Spin-correlation parameter $A_{nn}(\theta^*)$ for n-p elastic scattering at 790 MeV

S. Nath, G. Glass, J. C. Hiebert, J. A. Holt, R. A. Kenefick, and L. C. Northcliffe
Texas A&M University, College Station, Texas 77843-3366

D. P. Grosnick, D. Lopiano, Y. Ohashi, T. Shima, H. M. Spinka, and R. Stanek
Argonne National Laboratory, Argonne, Illinois 60439

T. S. Bhatia and J. J. Jarmer
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

P. J. Riley and S. Sen*
University of Texas, Austin, Texas 78712

J. A. Faucett† and G. Kyle
New Mexico State University, Las Cruces, New Mexico 88003

R. H. Jeppesen
University of Montana, Missoula, Montana 59801

G. E. Tripard
Washington State University, Pullman, Washington 99164
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The spin-correlation parameter A_{nn} for free n-p elastic scattering has been measured for the first time for incident-neutron-beam energy $E_n = 790$ MeV and c.m. angles $48° \leq \theta^* \leq 149°$. The data are compared with the widely differing predictions of several phase-shift analyses, clearly favoring one of them. They also are compared with recently published quasifree A_{nn} data for the more limited c.m. angular region $98° \lesssim \theta^* \lesssim 122°$.

Since nucleon-nucleon (N-N) forces are spin dependent, an unambiguous determination of the N-N scattering matrix requires measurement of at least nine observables, most of which involve nucleon spin. The $I = 1$ isospin channel has been studied quite extensively because of the relative ease and higher precision with which p-p experiments, as opposed to the n-p measurements, can be performed. This has resulted in considerable constraints on the p-p amplitudes and uniqueness in phase-shift-analysis (PSA) solutions.[1-4] By contrast, the situation for the $I = 0$ channel above 500 MeV is far from satisfactory because of the scarcity of spin-dependent n-p scattering data above that energy. As Arndt has shown clearly,[5] the n-p interaction remains "essentially undefined" throughout the 550–800-MeV region. Measurements of the transverse spin-correlation parameter A_{nn} in particular would be expected to improve the definition of the $I = 0$ solution considerably.[3]

The few spin-dependent n-p data available at energies near 800 MeV include some free[6-11] n-p and quasifree[12,13] p-n analyzing-power measurements and a polarization transfer measurement[7] for three backward c.m. angles ($\theta^* \geq 165°$). Recently, a Saclay group[14] has measured $A_{nn}(\theta^*)$ for quasifree p-n scattering at 794 MeV for $98° \lesssim \theta^* \lesssim 122°$. The first measurements of the free n-p spin-correlation parameter $A_{nn}(\theta^*)$ at 790 MeV are reported here.

The experiment was performed in the neutron-beam channel at the Clinton P. Anderson Meson Physics Facility (LAMPF). Although similar in some respects to another LAMPF experiment reported earlier,[11] it differs in three important ways. The neutron beam in the earlier experiment was obtained from the reaction $^2H(p,n)2p$ reaction induced by an 800-MeV *unpolarized* proton beam, in which the neutrons collimated at 20° were found to have vertical polarization of $\sim 20\%$ over a wide spectrum of energies from 225 to 675 MeV. In the present experiment, the polarized neutron beam was produced by longitudinal (*l*-type; along beam axis) polarization transfer in the $^2H(p,n)$ reaction at $\theta = 0°$ induced by 800-MeV *polarized* protons. The neutron spectrum for this reaction[15] is qualitatively different in that about 32% of the neutrons are contained in a sharp charge-exchange peak at ~ 790 MeV. The polarized p beam is about 100 times less intense than the unpolarized p beam. Partial compensation for this loss was achieved by replacing the magnetic spectrometer used in Ref. 11 with an array of multiwire proportional chambers (MWPC's) of much larger angular acceptance.

