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ARTICLES

^{2}H$(p,n)2p$ spin transfer from 305 to 788 MeV

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Measurements of the spin-transfer parameter K_{LL} for ^{2}H(p,n)2p at 0° to calibrate the neutron-beam polarization clarify a normalization discrepancy affecting np data at LAMPF. The new data are in good agreement with theoretical predictions.

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I. INTRODUCTION

Polarized neutrons for np elastic experiments at LAMPF [1,2] are produced by directing the primary polarized-proton beam onto a liquid-deuterium (LD2) target and collimating the neutrons at a laboratory scattering angle of 0° (180° c.m.). The neutron beam is polarized via the L-to-L spin-transfer observable K_{LL} for the ^{2}H(p,n) reaction. (L spin denotes longitudinal polarization, i.e., parallel to the momentum vector.) This measurement of K_{LL} affects the normalization of all polarized np experiments [3-15] that have used this facility at the BR neutron channel at LAMPF. Disagreement between this measurement and previous measurements [14,15] opens the question of renormalizing previous data as discussed in Sec. V.

This measurement of K_{LL} for ^{2}H(p,n) is a convenient calibration standard for neutron beams. The cross section is large [1,2], the background is small, and high resolution is not required. For example, this has been used to calibrate the long-flight-path neutron time-of-flight facility (NTOF) at LAMPF.

There is also intrinsic interest in this reaction [16,17]. The final-state interaction in ^{2}H$(p,n)2p$ selects two protons in a relative S state and thus enhances not only the cross-section but also the spin-transfer parameter K_{LL}. The present measurements agree more closely with the calculations than do the previous measurements.

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II. EXPERIMENTAL METHOD

A. Principle

The spin-transfer coefficient K_{LL} was measured by double scattering from two liquid-deuterium targets (LD2). The first LD2 target produced polarized neutrons near zero scattering angle via ^{2}H(p,n) with polarization $P_n = P_b K_{LL}$, where P_b is the polarization of the primary proton beam from the LAMPF accelerator. The second LD2 target produced polarized protons near zero scattering angle via ^{2}H(n,p) with polarization $P_p = P_n K'_{LL}$. By charge symmetry $K_{LL} = K'_{LL}$ so that

$$P_p = P_b K_{LL}^2.$$

By measuring P_b and P_p we deduce K_{LL}. Systematic errors from the angular acceptance, momentum acceptance, background, and absolute calibration are discussed below.

B. Proton beam

Polarized protons from the optically pumped source OPPIS were accelerated in the LAMPF accelerator to energies from 318 to 798 MeV. A solenoid and bending magnets precessed the spin direction to L (parallel or anti-parallel to the momentum). All components of the proton-beam polarization P_b were measured to ± 0.01 by two polarimeters separated by a 16° bend. The proton beam was focused to a spot with rms radius of about 3 mm and centered on the 25-cm-thick liquid-deuterium neutron-production target.

C. Neutron beam

Longitudinally polarized (L-spin) neutrons near 0° were produced by the ^{2}H(p,n) reaction. The nominal proton-beam energies are 318, 497, 647, 733, and 798 MeV. Energy loss in half the 25-cm-long LD2 target reduces these to 311, 491, 641, 728, and 794 MeV at the center of the neutron-production target. To get the neutron energies we must subtract the deuteron binding energy (2.2 MeV) and the mean kinetic energy of the two spectator nucleons (variously estimated as 2 to 5 MeV) to get 305, 485, 635, 722, and 788 MeV, which are the nominal energies (± 2 MeV) listed in Table I. Since we measure the geometric mean of the first and second scattering in this double-scattering experiment, and since the second scattering energy is 4 or 5 MeV lower, we have made small corrections of -0.002, -0.002, -0.001, -0.001, and 0 so the data in Table I apply to the nominal energies of 305, 485, 635, 722, and 788 MeV.

TABLE I. K_{LL} for ^{2}H(p,n) at zero neutron angle (180° c.m.). The total uncertainty includes statistics (stat.), 0.003 uncertainty from the shape of the angular distribution (Sec. II E), and 1.4% normalization uncertainty (see Sec. III).

Energy (MeV)	K_{LL}	±stat	±total
305	-0.411	±0.008	±0.010
485	-0.579	±0.007	±0.011
635	-0.686	±0.007	±0.012
722	-0.717	±0.008	±0.013
788	-0.720	±0.014	±0.017

Neutrons were collimated near 0° by a 3.6-m-long steel-and-lead collimator through a 3.6-m steel wall. The collimator was conical, pointing to a vertex at the neutron production (LD2) target, with a 0.2° half-angle (2.5 cm radius at a distance of 757 cm).

