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THE LOS ALAMOS EXPERIMENTS ON THE FEW NUCLEON SYSTEMS[§]

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A summary of recently studied proton-, pion-, and neutron-induced reactions on nuclei up to ^4He at LAMPF is given. Upgrades to the LAMPF experimental facilities for these studies are described. Some new proton-proton total cross sections in pure helicity states ($\Delta\sigma_L(pp)$) from the ZGS near 3 GeV/c are also presented.

1. INTRODUCTION

There are a variety of experiments at LAMPF studying the few nucleon problems. These measurements are performed with proton, pion and neutron beams. The goals include determination of the pion-nucleon, nucleon-nucleon and proton-deuteron elastic scattering amplitudes, tests of charge symmetry and charge independence, and the study of various other elastic and inelastic processes. A number of facility upgrades to enhance the LAMPF capabilities for studying the few nucleon problems (as well as other reactions) are in progress or are being considered. This paper will attempt to summarize some of the activity at LAMPF on this problem.

In this paper, the notation (B,T;S,R) = (beam, target; forward scattered, recoil) will be used to describe the nucleon-nucleon elastic scattering spin observables. In general, the spin directions are $\hat{N}$ (up and normal to the horizontal scattering plane), $\hat{L}$ (longitudinal, along the incident beam direction or the outgoing particle directions), and $\hat{S} = \hat{N} \times \hat{L}$. An "0" denotes that the spin direction is not measured.

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2. PROTON BEAM EXPERIMENTS

Proton-proton elastic scattering in the Coulomb-nuclear interference region has been studied in a series of experiments by a U.S.-Japan-Italy collaboration¹ at the LAMPF High Resolution Spectrometer (HRS).^{2,3} New results are available on a measurement of the spin parameter $C_{NN} = A_{NN} = (N,N;0,0)$ at small angles and beam kinetic energies of 650 and 800 MeV. These data⁴ were taken with a frozen spin polarized target, and are shown in Fig. 1.

There are three independent pp amplitudes at 0° . Their imaginary parts can be related by the optical theorem to the spin averaged total cross section, σ^{Tot} , and to the total cross section differences between antiparallel and parallel beam and target spins ($\Delta\sigma_T$ - transverse spins, $\Delta\sigma_L$ - longitudinal spins). The real part of the amplitude corresponding to $\Delta\sigma_T$ can be derived

FIGURE 1

The spin-spin correlation parameter $C_{NN} = A_{NN}$ for pp elastic scattering at 650 and 800 MeV as a function of c.m. angle from Ref. 4. The dashed and chain curves correspond to contributions from nuclear and interference terms, respectively. The solid curve represents the full fit to the data.

from the C_{NN} results, and compared to predictions from dispersion relations^{5,6} and phase shift analyses. The experimenters find good agreement with the dispersion relation results of Grein and Kroll⁵ at 800 MeV, but there is about a four standard deviation difference at 650 MeV. An updated calculation using more recent $\Delta\sigma_T$ data⁷⁻⁹ is needed.

At 800 MeV, the C_{NN} data indicate $\Delta\sigma_T \sim 5.3 \pm 0.4$ mb, which agrees with the weighted average of the $\Delta\sigma_T$ measurements.⁷⁻⁹ Finally, preliminary results⁴ for $C_{LL} = A_{LL} = (L,L;0,0)$ by the same group indicate close agreement with predictions of Ref. 5.

