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Analyzing power measurement for forward angle *n-p* scattering at 790 MeV

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A measurement of the analyzing power for *n-p* scattering has been made at center-of-mass angles, 8.8°, 15.0°, and 20.7° with a nearly monoenergetic polarized neutron beam peaked at 790 MeV. These angles represent an acceptance from 5° to 30° in the center of mass, and therefore extend to the smallest angles yet reached for measurement of this observable. The data are compared with the predictions of several phase shift analyses, and with the results from previous measurements that extend to larger angles for both free and quasifree *n-p* scattering.

I. INTRODUCTION

The nucleon-nucleon ($N-N$) interaction, which is composed of both isospin $I=0$ and $I=1$ contributions, requires study with both neutrons and protons. Proton-proton scattering experiments are used to establish the $I=1$ amplitudes since they involve only the $I=1$ components, a fact that makes it possible to use *n-p* scattering to extract the $I=0$ amplitudes. The analyzing power measurements reported here provide much needed data below 25° for *n-p* scattering, which has repeatedly been requested by those who do phase shift analysis.[1] The emphasis in this experiment is on free scattering at small angles, a region in which quasifree scattering becomes affected by Glauber screening,[2] an effect that introduces considerable uncertainty into the interpretation of the results. In free scattering these uncertainties are avoided. The analyzing power is determined by the interference between the $L\cdot S$ coupling term and the other terms in the N-N interaction. It selects out the three Wolfenstein amplitudes a, c, and m in the notation used by MacGregor, Moravcsik, and Stapp.[3] These amplitudes are used to express the M matrix with longitudinal and sidewise components of the nucleon spins omitted as follows:

$$M=a+c(\sigma_1\cdot\hat{\mathbf{n}}+\sigma_2\cdot\hat{\mathbf{n}})+m(\sigma_1\cdot\hat{\mathbf{n}})(\sigma_2\cdot\hat{\mathbf{n}}) , \tag{1}$$

in which σ_1 and σ_2 are the neutron and proton spin operators, respectively, and $\hat{\mathbf{n}}$ is the unit vector normal to the scattering plane. The analyzing power A (or polarization P), in terms of these amplitudes for a time reversal invariant interaction is given by

$$A=P=\frac{2\,\mathrm{Re}[c^*(a+m)]}{\sigma_0} , \tag{2}$$

where σ_0 is the spin-averaged differential cross section $d\sigma/d\Omega$.

Only in the last six years have measurements been made[4,5] down to center-of-mass angles between 10° and 20°. The measurements in Ref. 4 were for quasifree **p**-n scattering, where the neutron target was provided by a deuteron, and the smallest angle studied was ~14°. Korolev *et al.*[5] reported free **n**-p scattering results down to 11°, but used a polarized neutron beam with an energy spread of ~50 MeV, produced from the breakup of a polarized deuteron beam. The results of the two experiments are not in good agreement, and it could be conjectured that the reason for the disagreement is the quasifree nature of one of the experiments.[5] The present measurement extends down to ~9°, which is the smallest angle for which such measurements have been made. Furthermore, the energy spread of the neutron beam is only ~10 MeV.