The L-to-L spin-transfer parameter from deuterium is large while the other spin-transfer parameters are small, so that the neutrons were initially polarized in the L direction, almost independently of the precise proton-spin direction. Immediately after the neutron-production target, the proton beam was swept aside by bending magnets. The neutrons passed through the fringe fields of these magnets and were precessed about 60° from L spin. A vertical magnetic field (BRBM1) immediately after the collimator served two functions: (1) to precess the spin back to L spin, and (2) to sweep charged particles produced in the collimator out of the neutron beam, into a 60-cm-thick lead shield wall.

In view of the discrepancy between this measurement and previous measurements [14,15] it is important to examine the possible differences between the present and previous configurations. The only difference that we believe could be significant is the 3.8-cm-thick lead plug that was used in the previous experiments to attenuate gamma rays, but was not used in the present experiment. Calculations indicate that the effect of this plug on the neutron polarization was less than a few percent, but we plan to measure this soon.

D. Experimental layout

1. Target

The polarized neutron beam was directed onto a 15-liter liquid-deuterium target consisting of a cylinder 15-cm long and 12-cm in radius, with hemispherical end windows of 12-cm radius for a total length of about 39 cm. The end windows were 0.4-mm-thick Mylar plastic. The liquid deuterium was contained in an insulating vacuum with entrance and exit windows each of 0.4-mm-thick Mylar and Kevlar plastic. The vacuum chamber was contained in a protective tent with Mylar plastic entrance and exit windows 25-μm thick.

2. Proton spectrometer

Protons produced near 0° laboratory (180° c.m.) were detected in the Scylla magnetic spectrometer [18]. Two scintillators, S1 and S2, each 5-mm thick by 300-mm wide by 457-mm high, were placed upstream and downstream of a set of three multiwire proportional chambers (M1, M2, M3) to define the proton trajectory as described previously [18]. The proton scattering angle was measured

