# ARTICLES

## $np$ elastic spin-transfer measurements at 485 and 635 MeV

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We have measured the spin-transfer parameters $K_{LL}$, $K_{SL}$, $K_{LS}$, and $K_{SS}$ at 635 MeV from 50° to 178° c.m. and at 485 MeV from 74° to 176° c.m. These new data have a significant impact on the phase-shift analyses. There are now sufficient data near these energies to overdetermine the elastic nucleon-nucleon amplitudes.

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### I. INTRODUCTION

The 1991 status of the $np$ elastic phase-shift analysis near 650 MeV was summarized by Bugg and Bryan [1] as follows. "There are not enough accurate spin-dependent data to give a secure solution and most of the phase shifts are strongly correlated, with correlation coefficients as high as 76%." "To stabilize the solution, Wolfenstein (spin-transfer) parameter data are required of similar quality to those at 800 MeV." We present these new data here. With the inclusion of these data, Bugg reports stable solutions with small correlations at 650 MeV.

Previous spin-dependent data near 650 MeV include the analyzing power [2], the four spin-correlation parameters [3–6], and the four spin-transfer parameters reported here. These data are sufficient to over determine the elastic nucleon-nucleon amplitudes [7].

Previous measurements of the spin-transfer parameters are discussed in Sec. IV. The normalization of both present and previous LAMPF data is discussed in Sec. III.

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## II. EXPERIMENTAL METHOD

The experimental method used for this measurement is identical to that used for our recent measurement at 788 MeV and is described in detail in our previous paper [8]. Briefly, polarized protons from the LAMPF accelerator are used to produce a polarized neutron beam via the $^2\mathrm{H}(p,n)$ reaction from liquid deuterium. The polarized neutrons are precessed to $L$ or $S$ spin (parallel or perpendicular to the momentum vector in the horizontal scattering plane) by a dipole magnet and collimated onto a liquid-hydrogen target. Elastically scattered neutrons and protons are detected by a neutron detector [9] and by the Scylla magnetic spectrometer. The 30° vertical bend in Scylla precessed the $L$-spin component through approximately 90° while leaving the $S$-spin component unchanged, thus allowing us to measure both the $L$ and $S$ components ($P_L$ and $P_S$) with the Janus carbon polarimeter [10–12]. If $B_L$ is the $L$-spin component of the neutron beam then the spin transfer parameter $K_{LS}$ is defined by

$$K_{LS} = P_S/B_L$$

and similarly for $K_{LL}$, $K_{SL}$, and $K_{SS}$.

The sign conventions are confusing, so Table I from our previous paper is included here to define these parameters in terms of Arndt's widely used SAID scattering analysis and phase-shift program [13] and in terms of the comprehensive review paper by Bystricky, Lehar, and Winternitz [14].

### A. Spin direction

The spin direction of the 788-MeV polarized neutron beam at LAMPF as measured in our earlier experiment [8] disagreed by 1.5 standard deviations from previous measurements [15] and this disagreement was discussed in detail in Sec. II H of Ref. [8]. Following the procedures of Spinka [15] we determine a neutron-spin precession in the line-$B$ bending magnets LBBM6 and 7 (see Fig. 1) of $0.0307p/\beta$ deg, where $p$ is the beam proton momentum in MeV/$c$ and $\beta = v/c$ is the neutron velocity. The precession in the newly installed permanent magnet BRBM0 was measured and found to be $12.3/\beta$ deg.