II. THE EXPERIMENT

The present data were obtained at the Clinton P. Anderson Meson Physics Facility at Los Alamos (LAMPF), where neutrons scattered at small angles from a liquid hydrogen (LH_2) target were detected through their "conversion" in polyethylene (CH_2). The resultant protons from charge exchange scattering in the CH_2 of the free hydrogen and the bound protons in the carbon were then detected in a large acceptance spectrometer as shown in Fig. 1. The neutron beam was produced from an 800 MeV incident polarized proton beam *via* the quasifree charge exchange reaction $^2H(p,n)X$ in a liquid deuterium (LD_2) target.[6] A sweep magnet just downstream of the target deflected emerging charged particles (and the proton beam) into a beam dump. The neutrons produced in the reaction were collimated at 0° by an aperture of diameter 2.54 cm in a steel (and concrete) shielding wall of thickness 3.7 m, resulting in a neutron energy spectrum with a peak centered at ~790 MeV and a continuum of neutrons at lower energies. Not only is the cross section for neutron production largest at 0°, but the monoenergetic nature of the neutron energy spectrum is also optimized at this angle. Since the spin transfer parameter at 0° is greatest for longitudinal polarization,[7] a proton beam of longitudinal polarization was used, resulting in longitudinally polarized neutrons. These suffered some horizontal precession in the vertical field of the sweep magnet. This neutron polarization was converted to vertical by precession successively in the vertical and horizontal fields of magnets $M1$ and $M2$, respectively (see Fig. 1). The vertical field of $M1$ was used to precess the neutron spin to the longitudinal direction, primarily compensating for the precession in the sweep magnet. Magnet $M2$ precessed the neutron spin from longitudinal to vertical.

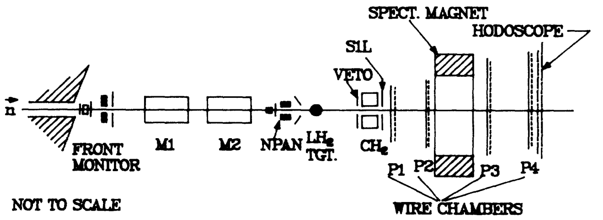

FIG. 1. Schematic of the experimental setup downstream of the neutron collimator. The front monitor, which was used to normalize the data, consisted of left and right scintillator telescopes within the neutron beam, as well as a hole counter that allowed the unscattered neutrons to pass without hitting any of its scintillator. The monitor target was a 2.54 cm thick slab of CH_2. The polarimeter NPAN was used only to determine the currents in the precession magnets $M1$ and $M2$ which would put the neutron polarization in the vertical direction. It was removed during data taking.

The vertically polarized neutron beam passed through a liquid hydrogen (LH_2) target of thickness ~25 cm situated 15 m downstream of the neutron production target. The resultant beam profile at the LH_2 target was of width 5 cm (full width at 1/10th of maximum intensity) and was accompanied by a broad halo. It was this beam spread and the halo that limited the smallest angle which could be probed. The halo also introduced a large target-empty background that substantially reduced the statistical significance of the data. The experimental layout in Fig. 1 also shows how the CH_2 blocks were straddling the beam in order to intercept the scattered neutrons. The inner edges of these blocks were at an angle ~2.5° with respect to the beam at the target. The CH_2 blocks presented a $\sim 15\times 15$ cm^2 square surface to the scattered neutrons and were 20 cm thick, and positioned at a mean distance of 132 cm from the target. Veto counters in front of the blocks were used to eliminate events caused by charged particles scattered from the LH_2 target. The large aperture spectrometer shown in Fig. 1 that was used to detect the "converted" protons consisted of four wire chambers ($P1$-$P4$) and two scintillator assemblies ($S1L$-$S1R$ and Hodoscope). On the upstream side of the spectrometer magnet there was $P1$, a drift chamber, and $P2$, a multiwire proportional chamber (MWPC). On the downstream side were $P3$ and $P4$, two considerably larger (3×1 m^2) drift chambers[8] ($P3$ and $P4$). The overall efficiency of the spectrometer was 0.4%, which included the effect of chamber efficiencies (60% on average) as well as the neutron to proton conversion rate in the CH_2 blocks. In front of the MWPC's were two scintillation counters ($S1L$ and $S1R$), straddling the beam and covering the area subtended by the two CH_2 blocks. A 25 counter hodoscope, consisting of 1.27 cm by 13×113 cm^2 scintillator paddles, was placed behind the last large drift chamber ($P4$). The scintillators were used to time the particles through the spectrometer. The timing data, when combined with the deflection information, gave a mass value for each particle and were used to separate the converted protons from all other types of particles coming from the CH_2 blocks.