Two groups have attempted to extract np spin parameters from pd quasielastic scattering measurements. For example, a number of $D_{ij} = (i,0;j,0)$ parameters, as well as differential cross sections and polarizations, were obtained at $\theta_{c.m.} \lesssim 70^\circ$ and 800 MeV using the HRS.^{10,11} The pp spin parameter data extracted from these experiments agree reasonably well with free pp measurements. This strongly suggests that the np spin parameters extracted in a similar way will also agree with free np results. Recently, these measurements were extended to larger $\theta_{c.m.}$ values in another beamline by the same group (Univ. Texas at Austin, Los Alamos, Univ. S. Carolina, VPI).¹² Preliminary results for the polarization $P = A = A_y = (N,0;0,0)$ are given in Fig. 2. The pp data extracted from the pd quasielastic scattering are in good agreement with previous measurements.^{10,13-17} The pn data are in reasonably good agreement with Refs. 10, 18-20, except perhaps near $100-110^\circ$. The solid lines are phase shift predictions by Arndt.²¹ Data on D_{ij} from this same experiment will be available soon, and D_{NN} results from free np scattering at 800 MeV and large $\theta_{c.m.}$ and from quasifree pd scattering at smaller $\theta_{c.m.}$ are presently being analyzed by a Texas A&M Univ.-Los Alamos collaboration.²²

$A_y(pp)$ 800 MeV SP86(Arndt)

$A_Y(pn)$ 800 MeV SP86(Armdt)

FIGURE 2

The polarization parameter for pp and pn elastic scattering as derived from pd quasi-elastic scattering. Previous pp data are from Refs. 10, 13-17 and pn data from Refs. 10, 18-20. The solid curve is a phase shift prediction (Ref. 21).

A test of charge independence was performed by the Northwestern Univ. group at HRS.²³ Cross sections and polarizations for the reactions

were measured at a polarized proton beam energy of 730 MeV and $\theta_{c.m.}(\pi) = 130^\circ$. The ${}^3\text{H}$ and ${}^3\text{He}$ were detected alternately by changing the HRS magnetic field on the order of once an hour. The measured ratio of cross sections was $d\sigma({}^3\text{H})/d\sigma({}^3\text{He}) = 2.193 \pm 0.007 \pm (0.024)$ and the difference of polarizations was $P({}^3\text{H}) - P({}^3\text{He}) = -0.0065 \pm 0.0040 \pm (0.0018)$. The first error is statistical and the second is systematic. Charge independence predicts 2 and

0, respectively, although differences in the ^3H and ^3He wavefunctions may modify these results.

In addition to the proton beam experiments above, two other reactions should also be mentioned. Last year, data were collected on the inelastic reaction $\vec{p}\vec{p} \rightarrow p n \pi^+$ with an L-type polarized target at five beam kinetic energies between 500 and 800 MeV.²⁴ All three particles were detected in coincidence, and these data are in the process of being analyzed. This experiment impacts the interpretation of the resonance-like behavior of the $^1\text{D}_2$ and $^3\text{F}_3$ pp partial waves. The second reaction is pd elastic scattering, being studied by a U.S.-Japan collaboration.²⁵ The goal of this work is the model independent determination of the pd elastic amplitudes over a range of angle and energies. Many of the past experiments were performed at the HRS and involved one-, two-, and three-spin observables (polarized beam, polarized target, and carbon polarimeter for the outgoing proton). This group is now preparing for larger angle three-spin measurements with an L/S-type polarized target.

There are several upgrades in progress at LAMPF that will affect studies of the few nucleon problem. A new buncher-chopper system for the polarized beam (100 ns instead of 5 ns separation of micropulses) will be used for experiments later this year, and a 600 m long neutron time-of-flight facility for (p,n) studies on nuclei will be ready in 1987. For 1988, a new optically pumped polarized ion source is being constructed that is expected to increase the polarized beam intensity by a factor of about 20 to $\sim 1 \mu\text{A}$ at 800 MeV. Finally, a medium resolution spectrometer is under construction for 1988. It will be especially useful for proton elastic scattering on light nuclei, for (p,p') and (n,p) reactions, and for nucleon-nucleon elastic and inelastic studies. These new facilities will greatly enhance LAMPF capabilities for proton and neutron beam experiments.

