucleon-nucleus optical potentials and will therefore omit a number of multiple scattering processes. These can only be properly included by a microscopic reduction of the $(A+2)$ -body problem.

In this work⁴ the nonrelativistic multiple scattering formalism of Watson⁵ and KMT⁶ was applied to dA elastic scattering. An optical potential was obtained through second-order in the elemental nucleon-nucleon (NN) t matrix and was organized such that the usual Watanabe folding potential appears as the leading term. This latter folding potential consists of a convolution of the nucleon-nucleus optical potentials, evaluated at half the deuteron incident kinetic energy, with the square of the s -state wave function of the deuteron. Corrections arising from deuteron-target nucleon double scattering, the deuteron d state, virtual deuteron break-up, additional nuclear medium effects, additional target nucleon correlation effects, and possible relativistic effects were explicitly identified. These corrections arise even when accurate, well understood nucleon-nucleus optical potentials are employed in the folding model. They are of the same order in the NN t matrix as the deuteron break-up corrections which are often included in calculations.⁷ Most of these corrections are small, however the additional medium effects are comparable to the break-up corrections.⁷ The leading term in the optical potential was obtained from Dirac phenomenology for $p + {}^{40}\text{Ca}$ at 362 MeV.

Predictions for $d + {}^{58}\text{Ni}$ at 700 MeV using the lowest-order, folding potential are shown in Fig. 1 in comparison with data.¹ Predictions for $d + {}^{40}\text{Ca}$ at 700 MeV including corrections due to the d state of the deuteron, target-nucleon - deuteron double scattering, and correlation effects beyond that accounted for in the nucleon-nucleus phenomenology, are indicated by the solid curves in Fig. 2. The effects of the additional medium corrections are shown by the dashed curves in Fig. 2. Overall, the theoretical description of the data is fairly good. Virtual deuteron break-up corrections should further improve the descriptions of these data, particularly the differential cross sections.

The results of this work demonstrate that nonrelativistic multiple scattering approaches provide an efficient model for organizing the complex, deuteron-nucleus scattering problem into a manageable, effective one-body problem which is readily

amenable to numerical analysis.

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Figure Captions

Figure 1. Predictions for $d + {}^{58}\text{Ni}$ at 700 MeV are compared with data.

Figure 2. Predictions (solid curves) for $d + {}^{40}\text{Ca}$ at 700 MeV which include corrections due to d state of deuteron, double scattering, and correlations are compared with data. Including the additional medium effects results in the dashed curves.

Figure 1

Figure 2

8.3 Coupled-Channels Dirac Equation Treatment of Large Angle $\vec{p}+^{40}\text{Ca}$ at 500 MeV

(L. Ray and G. W. Hoffmann; Ohio State; IBM; Saclay; Alberta)

As part of our study of relativistic effects in proton-nucleus scattering we have conducted a series of coupled-channels Dirac equation calculations for $\vec{p}+^{40}\text{Ca}$ elastic and inelastic scattering at 500 MeV.^{1,2} A longstanding problem in intermediate energy proton-nucleus physics concerns the inability of microscopic, theoretical models, either relativistic or nonrelativistic, to qualitatively reproduce angular distributions beyond momentum transfers of 3 fm^{-1} . It was originally suggested³ that coupling to strong, collective states was responsible for the disagreement with data. However, the necessity of including relativistic dynamics and deformed spin-orbit coupling hindered the success of coupled-channels calculations for several years.

We have now overcome these difficulties and have performed calculations using relativistic and nonrelativistic impulse approximation models for the optical potential and a collective model for inelastic transitions. Our calculations include coupling to strong collective states, relativistic dynamics, and deformed spin-orbit coupling and were made with the codes ECIS87 and CENITH.⁵

The effects of channel-coupling in the RIA - Dirac equation coupled-channels model for elastic scattering are shown in Figs. 1 and 2, where the solid (dashed) curves include (do not include) coupling to the first 3^- state in ^{40}Ca . With channel-coupling, the RIA - Dirac model is now able to reproduce the elastic scattering data⁶ through 10 orders of magnitude! In Figs. 3 and 4 RIA (solid curves) and NRIA (dashed curves) coupled-channels predictions for elastic scattering are compared with data. The nonrelativistic predictions are simple, first-order results (*i.e.*, no medium corrections or correlations). The differences between the dashed and solid curves display the effects of relativistic dynamics. The corresponding relativistic (solid curves) and nonrelativistic (dashed curves) predictions for the first few collective excitations in ^{40}Ca are shown in Figs. 5 and 6 in comparison with data.⁷ The superiority of the relativistic predictions is evident. Two publications^{1,2} have resulted from this work.

