Measurement of C_{LL} and C_{SL} in *np* Elastic Scattering at 484 and 634 MeV

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The spin-spin correlation parameters $C_{LL}=(L,L;0,0)=A_{LL}$ and $C_{SL}=(S,L;0,0)=A_{SL}$ for *np* elastic scattering were measured for incident polarized-neutron–beam kinetic energies of 484 and 634 MeV over the center-of-mass angles from $\simeq 80°$ to 180°. The data are important for determining the $I=0$ nucleon-nucleon amplitudes. These results are compared with phase-shift calculations.

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One of the most fundamental reactions at intermediate energies (up to 1 GeV) is nucleon-nucleon elastic scattering. The rich spin structure of the five isospin-1 ($I=1$) and five $I=0$ amplitudes provides considerable information on the strong interaction. Numerous calculations have been performed in attempts to understand these amplitudes.[1] Comparisons between the $I=1$ and $I=0$ amplitudes are also fruitful because the inelasticity is much higher in the $I=1$ channel than in the $I=0$ channel (the dominant $NN\rightarrow N\Delta$ and πd inelastic reactions occur only for $I=1$).

There are two other important reasons for the study of the nucleon-nucleon interaction. One is the need for these amplitudes as inputs to calculations of nucleon-nucleon scattering via multiple-scattering theory[2] or the Dirac phenomenology.[3] The other concerns the resonantlike behavior observed in several $I=1$ and perhaps one of the $I=0$ partial waves.[4–8] The cause of this behavior may be the coupling of the $I=1$ elastic and the $NN\rightarrow N\Delta$ channels or the existence of six-quark dibaryon states.

For these reasons, the more experimentally accessible *pp* ($I=1$) reaction has been studied extensively at intermediate energies, leading to a detailed knowledge of the amplitudes in terms of unique phase-shift solutions.[4–7] By comparison, the $I=0$ amplitudes above $\simeq 500$ MeV are not as well determined as a result of insufficient data.[4,6,7] The present *np* elastic-scattering measurements address the need for additional $I=0$ spin-parameter data. These are the first results from a large program of polarized-neutron beam, polarized-proton target experiments recently performed at the Clinton P. Anderson Meson Physics Facility (LAMPF) at Los Alamos. The spin parameters presented here have not been measured before in the *np* system at any energy.

Recent measurements of *np* elastic-scattering spin observables (other than total and differential cross sections and polarizations) include a number of observables from TRIUMF[9] up to 495 MeV, and from LAMPF[10,11] up to 790 MeV. Older results are few in number and generally have relatively large statistical uncertainties (see Ref. 4). Some *pd* quasielastic scattering spin parameters have also been measured and *np* parameters extracted.[12]

The experiment was performed at the BR channel at LAMPF. A beam of polarized neutrons was produced by directing a beam of polarized protons through a liquid-deuterium target. The resulting spectrum of neutrons produced at 0° consisted of two major strong-interacting components.[13] Approximately half had the same energy as the incident protons—the quasielastic component. With the incident proton beam longitudinally polarized, these neutrons had a polarization given by the product of the proton-beam polarization and the spin-transfer parameter K_{LL}.[14] A continuously operational polarimeter[15] upstream of the deuterium target and of a dipole magnet measured the proton-beam spin. The other component consists of neutrons from inelastic reactions in the deuterium. It exhibits a large width and an average energy that is $\simeq 350$ MeV below the quasielastic peak and is a source of background to the experiment. Present estimates of the centroid of the neutron quasielastic peak energies are 484 ± 5 and 634 ± 5 MeV.

The neutron beam passed through a collimator into the experimental area as shown in Fig. 1. The beam intensity (a few kilohertz) was monitored with a scintillator array (FMON) that measured charged particles scattered from a CH_2 target positioned in the beam just downstream of the collimator. Auxiliary monitoring was provided by scintillators placed after the polarized target (TMON) and before the beam dump (BMON). The fields of the dipole magnets (LORRAINE and CASTOR) were adjusted to provide the desired beam spin orientation at the polarized target. The final orientation was determined by measuring the asymmetry of *np* scattering with the neutron relative polarization analyzer (JPAN, see Hollas *et al.*[16] for a description of a similar polarimeter), which consisted of a cylindrical CH_2 target