Compensation for the loss of a momentum measurement was provided by a much better time-of-flight (TOF) measurement, made possible by a new technical development at LAMPF in which the normal 15-nsec rf microstructure of the beam was altered so as to concentrate the beam into one micropulse out of twenty with only a 50% loss in average intensity. (The peak intensity in each of

the depleted micropulses was less than 1% of that in the enhanced pulse.) This eliminated ambiguity in relative TOF measurements for the ~7-m flight path between the liquid-deuterium (LD$_2$) target and the detector system.

The LAMPF proton beam, of l-type polarization $P_p \sim 0.80$, was incident on an LD$_2$ target of thickness ~25 cm (see Fig. 1). A p-beam polarimeter[16] (upstream of the LD$_2$ target) was used to monitor P_p. Neutrons of l-type polarization P_n, collimated at 0°, entered the experimental area, while the proton beam was swept aside and dumped. The neutron-beam intensity was monitored with a scintillator array (FMON) that detected charged particles recoiling at angles from 0° to 25° from a polyethylene (CH$_2$) target positioned just downstream of the collimator. Since the longitudinal-polarization-transfer parameter $K_{ll}(0°)$ is -0.604 ± 0.016 at 800 MeV,[17] the neutron-beam polarization was $P_n \sim 0.46$. Although the neutrons emerged from the LD$_2$ target with l-type polarization, their spins precessed in the horizontal plane as they passed through the beam-sweeping magnet. Compensation for this was provided by an equal and opposite precession in the vertical field of magnet $M1$. A second magnet $M2$ (with horizontal transverse field) precessed the l-type polarization into n-type (vertical) polarization. The magnitude and direction of the n-type beam polarization P_b was determined from the left-right asymmetry of scattering measured with a polarimeter (NPAN), which could be moved into or out of the beam downstream of $M1$ and $M2$ (Ref. 18 describes a similar polarimeter). NPAN consisted of a cylindrical CH$_2$ target, viewed by symmetric left-right and up-down scintillator telescopes. It was used to optimize, empirically, the magnetic fields of $M1$ and $M2$.

With NPAN out of the beam, the neutrons were scattered in a vertically polarized proton target (PPT) of volume ~74 cm^3, about twice the volume of the target used in Ref. 11. The target consisted of beads of propanediol (C$_3$H$_8$O$_2$) of ~1-mm diameter, immersed in liquid ^{3}He, and was similar to that described by Tippens et al.[19] except that it was much larger in volume. The cryostat containing the target cell was located in the uniform (within $\pm 0.02\%$) vertical magnetic field (2.5 T) of a conventional C magnet. The absolute target polarization P_t was measured by NMR techniques with an estimated relative uncertainty of less than 4% and typically was ~0.70. The direction of the incident-beam polarization P_p was reversed at the source at ~2-min intervals, and its absolute magnitude was measured by the "quench-ratio" method, which is capable of determining P_p within $\pm 0.4\%$.[20] The uncertainty in the determination of P_p in this experiment was estimated to be less than 1%.

An elastic n-p scattering in the PPT was identified by coincident detection of both scattered neutron n and recoil proton p. The n detector was a neutron bar counter (NBC) hodoscope, consisting of twelve rectangular scintillator bars, each of size $101.6 \times 20.3 \times 7.0$ cm^3, shielded by a veto counter V, which ensured the rejection of charged particles in the neutron arm. The acceptance of this counter was 33% larger than that used in Ref. 11. The p-detector arm consisted of a pair of MWPC's ($W1$ and $W2$) giving both x and y coordinate information, a trigger scintillator $S1$, and a four-scintillator array $S2$, both of which provided TOF information. The event trigger was generated by a coincidence between $S1$, one of the $S2$ scintillators, and one of the NBC scintillators, in anticoincidence with the V counter. The solid angle subtended was ~50 msr, with $\theta_{lab} \sim \pm 6.0°$ in the horizontal plane for each setting. (This acceptance was almost an order of magnitude larger than that of the spectrometer used in Ref. 11.) The n-p elastic events produced by the 790-MeV monoenergetic group of neutrons were distinguished from those caused by the lower-energy neutrons in the tail of the spectrum by measurements of the TOF in both arms as well as the timing of the event relative to the rf cycle of the accelerator. Opening angle, coplanarity, and target-traceback constraints were used to eliminate inelastic n-p events and to reduce the background arising from quasifree scattering from bound protons in the nonhydrogenous components of the polarized target.