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Figure Captions

Figure 1. The solid curve is the result of a coupled-channels RIA-Dirac equation model calculation for 500 MeV $\vec{p}+^{40}\text{Ca}$ elastic scattering. The dashed curve results when coupling to the 3^- state is omitted.

Figure 2. Same as Fig. 1 except the analyzing power and spin rotation function are shown.

Figure 3. The RIA (solid curves) and NRIA (dashed curves) coupled-channels results for 500 MeV $\vec{p}+^{40}\text{Ca}$ are compared with cross section data.

Figure 4. Same as Fig. 3 except the analyzing power and spin rotation function.

Figure 5. The relativistic (solid) and nonrelativistic (dashed) coupled-channels results for the first few collective excitations in 500 MeV $\vec{p}+^{40}\text{Ca}$ are compared with cross section data.

Figure 6. Same as Fig. 5 except analyzing power.

Figure 1

Figure 3

Figure 2

Figure 4

Figure 5

Figure 6

8.4 Antisymmetrization Correction for Nucleon-Nucleus Elastic Scattering

(L. Ray)

As part of our general study of the nucleon-nucleus optical potential and the effective nucleon-nucleon interaction in intermediate energy proton-nucleus scattering we have evaluated the leading antisymmetrization correction which results in full, $(A+1)$ -body antisymmetrized theories of the optical potential. Traditional multiple scattering theories,¹ which are most often applied in nucleon-nucleus scattering calculations, do not account for the identical nature of the projectile and the nucleon constituents of the target nucleus except at the two-body level according to the prescription of Takeda and Watson (TW).² In this work³ a fully antisymmetrized nucleon-nucleus optical potential formalism⁴ was used to evaluate the leading antisymmetrization correction to the TW prescription. The new term is a three-body exchange potential which is linear in the NN effective interaction operator. From Ref. 3 this term is

$$PU_AP \simeq - \sum_{i \neq j} PT_i E_{0j} P, \quad (5)$$

where P projects the unsymmetrized elastic channel, T_i is the projectile - i^{th} -target-nucleon t matrix, and E_{0j} exchanges the projectile nucleon (0) and target nucleon (j). In applications of the unsymmetrized theory, the proper symmetry between target nucleons (i) and (j) is included in the antisymmetrized target wave function while that involving particles (0) and (i) is correctly treated by way of the NN effective interaction. The new term corrects the unsymmetrized optical potential by including the exchange of particles (0) and (j) while particles (0) and (i) interact.

Calculations were performed for $p + {}^{16}\text{O}$ and ${}^{40}\text{Ca}$ over a range of incident laboratory kinetic energies. Selected results are summarized in Table I which lists for each case the volume per nucleon of the empirical real, spin-independent proton + nucleus optical potential (U_{cent}), that of the local equivalent approximation to the antisymmetrization correction ($U_{A, \text{Local}}^{00}$), and the absolute value of the ratio of the two in percent. The correction diminishes rapidly with increasing energy, however, below 30 MeV the effect is several percent. Therefore for incident energies of several tens to hundreds of MeV the TW prescription is completely adequate. The dominant effect of the Pauli exclusion principle in nucleon-nucleus scattering continues to be that due to the blocking effect on the NN intermediate scattering states.

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TABLE I. Optical potential volumes.

Reaction	$RE[\langle U_{\text{cent}} \rangle] / A$ (MeV fm ³)	$RE[\langle U_{\text{local}}^{\text{00}} \rangle] / A$ (MeV fm ³)	Absolute value of ratio (%)
$p + {}^{16}\text{O}$, 20.8 MeV	-483.4	11.8	2.4
$p + {}^{16}\text{O}$, 30.4 MeV	-449.2	4.7	1.05
$p + {}^{16}\text{O}$, 39.7 MeV	-454.5	0.027	0.006
$p + {}^{16}\text{O}$, 49.5 MeV	-419.7	-0.29	0.07
$p + {}^{40}\text{Ca}$, 9.86 MeV	-497.5	19.6	3.9
$p + {}^{40}\text{Ca}$, 20.6 MeV	-388.1	7.65	2.0
$p + {}^{40}\text{Ca}$, 30.3 MeV	-402.3	-1.56	0.39
$p + {}^{40}\text{Ca}$, 40 MeV	-392.5	-2.12	0.54
$p + {}^{40}\text{Ca}$, 49 MeV	-302.8	-0.94	0.31
$p + {}^{40}\text{Ca}$, 76 MeV	-240.2	-0.016	0.007