The neutron-spin direction was determined with the neutron polarimeter (QPAN) and the data at 485, 635, and 788 MeV were consistent with these equations within the uncertainty of ±0.5°. Also, as in the 788-MeV paper [8], we used the relation

$$(K_{LS}+K_{SL})/(K_{LL}-K_{SS}) = \tan\theta_{\mathrm{lab}}$$

TABLE I. Sign convention and notation.

| This paper | Arndt | Bystricky |
|---|---|---|
| $K_{LS}$ | AT | $-K_{0sk0}$ |
| $K_{LL}$ | APT | $+K_{0kk0}$ |
| $K_{SS}$ | RT | $+K_{0ss0}$ |
| $K_{SL}$ | RPT | $-K_{0ks0}$ |

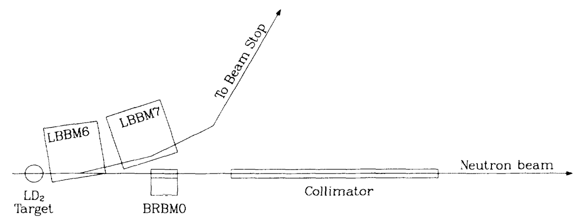


FIG. 1. Layout of BR neutron-production beam line at LAMPF. The primary proton beam is swept aside by LBBM6 and 7. The neutron beam is precessed by the fringes of LBBM6 and 7 and by BRBM0.

to calculate a correction to the spin direction that would minimize $\chi^2$. This agreed both with QPAN and with the above equations within the statistical uncertainty of ±1.2°.

In summary the present spin-precession data are consistent with our earlier paper [8] but differ by 1.5 standard deviations from the older data [15]. We have assigned the same 0.7° uncertainty to the spin direction as for the 788-MeV data.

### B. Background

As in our previous measurement [8] good $np$ elastic events were selected by cuts on proton momentum and both incident neutron and scattered proton time of flight. The final data were obtained without requiring the neutron detector in coincidence, but the neutron detector was used as a check on the background.

The background measured by extrapolating under the peak of good events was less than 2%. We measured the spin transfer for the background in the tails of the momentum spectra to be $0.6 \pm 0.1$ times that for the elastic events so this implies background corrections of 1% or less.

Data acquired with a neutron in coincidence had less background (see Fig. 2 of our previous paper [8]) but had larger statistical uncertainties. The average ratio of the spin-transfer parameters measured with and without the neutron detector in coincidence was $1.04 \pm 0.02$, compared with a ratio of $1.00 \pm 0.01$ at 788 MeV.

The main sources of background are the plastic windows of the liquid-hydrogen target. There are three windows that are visible to the detectors with a total thickness of 0.16 g/cm$^2$ of plastic compared with 2.5 g/cm$^2$ of liquid hydrogen. Since plastic is approximately half neutrons and half protons, and since half of the protons are shadowed within the nucleus, the background from bound protons is $0.04/2.5 = 1.6\%$. The spin transfer for quasifree scattering from bound protons is expected to be similar to free scattering. So we estimate that background corrections are less than 1%. No background corrections have been made to the data, but an uncertainty of 1% has been added quadratically to the overall normalization uncertainty (Sec. III) to account for the background.

TABLE II. Spin-transfer parameters from *np* elastic scattering at 635 MeV. The overall normalization uncertainty is 2%.