The quasifree contribution appeared as a low broad background distribution under the n-p elastic peak in the histogram of the coplanarity variable $\Delta\Phi$ [$=\Phi$(measured)$-\Phi$(predicted)]. A least-squares fit, with a Gaussian for the n-p elastic peak and a quadratic polynomial for the quasifree background, was made to the histogram. Background was determined separately for each of the four beam-target spin combinations. The shape of the quasifree contribution was confirmed independently by data taken with hollow graphite beads of approximately the same density replacing the propanediol beads of the PPT. The magnitude of this background contribution ranged from 5 to 15% of the unsubtracted signal. Data were collected at four nominal angular settings of the NBC (and the proton arm), corresponding to $\theta^* = 60°$, 90°, 120°, and 140°, and the final data for each beam-target spin combination were sorted into four bins of θ^* for each setting.

The spin-correlation parameter $A_{nn}(\theta^*)$ is given by

$$A_{nn} = \frac{1}{P_n P_t} \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)},$$

in which P_n and P_t are the average magnitudes of beam and target polarization and the quantities N are the normalized background-subtracted yields for the different
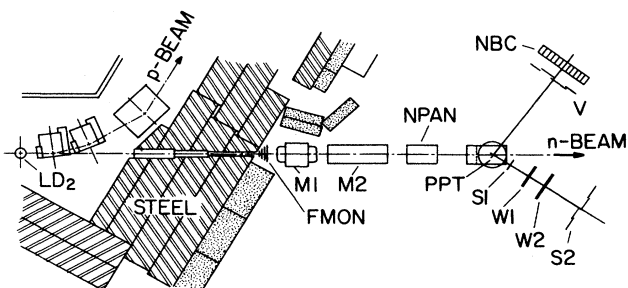

FIG. 1. Schematic diagram of the experimental layout.

TABLE I. Measured values of $A_{nn}(\theta^*)$ for free n-p elastic scattering at 790 MeV.

θ^* (deg)	$A_{nn}(\theta^*)$	θ^* (deg)	$A_{nn}(\theta^*)$
48.0	0.071 ± 0.094	112.1	0.147 ± 0.120
54.7	0.070 ± 0.091	116.8	-0.165 ± 0.124
61.4	0.068 ± 0.087	121.4	0.465 ± 0.114
68.0	0.055 ± 0.095	126.1	0.272 ± 0.103
80.9	0.050 ± 0.088	132.8	0.264 ± 0.091
87.0	-0.030 ± 0.086	138.3	0.401 ± 0.101
93.0	-0.070 ± 0.097	143.8	0.177 ± 0.077
99.0	-0.152 ± 0.097	149.0	0.190 ± 0.101

combinations of beam- and target-polarization direction. The quantity $N(\uparrow\downarrow)$, for example, is the yield obtained with P_n up ($\uparrow$) and P_t down ($\downarrow$).

The measured values of A_{nn} are presented in Table I. They also are shown in Fig. 2(a) along with the predictions of several PSA's.[1-4] The error bars show the statistical uncertainty, which includes the error in the fitting procedure but no systematic errors. An upper limit for the overall systematic uncertainty in the results is estimated to be $\sim 10\%$ of the values, arising primarily from the uncertainties in the K_{ll} parameter[17] and in P_t. Thus, the uncertainties of the results are primarily statistical. Also shown are the quasifree n-p A_{nn} values obtained by a Saclay group[14] at 794 MeV, the only other data available in this energy region. Although the two data sets are in agreement, within statistical accuracy, the much larger angular region spanned by the present data permits a qualitative determination of the angular dependence of A_{nn} which is not revealed by the Saclay data.