8.5 Spin-One Kemmer-Duffin-Petiau Equation and Intermediate-Energy Deuteron-Nucleus Scattering

(L. Ray; LANL; OSU; IBM)

The success of relativistic approaches in intermediate energy proton-nucleus (pA) scattering encourages the application of relativistic equations to other probes of nuclei, such as the deuteron. We used the 10 dimensional, spin-one representation of the Kemmer-Duffin-Petiau (KDP) equation¹ as the basis for a relativistic treatment of deuteron-nucleus scattering. The KDP formalism yields a first-order, multi-component relativistic equation for spin-1 particles given by

$$(i\beta^\mu \partial_\mu - m - U)\psi = 0, \quad (6)$$

where β^μ represent a set of 10×10 matrices.¹ We chose the KDP potential, U , to be a sum of scalar and vector terms, each of which was obtained by folding the Dirac phenomenological scalar and vector optical potentials for pA scattering with the deuteron wave function. The KDP equation was manipulated into Schrödinger-like form resulting in effective central, spin-orbit, and tensor potentials.

In Fig. 1 the elastic scattering observables calculated with the KDP model are compared with 400 MeV $d + {}^{58}\text{Ni}$ differential cross section and vector and tensor analyzing power data.² The predictions qualitatively describe the data. In Fig. 2, KDP predictions (solid curves) and the results of a Schrödinger equation-Watanabe model calculation³ (dashed curves) are compared with data² for 700 MeV $d + {}^{40}\text{Ca}$ elastic scattering. Both calculations use the same Dirac phenomenological scalar and vector optical potential obtained by fitting $p + {}^{40}\text{Ca}$ elastic scattering data at 362 MeV. For the nonrelativistic calculations the Schrödinger equivalent central and spin-orbit potentials corresponding to the Dirac phenomenology for $p + {}^{40}\text{Ca}$ were folded with the deuteron wave function to produce the $d + {}^{40}\text{Ca}$ optical potential for use in the Schrödinger equation. Comparison of these two sets of calculations provides a concise delineation of the differences between the relativistic KDP and nonrelativistic Schrödinger equation approaches to deuteron-nucleus scattering. We find that the KDP method provides a reasonable starting point for describing such data.

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Figure Captions

Figure 1. Elastic scattering observables calculated with the KDP model are compared with data for 400 MeV $d + {}^{58}\text{Ni}$.

Figure 2. KDP predictions (solid) and Schrödinger equation - Watanabe model results (dashed) are compared with data for 700 MeV $d + {}^{40}\text{Ca}$ elastic scattering.

Figure 1

Figure 2

8.6 Effective Interactions for Nucleon-Nucleus Scattering Above 300 MeV

(L. Ray)

Recently a major calculation was completed of the NN effective interaction in the nuclear medium at intermediate energies.¹ The principal motivation for this work was the fact that all previous nonrelativistic calculations of nucleon-nucleus scattering at energies above 400 MeV relied on the impulse approximation (IA); such models fail to quantitatively describe data, particularly the spin observables. Medium effects play an important role in describing nucleon-nucleus scattering data at lower energies and it is possible that such corrections might be significant at higher energies also. Furthermore the success of the relativistic Dirac equation models and the contrasting failure of the nonrelativistic IA predictions have brought into question the value of a nonrelativistic description of nuclei. Before such conclusions can be drawn the systematic corrections in both theories must be studied in more detail.