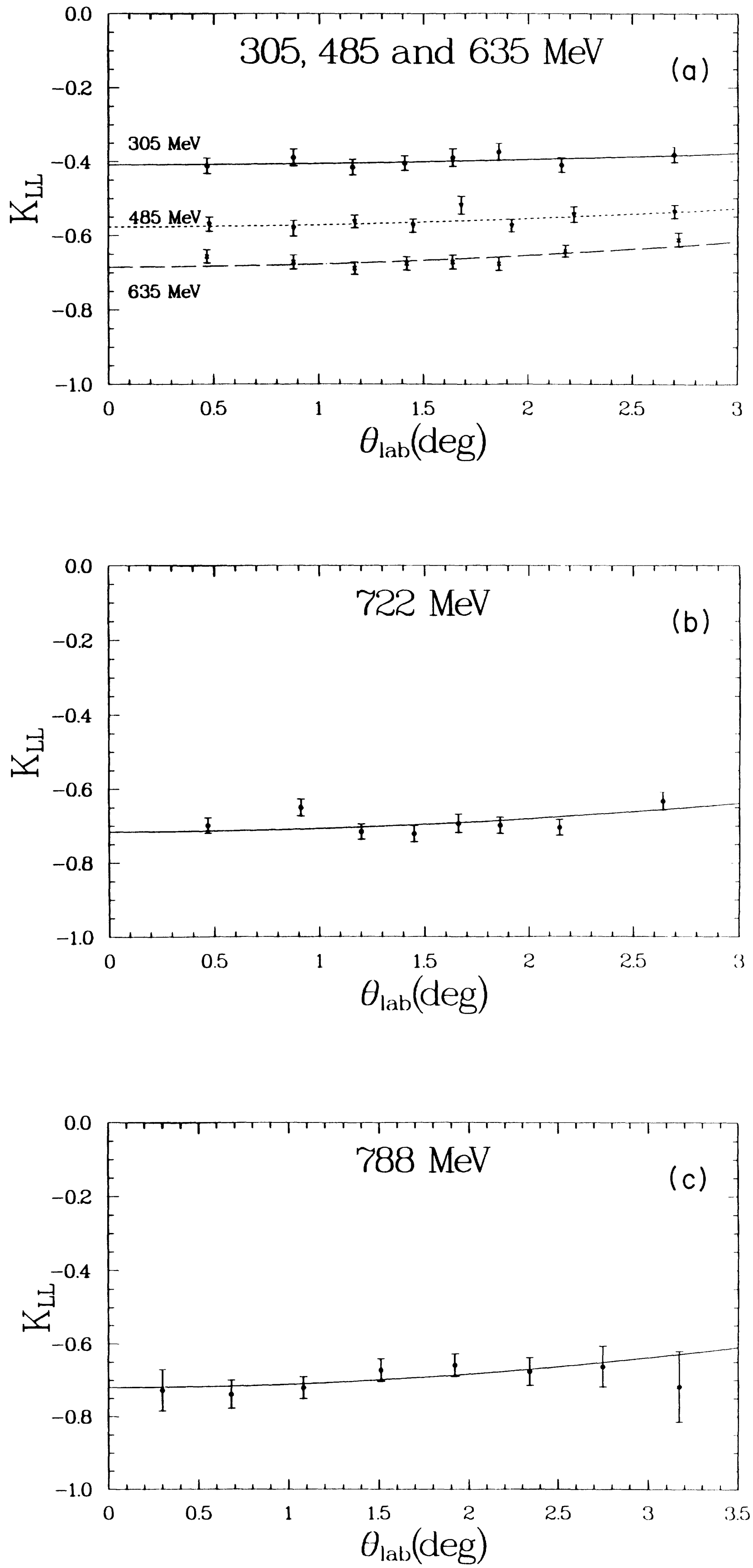

FIG. 1. K_{LL} vs laboratory scattering angle (at several energies). The fit is discussed in Sec. II E.

with a resolution of ±2.5 mr and an absolute accuracy of about 1 mr; so the uncertainty in the mean proton scattering angle was $\pm0.1°$ c.m. The scintillators measured the time relative to the accelerator rf with a resolution of $\pm$ 0.5 to 0.6 ns over the 15-m flight path from the LD2 neutron-production target to the scintillators.

After passing through S1, M1, M2, M3, and S2, the scattered protons were deflected 30° in a vertical plane through Scylla, a bending magnet 1.22-m long with a gap 0.25 m wide by 0.56 m high. The Scylla magnet served two purposes: (1) to select the proton momentum, and (2) to precess the final-state L-spin component through about 90° to allow this component to be measured by the Janus polarimeter. Momentum resolution was ±1.3–2.3% limited by energy loss from the large LD2 target. Typical cuts (both on momentum and time-of-flight) were ±2.5 standard deviations. The average spin precession in Scylla was deduced from the bend angle, which was measured to better than 0.2%.

3. *Janus Polarimeter*

The Janus carbon polarimeter has been described in detail [19]. Janus has been used in eleven previous LAMPF experiments and is well understood. It has been extensively calibrated [20,21] to 2% and its calibration agrees well with that of similar devices at Saturne [22], TRIUMF [23,24] and SIN/PSI [25].

E. Angular distribution

As discussed in Sec. C (Neutron Beam), neutrons from the first scattering were collimated within a cone of 0.2° half angle. Protons from the second scattering, however, extended from laboratory scattering angle $\theta = 0°$ to $2.7°$. It is convenient to parametrize the angular distribution by $K(\theta) = K(0)(1 - c\theta^2)$. Since the first scattering was always close to zero then we measure $\sqrt{K(0)K(\theta)} \approx K(0)(1 - 0.5c\theta^2)$. We obtained values of the coefficient c by three different methods: (1) from the calculations of Bugg and Wilkin [17]; (2) from various np phase-shift solutions [26–29], and (3) from fits to our data with c as a free parameter. Differences among these three methods were not significant, and contributed 0.003 to the final uncertainty of $K(0)$. Final values of c were 0.017, 0.019, 0.022, 0.024, and 0.025 (deg)$^{-2}$ for the five energies 305, 485, 635, 722, and 788 MeV, respectively. Fits to the data are illustrated in Fig. 1.

F. Background

The reactions of interest are the ^{2}H(n,p) reaction and the charge-symmetric reaction ^{2}H(p,n) at 0° laboratory. These events were selected by cuts on incident neutron time-of-flight, scattered proton time-of-flight and momentum, as discussed in detail in Ref. [18].

Background reactions are (a) the same reaction in which the nn and pp pair carry off significant momentum (with little or no final-state interaction); (b) C(n,p), N(n,p), etc. from target windows, scintillators, and air; (c) H(n,p) from target windows and scintillators.