| $\theta_{c.m.}$ (deg) | $\theta_{lab}$ (deg) | $K_{LS}$ | $K_{LL}$ | $K_{SS}$ | $K_{SL}$ |
|---|---|---|---|---|---|
| 178.03 | 0.85 | -0.012±0.040 | -0.555±0.031 | -0.042±0.061 | -0.005±0.047 |
| 176.46 | 1.53 | 0.038±0.056 | -0.494±0.038 | -0.073±0.077 | -0.048±0.059 |
| 174.82 | 2.24 | 0.009±0.046 | -0.506±0.031 | -0.169±0.072 | -0.085±0.059 |
| 170.31 | 4.19 | 0.049±0.057 | -0.385±0.057 | -0.519±0.053 | 0.119±0.055 |
| 168.63 | 4.92 | 0.117±0.057 | -0.295±0.057 | -0.612±0.054 | 0.053±0.053 |
| 166.71 | 5.75 | 0.055±0.057 | -0.338±0.057 | -0.732±0.054 | 0.075±0.053 |
| 159.58 | 8.85 | -0.034±0.052 | -0.325±0.052 | -0.586±0.057 | 0.118±0.056 |
| 157.59 | 9.72 | 0.003±0.047 | -0.300±0.047 | -0.465±0.052 | 0.026±0.052 |
| 155.43 | 10.66 | 0.004±0.047 | -0.482±0.047 | -0.508±0.049 | 0.057±0.049 |
| 148.23 | 13.82 | -0.098±0.054 | -0.562±0.055 | -0.190±0.056 | 0.021±0.056 |
| 146.15 | 14.74 | -0.091±0.048 | -0.545±0.050 | -0.146±0.052 | 0.047±0.052 |
| 143.75 | 15.80 | -0.119±0.044 | -0.625±0.046 | -0.033±0.046 | 0.092±0.047 |
| 137.53 | 18.57 | -0.262±0.033 | -0.650±0.036 | 0.035±0.037 | 0.034±0.039 |
| 134.70 | 19.83 | -0.239±0.031 | -0.642±0.033 | 0.113±0.035 | -0.008±0.036 |
| 131.65 | 21.21 | -0.208±0.031 | -0.688±0.033 | 0.096±0.035 | -0.016±0.036 |
| 126.67 | 23.47 | -0.302±0.038 | -0.789±0.039 | 0.109±0.035 | -0.045±0.037 |
| 123.49 | 24.92 | -0.321±0.036 | -0.704±0.038 | 0.107±0.035 | -0.096±0.037 |
| 120.10 | 26.48 | -0.217±0.034 | -0.687±0.036 | 0.143±0.033 | -0.053±0.034 |
| 115.89 | 28.43 | -0.281±0.036 | -0.643±0.039 | 0.044±0.038 | -0.143±0.040 |
| 112.85 | 29.85 | -0.278±0.036 | -0.631±0.039 | 0.059±0.038 | -0.041±0.039 |
| 109.38 | 31.48 | -0.268±0.029 | -0.612±0.032 | 0.006±0.031 | -0.104±0.032 |
| 105.27 | 33.43 | -0.282±0.042 | -0.570±0.046 | -0.065±0.039 | -0.094±0.041 |
| 102.01 | 34.99 | -0.315±0.040 | -0.559±0.042 | -0.009±0.036 | -0.027±0.037 |
| 98.61 | 36.63 | -0.324±0.038 | -0.505±0.040 | -0.064±0.034 | -0.055±0.040 |
| 94.71 | 38.52 | -0.339±0.039 | -0.511±0.042 | -0.037±0.042 | 0.096±0.045 |
| 91.56 | 40.07 | -0.231±0.040 | -0.392±0.040 | -0.082±0.039 | 0.053±0.041 |
| 88.20 | 41.73 | -0.242±0.035 | -0.395±0.037 | -0.121±0.035 | 0.096±0.036 |
| 84.83 | 43.41 | -0.236±0.037 | -0.265±0.040 | -0.090±0.038 | 0.100±0.040 |
| 81.71 | 44.99 | -0.217±0.033 | -0.240±0.035 | -0.109±0.036 | 0.070±0.035 |
| 78.34 | 46.70 | -0.182±0.031 | -0.272±0.032 | -0.160±0.031 | 0.083±0.033 |
| 74.55 | 48.64 | -0.210±0.039 | -0.186±0.042 | -0.042±0.039 | 0.043±0.028 |
| 71.34 | 50.29 | -0.134±0.041 | -0.134±0.043 | -0.196±0.041 | 0.099±0.044 |
| 68.11 | 51.98 | -0.187±0.051 | -0.092±0.054 | -0.166±0.052 | 0.078±0.054 |
| 65.18 | 53.51 | -0.037±0.032 | -0.075±0.036 | -0.136±0.033 | 0.156±0.036 |
| 62.19 | 55.10 | -0.068±0.041 | -0.143±0.045 | -0.197±0.066 | 0.089±0.043 |
| 59.15 | 56.71 | -0.008±0.047 | -0.064±0.052 | -0.099±0.046 | 0.113±0.049 |
| 55.94 | 58.44 | 0.021±0.060 | -0.028±0.068 | -0.134±0.062 | -0.012±0.057 |
| 53.04 | 60.00 | 0.091±0.068 | 0.047±0.075 | 0.029±0.057 | 0.013±0.061 |
| 50.13 | 61.58 | 0.086±0.093 | -0.072±0.099 | 0.024±0.075 | -0.047±0.080 |