The present work involves a calculation of Pauli blocking and intermediate binding energy corrections to the nonrelativistic NN effective interaction above 300 MeV. The nonrelativistic NN coupled-channels isobar model of Ref. 2 was used. This model is based on a meson exchange interaction together with nucleon-isobar [$\Delta(1232 \text{ MeV})$ and $N^*(1440 \text{ MeV})$] coupling and short-range phenomenology. It successfully describes the $J \leq 6$, $T = 0$ and 1 NN scattering states from 0 to 1000 MeV.³

The nonrelativistic NN effective interaction of the Watson multiple scattering theory⁴ was approximately evaluated. It is given in t matrix operator form by

$$t^W = v + vGQt^W, \quad (7)$$

where v represents the NN interaction (unmodified in the nuclear medium), Q projects all antisymmetric states of the target except the ground state, and the propagator, G , is given by

$$G = (E - H_0 - H_A + i\epsilon)^{-1}. \quad (8)$$

In the energy denominator H_0 is the kinetic energy operator and H_A is the nuclear Hamiltonian.

Exact evaluation of t^W represents a very formidable task. In this work the projected propagator GQ for finite nuclei was replaced by that corresponding to two interacting nucleons in infinite nuclear matter with Fermi momentum k_F where NN, $N\Delta$, and NN^* channels were included. Operator Q becomes the usual Pauli blocking factor. The energy denominator in this approximation contains an intermediate binding potential U which acts on only the target nucleon. This potential was assumed to have the velocity dependent form, $U(k^2) = A + Bk^2$ where the parameters A and B were determined from optical model phenomenology.

The free NN t matrix is given by

$$t = v + vgt \quad (9)$$

where

$$g = (E_0 - H_0 + i\epsilon)^{-1}. \quad (10)$$

The free NN t matrix and that of the Watson theory are related by

$$t^W = t + t(GQ - g)t^W. \quad (11)$$

In these calculations the NN model was used to evaluate the second term on the right-hand-side of this expression. The evaluation of t^W was facilitated by introducing a wave function ψ defined by

$$t^W \phi = v\psi \quad (12)$$

where ϕ is a NN plane wave. The wave function ψ was obtained by solving the integral equation

$$\psi = \phi + GQv\psi \quad (13)$$

in coordinate space using standard partial wave expansions. The final, estimated density dependent on-momentum-shell t matrix was obtained from the definition

$$\langle t^W(k_F) \rangle_{Final} \equiv \langle t \rangle_{Arndt} + \langle t^W(k_F) - t^W(k_F = 0) \rangle_{Model}, \quad (14)$$

where $\langle t \rangle_{Arndt}$ denotes the free NN t matrix obtained from the Arndt phase shift analysis.³

The proton-nucleus optical potentials were evaluated by folding the density dependent interactions with the nuclear density, using the local density approximation (LDA). The proton densities were obtained from electron scattering and the neutron densities from Hartree-Fock-Bogoliubov models.⁵ Second-order optical potential terms were also included arising from Pauli, short-range repulsion and center-of-mass correlations.⁶ Calculations were performed for $p + {}^{16}\text{O}$, ${}^{40}\text{Ca}$, and ${}^{208}\text{Pb}$ at proton incident energies of 300, 320, 400, 500, 613, 650, and 800 MeV. Differential cross sections, analyzing powers and spin rotations were computed and compared with available data.

The results for $p + {}^{40}\text{Ca}$ are shown in Figs. 1-3 where calculations with (without) density dependence are shown by the solid (dashed) curves. Medium effects tend to fill-in the minima in the differential cross sections, producing generally better agreement with the data. The structure in the analyzing powers is better reproduced. Problems remain in describing the forward angle A_y data, but much of the original discrepancy in the IA predictions has been removed. Substantial improvement in the spin rotation predictions results when medium corrections are included. These results are consistent with the medium effect calculations of von Geramb⁷ at the lower energies of 300 and 400 MeV. At higher energies further

improvement results when electromagnetic spin-orbit effects are included.⁸ Similar results for ^{16}O and ^{208}Pb are shown in Ref. 1.

It is also important to evaluate the impact of medium corrections on the determination of nuclear structure which has been conducted over the last 10 years using the high quality, 800 MeV elastic scattering data from the HRS at LAMPF. One such study involves fitting the cross section data for $p + ^{40}\text{Ca}$ over a range of energies by varying the neutron density distribution. Fig. 4 shows the resulting neutron - proton root-mean-square radius difference (where $\Delta r_{np} \equiv \langle r_n^2 \rangle^{\frac{1}{2}} - \langle r_p^2 \rangle^{\frac{1}{2}}$) in ^{40}Ca as a function of energy where medium corrections were included (solid dots) and where they were not included (crosses). The dashed line in the figure indicates the expected value. Medium corrections improve the agreement, however some unwanted energy dependence remains and the overall values of the extracted radii are still too small by about 0.2-0.3 fm, indicating that some dynamics is still missing in the model. Extraction of neutron isotopic density differences from non-relativistic impulse approximation analyses of the 800 MeV data^{6,9} was, however, shown to be unaffected by medium corrections.