2. PION BEAM EXPERIMENTS

There is considerable research on pion scattering from light nuclei at LAMPF. The reactions studied include elastic and single and double charge exchange scattering, inelastic processes ($\pi^- p \rightarrow \gamma n$, $\pi^+ d \rightarrow p n \pi^+$, pion absorption, etc.) and tests of charge symmetry. Only a few of the current experiments are mentioned below.

A lengthy research program to more accurately determine the pion-nucleon amplitudes at LAMPF energies has been underway for some time.²⁶⁻²⁹ These experiments have been performed by a UCLA, George Washington Univ., Catholic Univ. of America, Abilene Christian Univ., Los Alamos collaboration at beam momenta up to 687 MeV/c. Recent results with an N-type polarized target are given in Refs. 27-29. At present, measurements of the R and A spin parameters for $\pi^{\pm}p$ elastic scattering are in progress with an L/S-type frozen spin target.

At somewhat lower energies, this same group has been studying $\pi^{\pm}$ elastic scattering from ^3He and ^3H , with an emphasis on the search for possible charge symmetry breaking effects.³⁰ Recent data collected with the EPICS spectrometer at beam energies of 142, 180 and 220 MeV and scattering angles of 40, 60, 80, 90 and 110° are being analyzed. Preliminary results indicate that the 180 MeV data agree well with the earlier results and that effects of comparable magnitudes are seen at the other two energies. Further theoretical work is necessary to understand these observations before definitive statements on the magnitude and cause of a charge symmetry breaking effect can be made.

A U.S.-Japan team³¹ has been studying $\pi^{\pm} + ^4\text{He}$ elastic and inelastic scattering (including the $(\pi, \pi p)$ reaction) using the EPICS spectrometer. Some of these results at 180 MeV are given in Ref. 32. They find that the isospin mixing between $I = 0$ and $I = 1$ states in ^4He at excitation energies between 23 and 30 MeV is small, contrary to indications from photonucleon cross sections $((\gamma, p)$ and (γ, n) reactions). The elastic data are at lab scattering angles of 40° - 120°, for π^- energies of 140, 180, and 240 MeV, and for a number of π^+ energies between 90 and 240 MeV. These measurements will be extended to larger angles later this year.

3. NEUTRON BEAM EXPERIMENTS

A three year program to measure free np spin-spin correlation parameters for $\theta_{\text{c.m.}} \sim 50^\circ$ to 160° and $T_{\text{lab}} = 500, 650$ and 800 MeV recently completed data taking. The spins of both the polarized neutron beam and the polarized proton target were in the horizontal scattering plane. The spin parameters measured were $C_{SS} = (S, S; 0, 0)$, $C_{LS} = C_{SL} = (L, S; 0, 0)$ and $C_{LL} = (L, L; 0, 0)$. Interference with the polarized target magnet coils prevented detection of

both outgoing particles in coincidence. Consequently, only the recoil proton was measured in a magnetic spectrometer.

Preliminary results over part of the angular range are shown in Fig. 3. Fairly good agreement with phase shift predictions can be seen at 500 MeV, where a variety of different spin parameters were previously measured at TRIUMF and elsewhere, and also at 650 MeV. Refinements to the values shown in Fig. 3 are expected soon for improved magnetic field integrals, background subtraction and cuts on the target projections and the particle mass.

FIGURE 3

Preliminary results for C_{LL} and C_{SL} for free np elastic scattering at 500 and 650 MeV. The curves are phase shift predictions. The quoted errors are presently dominated by uncertainties in the background subtraction.

Basically the same apparatus used for measurements of C_{SS} , C_{SL} and C_{LL} was also employed in a short experiment to determine the polarization of free np scattering at 800 MeV and small $\theta_{c.m.}$. These data were collected late in 1985 and they are presently in the process of being analyzed.²² An experiment is presently underway to measure C_{NN} for np elastic scattering at 800 MeV. In this case, the two outgoing particles are being detected in coincidence and the buncher-chopper system will allow rejection of low energy beam neutron events.