TABLE III. Spin-transfer parameters from *np* elastic scattering at 485 MeV. The overall normalization uncertainty is 2%.

| $\theta_{c.m.}$ (deg) | $\theta_{lab}$ (deg) | $K_{LS}$ | $K_{LL}$ | $K_{SS}$ | $K_{SL}$ |
|---|---|---|---|---|---|
| 176.1 | 1.7 | 0.034±0.046 | -0.450±0.029 | -0.220±0.062 | 0.000±0.050 |
| 157.0 | 10.3 | 0.094±0.030 | -0.309±0.031 | -0.659±0.036 | -0.014±0.034 |
| 146.5 | 15.0 | -0.006±0.028 | -0.449±0.031 | -0.469±0.040 | 0.044±0.039 |
| 135.4 | 20.1 | -0.184±0.030 | -0.590±0.032 | -0.134±0.032 | 0.069±0.033 |
| 114.2 | 30.0 | -0.347±0.039 | -0.524±0.041 | 0.190±0.040 | -0.092±0.041 |
| 93.1 | 40.2 | -0.133±0.043 | -0.345±0.046 | | |
| 74.2 | 49.7 | -0.038±0.084 | -0.016±0.091 | | |

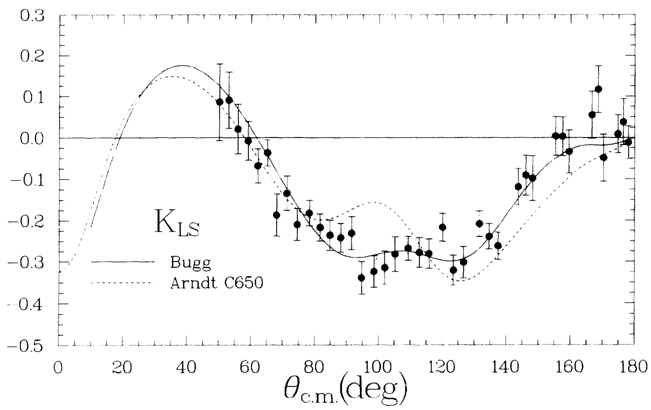


FIG. 2. Spin-transfer observables KLS at 635 MeV compared with recent phase-shift fits by Arndt and Bugg.

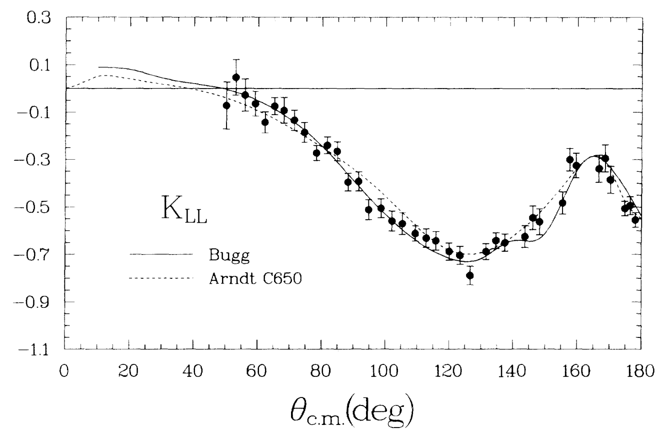


FIG. 3. Spin-transfer observables KLL at 635 MeV compared with recent phase-shift fits by Arndt and Bugg.