Case (a) has been studied by Riley *et al.* (see Fig. 3 of Ref. [14]) and by the NTOF Collaboration at LAMPF. Since the spin-transfer parameter for this background is similar to that in the main peak, this background correction is small. Events with momentum more than 50 MeV/c from the main peak were excluded from the analysis. As in our previously reported measurements [18], we monitored this background by extrapolating under the peak of the momentum spectrum and found it to be less than 1% at every energy. Thus we estimate the correction for case (a) to be less than 0.001.

Case (b), C(n,p), has also been studied by the NTOF Collaboration at LAMPF. We estimate the background from C, N, and O to be less than 1% with spin-transfer parameters within 10% of that for deuterium, so again the correction is less than 0.001.

Case (c), H(p,n) events, would appear under the main peak of our momentum spectrum and so were included in the analysis. However, this source of background can be easily calculated. We calculate that these events were 1% of the total, with K_{LL} differing by 0.1 from deuterium (see Fig. 2), resulting in a correction of 0.001 which has been applied to the final results.

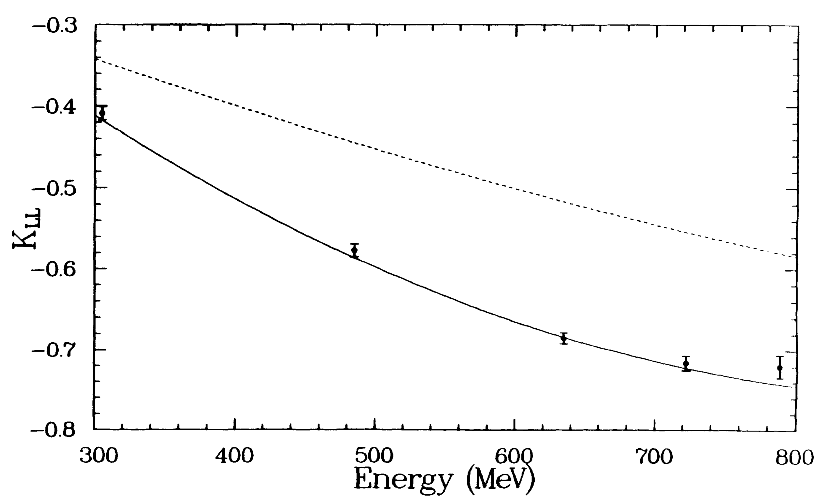

FIG. 2. K_{LL} vs energy; data are compared with calculations by Bugg and Wilkin for ^{2}H(p,n) (solid line) and $p(p,n)$ (dashed line).

III. NORMALIZATION

The polarization of the primary proton beam P_b was measured by two beam-line polarimeters (separated by a bend to measure all three spin components). The beam-line polarimeters have been calibrated to 1% for a well-focused beam spot, and agree well with similar measurements at TRIUMF, SIN/PSI, and Saturne (see Ref. [30] and references therein). With a less well-focused beam the analyzing power decreases by about 2% as shown by the different columns in Ref. [30]. For the line B (LB) polarimeters used here we have used the analyzing powers A_{LB} from Ref. [30] and assigned an uncertainty of 2%. Since we measure the square of K_{LL} then the contribution to the uncertainty in K_{LL} is 1%.

The Janus polarimeter, used to measure the final proton polarization P_p, has been calibrated [21] to 2%. The calibration agrees well with similar devices at TRIUMF [23,24], SIN/PSI [25], and Saturne [22]. Again, since we measure K_{LL}^2 this contributes 1% to the uncertainty in K_{LL}.

Combining these two 1% normalization uncertainties quadratically we estimate the total normalization uncertainty to be ±1.4%. In principle this uncertainty could be energy dependent, but since most of the possible errors in Refs. [21] and [30] are either constant or smooth functions of energy, this 1.4% will also be constant or a smooth function of energy. This conclusion is reinforced by the good agreement between the data and the curve in Fig. 2 (see Sec. IV).

IV. RESULTS

Results are listed in Table I and illustrated in Fig. 2 in comparison with updated calculations by Bugg following the method of Bugg and Wilkin [17]. The solid curve is a fit by these calculations: $K = 0.886G^2 - 1.642G + 0.001$, where G is the beam energy in GeV. The data and curve have $\chi^2 = 1.0$ per point. If the data are multiplied by 1.01 then χ^2 becomes 0.6 per point.