This work shows that medium corrections to the intermediate proton-nucleus optical potential continue to be significant up to 800 MeV. Pauli blocking effects diminish quickly above energies of a few hundred MeV as expected. However, binding potential effects persist to higher energies. This work makes it clear that new physics issues associated with relativistic dynamics, possible changes in the bound nucleon form factors, variation in meson masses in the nuclear medium, etc., can only be reasonably studied when the physics included in conventional NR multiple scattering theory has been fully exploited in the numerical applications.

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Figure Captions

Figures 1-3. Results of calculations for $p + {}^{40}\text{Ca}$ elastic scattering from 300-800 MeV. The solid curves show the results using density dependence and the dashed curves are the results without density dependence.

Figure 4. The deduced neutron - proton rms radius difference in ${}^{40}\text{Ca}$ as a function of energy. The solid dots indicate the results using the density dependent interaction; the crosses are the results without density dependence.

Figure 1

Figure 2

Figure 3

Figure 4

8.7 Analyzing Powers for $\vec{p} + {}^{208}\text{Pb}$ at Large Momentum Transfers

(L. Ray; UCLA; LANL; Minnesota)

Analysis of large angle ($22^\circ - 37^\circ$ c.m.) analyzing power data for 800 MeV $\vec{p} + {}^{208}\text{Pb}$ elastic scattering and inelastic excitation to the 3^- , 2.61 MeV state were carried out.¹ The new measurements extend the momentum transfer range (to 4.7 fm^{-1}) and improve the statistical quality of previous data for this target.² The data were taken with the HRS at LAMPF and are consistent, within statistics, with previous measurements.² Analyses of large-angle differential cross-section and analyzing power data can in principle provide new information about off-shell, correlation, and multistep effects.

The new data and theoretical predictions are shown in the figure along with the previous data (solid squares) of Ref. 2. The dashed and solid curves for elastic scattering represent theoretical *predictions* that use nonrelativistic impulse approximation (NRIA) - Schrödinger equation and relativistic impulse approximation (RIA) - Dirac equation models, respectively. Both calculations use Arndt SP87 NN amplitudes and a proton density determined by electron scattering. Neutron densities were varied in order to fit the forward angle differential cross-section data. Scalar densities for the relativistic model were obtained from relativistic mean field models.³ The overall structure of the elastic analyzing power data is better reproduced by the RIA model.

The predictions for inelastic scattering were made by using the standard DWBA collective model with deformed spin-orbit coupling. For the RIA prediction the Schrödinger equivalent potential of the Dirac optical potential provided the input for the DWBA calculations. The RIA based predictions are somewhat better.

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Figure Caption

Figure 1. New analyzing power data for 800 MeV $\vec{p} + {}^{208}\text{Pb}$. The solid curves are the relativistic model predictions, while the dashed curves are the nonrelativistic model predictions.

8.8 Comparison of Dirac and Schrödinger Descriptions of Spin Observables for Proton-Nucleus Elastic Scattering at 650 and 800 MeV

(L. Ray and W. R. Coker (Univ. of Texas))

The significant improvement in the nonrelativistic (NR) Schrödinger equation description of proton-nucleus elastic scattering brought about by medium corrections to the effective NN interaction¹ warrant further investigation of NR scattering models. At 650 and 800 MeV electromagnetic effects due to the coupling between the projectile proton's magnetic moment and the current induced by the motion of the target nucleus electric charge (in the c.m.) qualitatively affect the forward angle spin observable predictions.² NR calculations have been made³ in which medium effects, correlations, and the electromagnetic spin-orbit (EMSO) potential were all included. These were compared with data and with predictions of the relativistic impulse approximation (RIA) - Dirac equation approach⁴ where the proton anomalous magnetic moment term was included.