The PSA predictions were obtained through use of the SAID code of Arndt, Hyslop, and Roper.[1] The solid curve is the recently (summer 1988) updated energy-dependent solution SM88 of the VPI group.[1] The dashed curve is the most recent solution (S670) of the Saclay group,[2] as given by the SAID code. The extreme differences of the predictions are an illustration of Arndt's statement[5] that the n-p interaction remains "essentially undefined" above 550 MeV. It is not surprising, perhaps, that the 1980 prediction of Hoshizaki and co-workers[4] (not updated) is so different from the others, because it was derived from a less complete data base. Although the data base for the 1982 BASQUE[21] prediction[3] was also less complete than is presently available, the prediction, while off in magnitude, more plausibly predicts the trend of the angular dependence observed in the present experiment. The strong disagreement between the Saclay prediction[2] and that of the VPI group[1] is notable, since both predictions are derived from essentially the same data base (not including the data shown in Fig. 2) but involve different assumptions about unknown phase parameters. The VPI prediction is decisively favored by the results of the present experiment. This situation is markedly different from that at lower energy (484 and 634 MeV) where the A_{ll} and A_{sl} predictions of the VPI and Saclay groups are
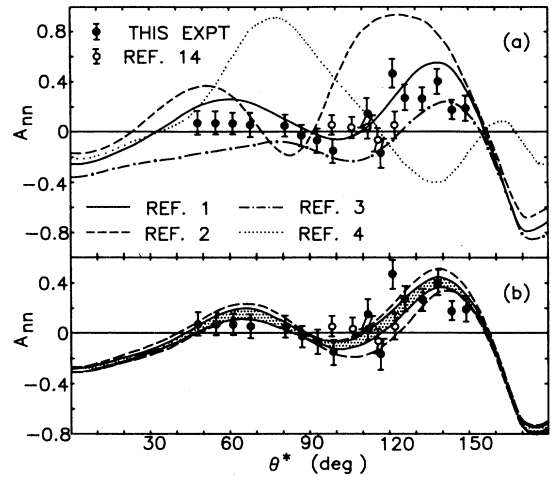

FIG. 2. Spin-correlation parameter A_{nn} for n-p elastic ($\bullet$) and quasifree ($\circ$) scattering near 800 MeV: (a) comparison with energy-dependent PSA predictions of Refs. 1–4; (b) comparison with error corridors of single-energy fit C800 of Ref. 1 before (---) and after (——) inclusion of the data of this experiment.

very similar and qualitatively in agreement with the experimental data.[22]

The effect of the present data set on the 800-MeV VPI single-energy PSA solution C800 is shown by the error corridors in Fig. 2(b). The effect is quite noticeable despite the relatively large uncertainties of the data. While the shape and magnitude of the prediction is little changed, the error corridor is narrowed substantially, especially for angles near $\theta^* = 120°$. Similarly, the phase parameters are also little changed; the only ones changing by more than 1° are the δ parameter (see Ref. 1) for $^1P_1$ (1.55° less negative) and the ρ parameter for $^3G_3$ (1.26° more positive).

In conclusion, the data presented here are the first measurements of $A_{nn}(\theta^*)$ for free n-p scattering near 800 MeV and are a significant addition to the data base for n-p elastic scattering in that region. Furthermore, despite their limited statistical accuracy, the present results clearly discriminate in favor of the VPI PSA solution[1] and solidify it noticeably. Further improvement will require additional data of higher statistical accuracy.

RAPID COMMUNICATIONS

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*Present address: Thomas More College, Crestview Hills, KY 41017.

†Present address: Los Alamos National Laboratory, Los Alamos, NM 87545.

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