The present results disagree with the previous measurements of Riley *et al.* [14] and Chalmers *et al.* [15]. These earlier measurements share a common systematic uncertainty of 7% resulting from the *np*-elastic analyzing power [3] to which both of these results were normalized. The disagreement with these earlier data suggests that the *np*-elastic analyzing power data [3] should be renormalized.

We believe that the previous results [14,15] are less reliable for the following reasons.

(1) The previous analyzing power data [3] are about 10% higher than results from other measurements (see Refs. [28], [31], [32] and references therein). Our suggested renormalization would improve the agreement.

(2) Reference [3], Section F states that the measured polarization of the polarized-proton target used in the experiment was 0.70 ± 0.02. Reference [3], Section G states that this estimate was decreased by 4%, i.e., to 0.67. The renormalization suggested here would be consistent with a target polarization of 0.74. When the same target system was used with a smaller active volume the year before Newsom's experiment, the target polarization was reported [33] to be 0.83, so 0.74 is not unreasonable.

(3) The previous measurements of K_{LL} for $^2\mathrm{H}(p,n)$ are normalized to the data of Ref. [3] and disagree with the theoretical predictions (see Fig. 3 of Ref. [15]). The present results agree well with predictions (see Fig. 2 of this paper).

(4) In the $^2\mathrm{H}(p,n)2p$ reaction with a spin-zero diproton, the particle spins are $1+\frac{1}{2}$ goes to $\frac{1}{2}+0$. For this case there is a sum rule [17,34]: $K_{LL} + 2K_{NN} = -1$. At 788 MeV we measured $K_{NN} = -0.13 \pm 0.03$ which gives $K_{LL} + 2K_{NN} = -0.98$. The previous data [14,15] do not obey this rule.

(5) If we use the previous normalization [14,15], then our recent measurement of spin transfer in *np*-elastic scattering [18] gives $K_{LL}^2 + K_{LS}^2 = 1.29 \pm 0.03$ which is impossible since $K_{LL}^2 + K_{LS}^2 \leq 1$. Using the normalization of the present measurement gives $K_{LL}^2 + K_{LS}^2 = 0.96$.

(6) At 90° c.m. there are internal consistency checks [35] among the spin correlation parameters which can be used to derive the neutron-beam polarization. Taking each energy separately, the *np* data are consistent with the present normalization with $\chi^2 = 4$ for 3 energies, but with the previous normalization with $\chi^2 = 9$ or 10.

V. RENORMALIZATION OF PREVIOUS DATA

The calibration reported here suggests that several previous data sets should be renormalized as follows.

Newsom *et al.* [3] measured the *np* analyzing power from 375 to 775 MeV using an unpolarized neutron beam incident on a polarized target. This measurement used a white neutron beam spectrum, thus measuring the full range of energies simultaneously at each angle. A possible source of error was the measurement of the target polarization as discussed in Item 2 of Sec. IV. If so, then a single renormalization factor should apply to the whole data set. The previous measurements [14,15] of K_{LL} are normalized to the Newsom data; so, we have determined a renormalization factor from the ratio of these previous [14,15] to the present measurements. At each energy there is a 2% uncertainty from each of the present and previous measurements as well as from the Newsom data, so the ratio at one energy has an uncertainty of 3–4%. All are consistent with the mean ratio of 0.88 ± 0.02 with $\chi^2 = 1.6$ per degree of freedom.

Ransome *et al.* [10,11] normalized to Ref. [14] with K_{LL} for $^2\mathrm{H}(p,n)$ in the denominator, so we should multiply by 0.64/0.72. Reference [36] [the measurement of K_{LL} for $\mathrm{Li}(p,n)$] was also normalized to Ref. [14] but with K_{LL} for $^2\mathrm{H}(p,n)$ in the numerator, so we should multiply by 0.72/0.64.

Nath *et al.* [9] and Glass *et al.* [4] were normalized to Ref. [15], so we should multiply by 0.604/0.720.

The data of Rawool, Garnett *et al.* [5–8] and Beddo [12,13] extend over several energies and were all normalized to Chalmers *et al.* [15]. Therefore we should multiply by 0.604/0.720 at 788 MeV, 0.637/0.686 at 635 MeV, and 0.499/0.579 at 485 MeV. Beddo interpolated for the intervening energies (Table 6.2 of Ref. [12]) so the appropriate factors are 0.568/0.643 at 568 MeV and 0.620/0.717 at 722 MeV.

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