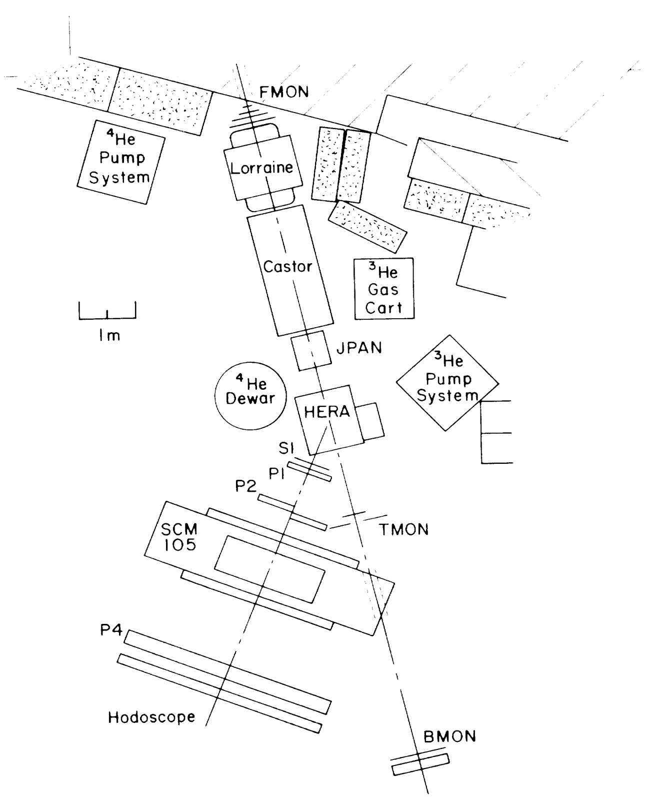

FIG. 1. Schematic diagram of the apparatus. The beam enters at the top.

inserted into the beam, brass blocks for degrading the energy of the scattered protons, and an array of plastic scintillator detectors. The neutron beam then interacted with the polarized-proton target (located within the superconducting magnet HERA) which consisted of 1,2-propanediol ($C_3H_8O_2$) beads cooled by liquid ^{3}He. The target cryostat was similar to that described in Auer *et al.*[17] and Raoul *et al.*[17] except that the size was 3.7 cm diameter by 5.5 cm along the beam direction. The target polarization was parallel or antiparallel to the beam momentum and was reversed several times during the measurement of each spin parameter. Both the proton beam and the target polarizations were typically (75–80)%, and the neutron-beam polarization was (40–50)%. The beam spin was ıeversed once every 2 min.

The momenta of the recoil protons from *np* scattering were measured with a large-acceptance ($\simeq 100$ msr) spectrometer. A scattering event was triggered in the electronics by a coincidence between the front scintillator (S1), the multiwire proportional chambers (P2), and one of the 25 scintillator paddles that formed the hodoscope at the end of the spectrometer. The information from P2 and from the drift chambers (P1 and P4) allowed reconstruction of the tracks of the scattered particles before and after traversal of the spectrometer magnet (SCM105), which had an aperture of 79×213 cm^2.

Data were collected at both 484 and 634 MeV for each of the laboratory spectrometer settings, $\theta_s = 10°$ and 35°. These were divided into six angular bins, each subtending about 4° in the laboratory frame. For the present analysis the SCM105 field was divided into three regions: a central region, where the field was roughly constant, and the two edge regions, where the field was varying. Within each region the field was described by a single polynomial for computation of the integrated field length ($\int B\,dl$).

Missing-mass spectra were obtained for each energy, angle bin, and relative beam and target polarization. Each spectrum showed the *np* elastic-scattering peak on a roughly exponential background whose shape and relative size depended on energy and angle. The peak accounted for typically (10–25)% of the counts in the region of the peak. For all the 484-MeV and the 634-MeV data at $\theta_s = 10°$, a spectrum obtained with a carbon target was used to subtract most of the background. The background that remained was fitted with a quadratic polynomial by the least-squares method. In the case of the 634-MeV data at $\theta_s = 35°$, carbon spectra were not taken. The background was described by either a quadratic polynomial or by a function of the form $\exp(ax^2 + bx + c)$. The latter form gave a better χ^2 value for the fits at the larger laboratory angles.

To ensure the consistency of the subtraction procedure, the fit was made to the background of the sum of the normalized spin parallel and antiparallel spectra. The resulting function was divided by two and used to subtract the backgrounds from the spectra for the two polarizations.

The laboratory coordinate system is defined by the unit vectors $\hat{\mathbf{L}}$, $\hat{\mathbf{S}}$, and $\hat{\mathbf{N}}$, where $\hat{\mathbf{L}}$ is parallel to the beam momentum, $\hat{\mathbf{S}}$ is perpendicular to $\hat{\mathbf{L}}$ and in the scattering plane, and $\hat{\mathbf{N}}=\hat{\mathbf{L}}\times\hat{\mathbf{S}}$. The spin-spin correlation parameters $C_{LL}(\theta)=(L,L;0,0)=A_{LL}$ and $C_{SL}(\theta)=(S,L;0,0)=A_{SL}$ were calculated with the formula

$$C(\theta)=\frac{1}{P_bP_t}\frac{I^+(\theta)-I^-(\theta)}{I^+(\theta)+I^-(\theta)},$$