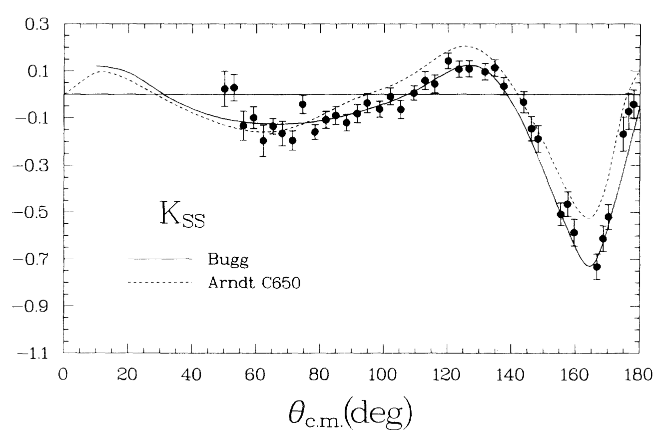


FIG. 4. Spin-transfer observables KSS at 635 MeV compared with recent phase-shift fits by Arndt and Bugg.

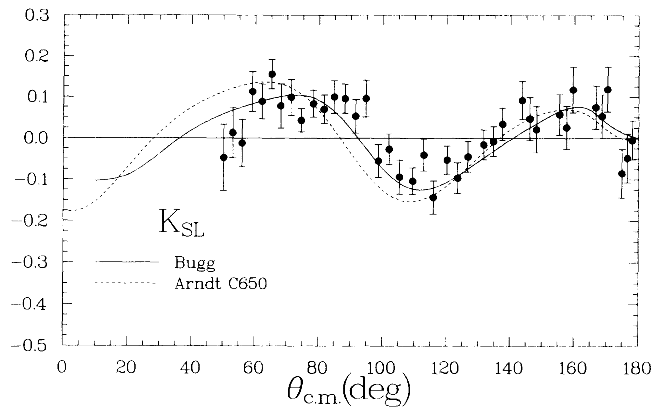


FIG. 5. Spin-transfer observables KSL at 635 MeV compared with recent phase-shift fits by Arndt and Bugg.

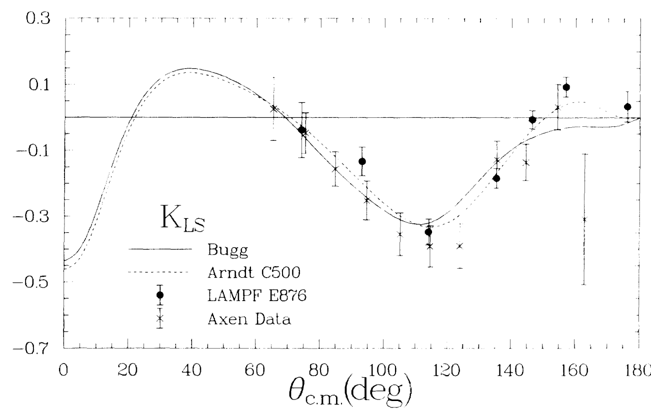


FIG. 6. Spin-transfer observables KLS at 485 MeV with Axen's data, compared with recent phase-shift fits by Arndt and Bugg.

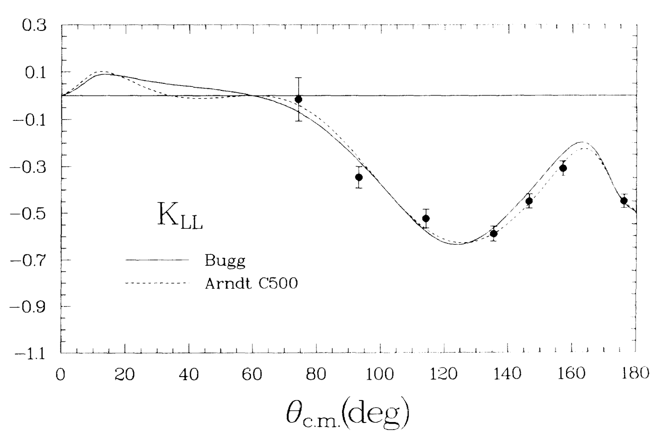


FIG. 7. Spin-transfer observables KLL at 485 MeV compared with recent phase-shift fits by Arndt and Bugg.