The NR calculations including medium corrections and correlations are described in section 8.6 of this document and in Ref. 1. The electromagnetic spin-orbit interaction adds a $1/q$ dependent term to the single spin-flip amplitude, $c(q)\vec{\sigma}^p \cdot \hat{n}$, which leads to a long-range contribution to the proton-nucleus spin-orbit optical potential which is of the form,

$$U_{EMSO}/r^3 \vec{\sigma} \cdot \vec{\ell}, \quad (15)$$

where U_{EMSO} is a complex number. This long-range potential was handled in the calculations by way of a Gaussian convergence factor procedure.³

The RIA calculations were carried out as in Ref. 4 except a corrected form for the nuclear tensor potential was used⁵ and the proton anomalous magnetic moment term was included. Both calculations used the SP89 NN phase shift solution of Arndt and the same proton and neutron (vector) densities determined from electron scattering analyses and Hartree-Fock-Bogoliubov theory, respectively. The scalar and tensor densities for the RIA calculations were taken from relativistic mean field theory.

Calculations were done for $p + {}^{16}\text{O}$, ${}^{40}\text{Ca}$ and ${}^{208}\text{Pb}$ at 650 and 800 MeV. The results for ${}^{40}\text{Ca}$ and ${}^{208}\text{Pb}$ are shown in Figs. 1 and 2, respectively. The solid curves are the nonrelativistic predictions, including the EMSO potential, medium corrections, and correlations. The dashed curves indicate the RIA predictions while the dashed-dotted curves represent NR predictions without the EMSO term, but including correlations and medium effects.

For both nuclei the EMSO potential has significant effects at forward angles (especially for ${}^{208}\text{Pb}$) and, for the model discussed here, results in improved descriptions of the data. Overall, both the NR and RIA predictions are in good

agreement with each other and the data. The same is true for the ^{16}O cases.³ Application of the NR, density-dependent optical potential with the EMSO potential will be done for cases at lower energies.

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Figure Captions

Figures 1-2. The solid curves are predictions from the nonrelativistic model, including EMSO potential, medium corrections and correlations. The dashed curves are the corresponding relativistic model predictions. The dashed-dotted curves are the nonrelativistic model results when the EMSO effect is omitted, but medium effects and correlations are included.

Figure 1

Figure 2

8.9 Nonrelativistic Density-Dependent Calculations for $\vec{p} + {}^{13}\vec{C}$

(L. Ray)

The nonrelativistic density-dependent effective interaction model developed by our group¹ has been used to predict the spin observables for polarized proton elastic scattering from polarized ${}^{13}\text{C}$. The calculations use a NR-DWBA formalism, similar to that developed in Ref. 2 for the relativistic $p + {}^{13}\text{C}$ calculation. The nonrelativistic DWBA matrix element for the valence nucleon contribution to the $p + {}^{13}\text{C}$ elastic scattering amplitude can be evaluated using four component forms for the distorted waves and bound state wave functions together with the five term, McNeil-Ray-Wallace³ form for the Lorentz invariant NN interaction. This is true provided all lower components of wave functions are set to their nonrelativistic limits.² The RIA-DWBA computer code (DIAMOND) can then be directly used for nonrelativistic density-dependent calculations, when suitably modified for the density-dependent interaction.

Calculations for 500 MeV $\vec{p} + {}^{13}\vec{C}$ elastic scattering, $\hat{n}$ -type polarized target spin observables A_{oon} and A_{oonn} are shown in Figs. 1 and 2. The solid curves indicate the NRIA-DWBA calculations also given in Ref. 4. The dashed curves represent the same NRIA-DWBA calculation except the newer, SP89 NN phase shift solution was used. The dashed-dotted curves are the nonrelativistic density-dependent predictions using the SP89 NN phase shift solution and the density-dependent corrections from Ref. 1 for each component of the NN force. Both the upgrade to more recent phase shift solutions (*i.e.*, from SP82 to SP89) and density-dependence have only modest effects on the observables, compared to the differences between theory and data.

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Figure Captions

Figures 1-2. The solid curves are the NR1A-DWBA results of Ref. 4 for 500 MeV $\bar{p} + {}^{13}\bar{\text{C}}$ observables A_{oonn} and A_{oonn} . The dashed curves resulted when newer SP89 NN amplitudes were used. The dashed-dotted curves result from using the SP89 amplitudes and density dependent corrections.

Figure 1

Figure 2

9 Publications (1988 - 1990)

9.1 Journal and Conference Proceedings in Print

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