where $I^{\pm}(\theta)$ are the background-corrected intensities of elastic np scattering at a center-of-mass angle θ. For C_{LL}, the superscript + (−) indicates parallel (antiparallel) spin states and for C_{LS}, + (−) indicates $\boldsymbol{\sigma}_t\times\boldsymbol{\sigma}_b$ parallel (antiparallel) to $\hat{\mathbf{N}}$. P_t and P_b ($\boldsymbol{\sigma}_t$ and $\boldsymbol{\sigma}_b$) are the target and beam polarizations (spins), respectively. The measured values of C_{LL} and C_{SL} are shown in Fig. 2. The error bars reflect both the statistical uncertainty and an estimate of the systematic uncertainty for differences between various fitting techniques. [Corrections have been applied to the C_{SL} results for a small admixture of C_{LL} ($\boldsymbol{\sigma}_b$ was 15° from $\hat{\mathbf{S}}$ as a result of an improperly adjusted magnet current) and for the precession of the neutron spin and rotation of the scattering plane caused by the polarized-target magnetic field.] There is an overall systematic error of ±10% from the absolute target and neutron-beam polarizations.[14]

The results of phase-shift calculations[4-6] (the present data were not included in these calculations) are also shown in Fig. 2. The agreement with C_{LL} is excellent at 484 MeV, except for the Hoshizaki *et al.*[6] calculation, and good at 634 MeV, reproducing the dramatic drop from $\simeq +0.7$ at 140° to $\simeq -1.0$ at 180°. At 634 MeV, the three calculations show significant differences in structure. There is good agreement with C_{SL} at both energies. The rapid change in C_{LL} is consistent with the model calculations of Chia,[18] as modified in Ref. 10, and with the behavior found at much higher energies as well (see Fig. 14 in Berger, Irving, and Sorensen[19]). Pion-exchange contributions are responsible for the rapid variation of C_{LL} in these models.

As a crosscheck of our result, the following $\theta_{\text{c.m.}}=90°$ relationship[20] should hold:

$$2C_{LL,np}=1-C_{NN,np}+\tfrac{1}{4}(C_{NN,pp}-1+2C_{LL,pp})\times(d\sigma_{pp}/d\Omega)(d\sigma_{np}/d\Omega)^{-1}. \quad (1)$$

We have obtained $d\sigma_{np}/d\Omega$ by linear interpolation of the data with $85° < \theta_{\text{c.m.}} < 95°$ in Keeler *et al.*[21] for 493 MeV and Evans *et al.*[22] for 647.5 MeV. All the pp parameters and $C_{NN,np}$ were derived from the phase-shift analysis of Arndt, Hyslop, and Roper.[4] Then, Eq. (1) predicts that for 484 MeV, $C_{LL,np}=0.358\pm0.048$, which agrees well with our measurement of 0.341 ± 0.105 (the uncertainty quoted here includes the systematic uncertainty). For 634 MeV, the predicted value is 0.473 ± 0.036—within two standard deviations of the measured value, 0.650 ± 0.109. The degree of agreement reflects the self-consistency and reliability of the various experiments.

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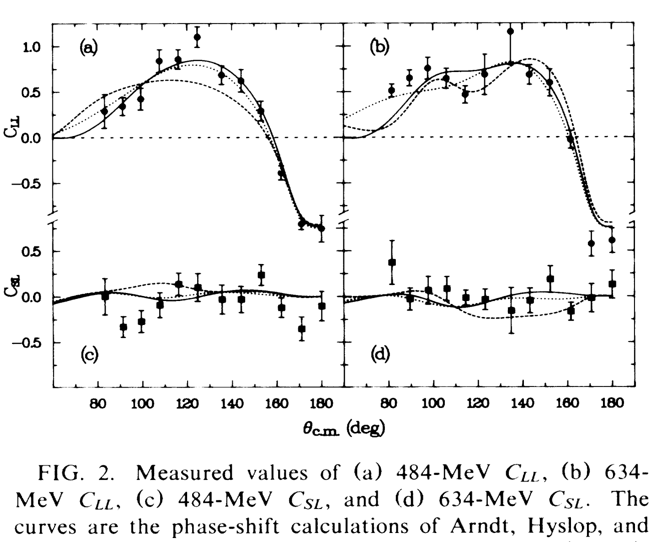

FIG. 2. Measured values of (a) 484-MeV C_{LL}, (b) 634-MeV C_{LL}, (c) 484-MeV C_{SL}, and (d) 634-MeV C_{SL}. The curves are the phase-shift calculations of Arndt, Hyslop, and Roper (Ref. 4), solid lines; Hoshizaki and co-workers (Ref. 5), dashed lines; and Dubois *et al.* (Ref. 6), dotted lines.

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