In the past few years, model independent amplitude analyses³³ for pp elastic scattering have been achieved for data from SIN,³⁴ LAMPF,³⁵ and the ZGS³⁶. Results from a single experimental group dominated the data base in each of these cases. Based on experience with the pp system at LAMPF, phase shift predictions generally did not fit data for new spin observables very well until a model independent amplitude analysis could be performed. In the np case, this is likely to be true as well.

Using this experience as a guide, the number of additional np measurements needed to obtain unique phase shifts can be obtained. It has been shown³⁷ that measurements with polarized beam and/or polarized target ($d\sigma/d\Omega$, P , C_{NN} , C_{SS} , C_{SL} , C_{LL}) at $\theta_{c.m.}$ and $\pi - \theta_{c.m.}$, and knowledge of the pp amplitudes at $\theta_{c.m.}$, allows the model independent determination of the $I=0$ amplitudes up to discrete ambiguities. The absolute phase at each angle is anchored to the phase of the pp amplitudes. Therefore, the free np elastic data on C_{NN} , C_{LL} , C_{SL} and C_{SS} from these experiments, and existing data on the other parameters, will allow an $I=0$ amplitude determination at 500, 650, and 800 MeV at about 10 angles between $\theta_{c.m.} = 50^\circ$ and 90° . At each energy, there will be four discrete solutions as a function of angle. The existence of other spin parameter results may allow a unique solution at each energy.

Nevertheless, it is expected that additional measurements at 650 and especially 800 MeV may be required to clearly establish the $I=0$ amplitudes. Experimental difficulties with producing monoenergetic neutron beams and with the detection of neutrons probably leads to considerably larger systematic errors for np than for pp scattering. Differences in data sets from various experiments on polarization, total and backward differential cross sections outside quoted errors are probably caused by these experimental difficulties. Thus, it will be important to overdetermine the amplitudes, providing consistency checks on the data. For example, it is considered important to measure $K_{ij} = (1,0;0,j)$ for free np scattering at LAMPF for this purpose. The new high intensity polarized ion source with the buncher-chopper planned for LAMPF should make such experiments feasible over the full angular range.

4. NEW $\Delta\sigma_L(pp)$ RESULTS

Final results for $\Delta\sigma_L(pp)$ from the ZGS at several new energies have revealed intriguing energy behavior. The experiment was similar to those reported previously.³⁸⁻⁴⁰ The results are shown in Fig. 4 along with some of

the earlier data. The errors plotted are purely statistical; systematic uncertainties are estimated to be 6% of $\Delta\sigma_L$. Coulomb-nuclear interference corrections are not included. It should be noted that the Saclay measurement⁴¹ near 3.25 GeV/c is consistent with the new data.

Although the statistics are not compelling, a new peak structure is indicated near 2.75 GeV/c. If it is due to a resonance, the mass is around 2700 MeV with a width less than 80 MeV. Earlier indications of structure near this mass include pp spin-spin correlation parameter data at $\theta_{c.m.} = 90^\circ$ ($k^2 C_{LL} d\sigma/d\Omega$ ⁴² and $k^2 C_{NN} d\sigma/d\Omega$ ⁴³, where k is the c.m. momentum) and polarization for the $pp \rightarrow d\pi$ reaction from Saclay.⁴⁴ Cloudy Bag model predictions^{45,46} include a narrow s-wave state near 2700 MeV, which may be consistent with the new structure. It is highly desirable to measure additional $\Delta\sigma_L(pp)$ data in finer steps near 2.75 GeV/c to clarify the energy dependence in this energy region.

Fig. 4

The $\Delta\sigma_L(pp)$ dependence on P_{lab} from 2.5 to 3.5 GeV/c from the new measurements reported (open circles) and from Ref. 40 (closed circles). The errors shown are statistical only. The curve is to guide the eye.

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