The angle and momentum resolutions of the spectrometer were 0.25° and 70 MeV/c (FWHM), respectively. These resolutions were more than adequate, since the neutron scattering angle could be measured with an accuracy no better than ±1.8°, and the momentum determination of the scattered neutron was also relatively inaccurate, no better than ±50 MeV/c for neutrons elastically scattered from the free protons in the CH_2, and ±100 MeV/c for the neutrons quasifree scattered from carbon. In spite of this poor resolution, however, the elastically scattered neutrons from the LH_2 target were easily separated from the inelastic component associated with pion production, which contributed to the inferred incident neutron energy spectrum at least 150 MeV below the peak energy (~800 MeV).

The analysis of the data entailed a computation of the incident neutron energy from the observed proton angle and proton momentum. A typical spectrum of this inferred incident neutron energy is shown in Fig. 2. A distinct charge exchange peak from free protons in the CH_2 blocks can easily be discerned. Beneath this peak is a broad distribution that is attributed to the quasifree contribution from the carbon in the CH_2. The latter, with incident energy >700 MeV, was included as part of the signal plus background yield. The dominant sources of background were the target walls and the beam halo that missed the target, but hit the CH_2 blocks. These backgrounds were measured with the LH_2 target flask empty (i.e., containing only cold H_2 gas). Both the target-full data and the target-empty data resulted in spectra similar to that shown in Fig. 2. Another source of background was double scattering, the first scattering from the LH_2 target being followed by a second scattering from material surrounding the target. This background was measured with a shadow bar placed to block the direct scattering from the target. The inefficiency of the veto counters also contributed a background that was measured with the CH_2 blocks removed and the target still full of LH_2. These latter two types of background were found to be only $\leq 15\%$ of the target-empty background, and were therefore neglected.

The analysis of these data utilized the left and right scattering made possible by the two CH_2 blocks on each side of the beam. That made it important to establish the equality of the acceptance for left and right scattering from each block, in order to avoid an extraneous asymmetry that could be introduced by any polarization of the scattered neutrons. A study of these acceptances was made and they were found to be equal to within 10%.

The data were divided into nine sets of runs, which permitted consistency checks between data taken during different periods. If the χ squared per degree of freedom (χ^2/ν) value for the analyzing power in any of the three angle bins was greater than 1.0, the error was increased for that bin over and above the statistical error by the scaling factor $\sqrt{\chi^2/\nu}$. Therefore the error quoted here represents errors from both statistical sources and from internal inconsistencies. The scaling factor was less than 1.3 for any one angle bin.

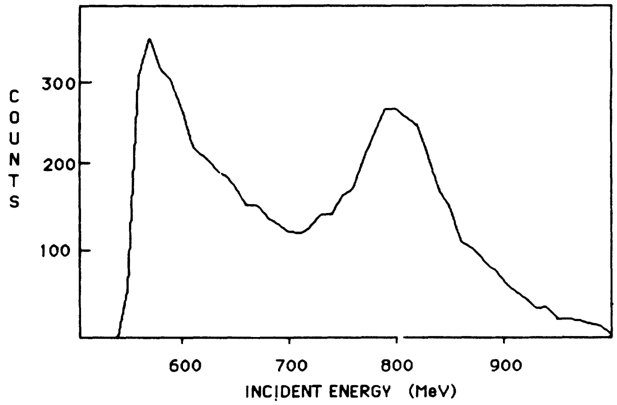

FIG. 2. A typical incident neutron energy spectrum as computed from the observed proton momentum, angle, and projection back to the center of one of the CH_2 blocks. The neutron angle was determined assuming that neutrons scattered from the center of the LH_2 target and converted in a plane centered along the scattering direction of the CH_2 blocks.

III. RESULTS AND DISCUSSION

The data are shown in Fig. 3 along with data from two other analyzing power measurements[4,5] below 90° in the energy region 780–800 MeV. Also shown in this figure are various phase shift analysis (PSA) predictions.[9] It is interesting to note that, unlike the data of Korolev *et al.*,[5] the data of the present experiment fit the PSA of Arndt, Hyslop, and Roper[9] well. The database for the PSA contains the data from both Korelev *et al.*[5] and the present experiment, although the effect of the present data on the PSA is very small. The database also contains some very precise quasifree data from Barlett *et al.*,[4] which agree well with the PSA, but not with the data of Ref. 5. The broad incident energy distribution associated with the data of Ref. 5 is not expected to be a reason for this discrepancy, since the energy dependence of the analyzing power at larger angles has been found to be very slight;[10,11] it is reasonable to assume that the energy dependence at smaller angles is not significantly different. Furthermore, the neutron beam polarization in Ref. 5 was determined with the assumption that it was the same as the proton polarization after deuteron breakup; the latter polarization was measured simultaneously with quasielastic *p*-*p* scattering of the polarized deuteron beam. This assumption along with the measured polarizations of both the deuteron and the quasifree proton

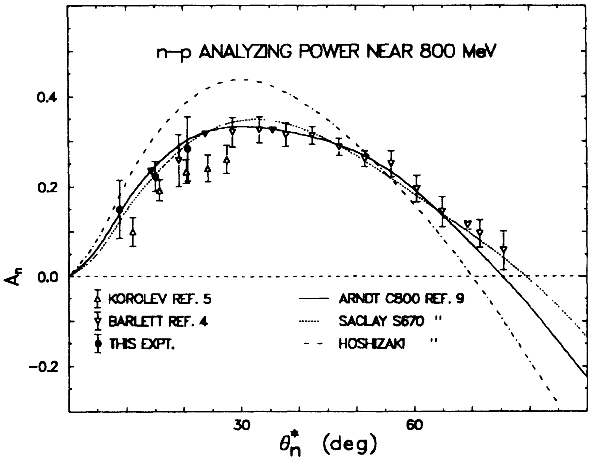

FIG. 3. Analyzing power results, A_n, of the present experiment compared with other data and predictions of several PSA's. The errors shown are the statistical errors multiplied by the scaling factor described in the text. The PSA predictions are all taken from the SAID program provided by Arndt, Hyslop, and Roper.[9] The data are plotted against the center-of-mass neutron scattering angle, Θ_n^*. Some of the data from Ref. 4 with poorer statistics have been left out for clarity.

were claimed to be consistent when the deuteron *D* state admixture was taken into account.

It should be noted that the present results are dependent on neutron beam polarization which is computed with the value of the analyzing power measured near 110° in the center of mass in a previous LAMPF experiment.[10] Should the results of Ref. 10 be wrong by a significant factor, our agreement with Arndt, Hyslop, and Roper[9] may deteriorate accordingly. It should also be noted that the results of Barlett *et al.*,[4] which do not depend on the results of Ref. 10, agree very well with the present results and the PSA predictions.[9] This agreement with Ref. 9 may simply reflect the fact that the data of Ref. 10 include some points with very small errors, although the PSA fit hardly changes when these data are "removed." It should be noted, however, that the procedure provided by Arndt, Hyslop, and Roper[9] for the exclusion of certain sets of data is not complete; only the real part of the phases are allowed to vary for the modified solution. The agreement of the present data with the PSA indicates that the quasifree measurements of Ref. 4 are most likely a very good representation of the free *n*-*p* scattering analyzing power down to angles near 14°. It would be desirable if this could be verified with measurements of better precision, since it is important to see if indeed the screening corrections of Glauber[2] for the analyzing power are small down to these angles.

An interesting feature that these measurements exhibit is the relationship of the spin-dependent cross section, defined in terms of analyzing power A and the spin-averaged differential cross section $\sigma_0(\Theta)$ as,

$$\sigma_{\text{spin}}=\sigma_0(\Theta)A(\Theta)\ , \tag{3}$$

for the $I=0$, $I=1$, and interference contributions to the reaction. Because of the symmetries associated with the amplitudes involved in this spin-dependent cross section, a separation of the pure $I=0$, the pure $I=1$ and the interference components can be obtained in terms of measured quantities:[3]

$$\sigma_{\text{spin}}(I=1)=\sigma_{\text{spin}}(p\text{-}p)\ , \tag{4}$$

$$\sigma_{\text{spin}}(I=0)=\text{antisymmetric part of}\ [\sigma_{\text{spin}}(n\text{-}p)-\sigma_{\text{spin}}(p\text{-}p)]\ , \tag{5}$$

and

$$\sigma_{\text{spin}}(\text{interference})=\text{symmetric part of}\ [\sigma_{\text{spin}}(n\text{-}p)-\sigma_{\text{spin}}(p\text{-}p)]\ , \tag{6}$$

where *n*-*p* refers to the present analyzing power measure-

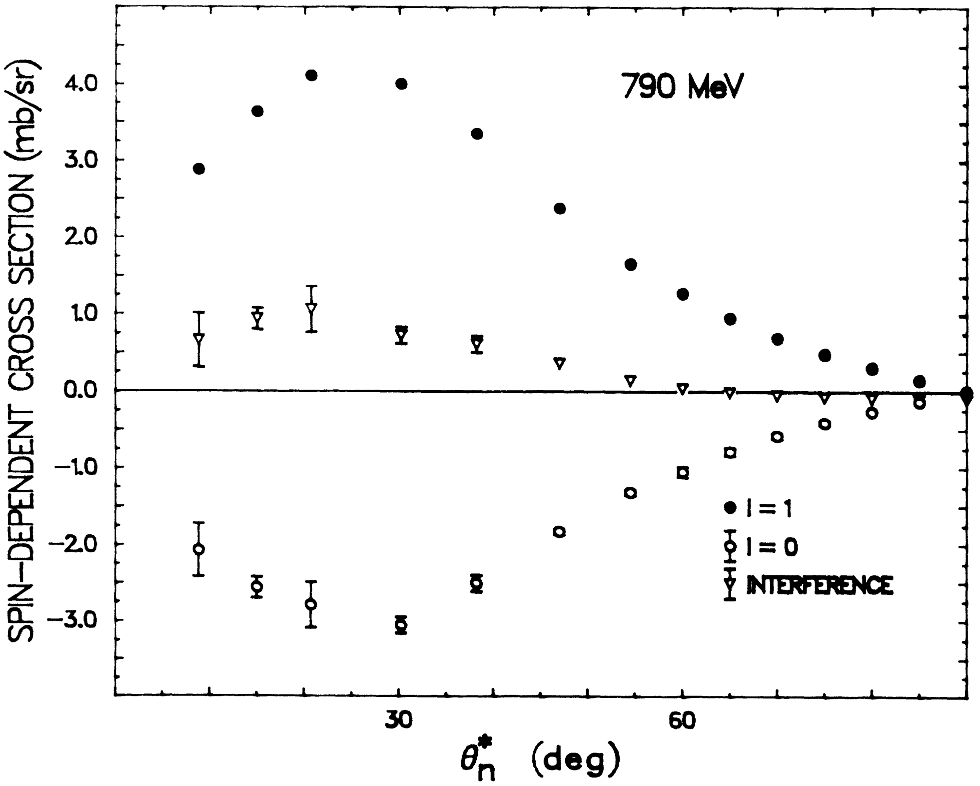

FIG. 4. The $I=0$, $I=1$, and the interference contributions to the spin-dependent cross section, as defined in the text. The points above 20° are computed from Refs. 4, 10, and 12.

ments along with n-p cross section measurements[12] and the analyzing power measurements in the charge exchange region,[13] while p-p refers to analyzing power and cross section values taken from the well established p-p phase shift predictions.[9] Results of this computation are shown in Fig. 4 and explicitly demonstrate how these measurements influence the determination of $I=0$ parts of the N-N interaction.

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