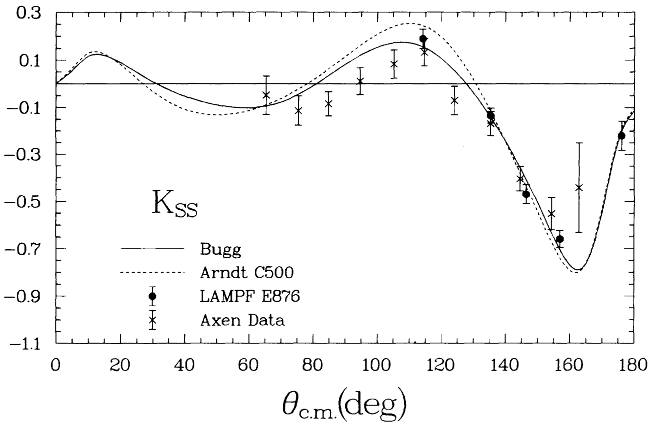


FIG. 8. Spin-transfer observables KSS at 485 MeV with Axen's data, compared with recent phase-shift fits by Arndt and Bugg.

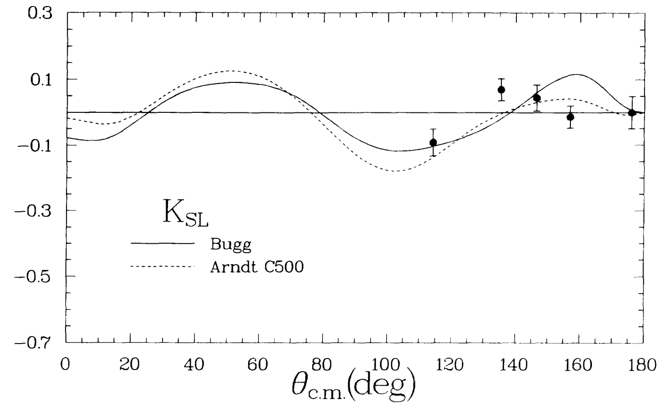


FIG. 9. Spin-transfer observables KSL at 485 MeV compared with recent phase-shift fits by Arndt and Bugg.

## III. NORMALIZATION

As discussed in detail in Ref. [8] the overall normalization is tied to the measurement [16] of $K_{LL}$ for the $^2$H$(p, n)$ reaction, which has a 1.8% uncertainty. When we add quadratically the 1% uncertainty in background subtraction as discusssed in Sec. II B, the total normalization uncertainty is 2%.

The remeasurement of the LAMPF neutron-beam polarization [16] also affects the normalization of much of the previous LAMPF spin-dependent data, as discussed in Ref. [16].

## IV. RESULTS AND PREVIOUS DATA

The measured observables are defined in Table I, listed in Tables II and III, and are illustrated in Figs. 2–9 in comparison with recent phase-shift analyses before [13] and after [1] including these data.

There are two previous measurements of spin-transfer parameters near these energies. Leung [17] measured $K_{SS}$ and $K_{SL}$ at 520 and 600 MeV at Berkeley in 1970. The 635-MeV data reported in this paper have ten times the number of points and one quarter the uncertainty for each point, i.e., more than one hundred times the statistical weight as Leung's data. Axen [18] measured $K_{SS}$ and $K_{LS}$ at 495 MeV at TRIUMF in 1980. Axen's data are generally in agreement with our 485-MeV data.

## ACKNOWLEDGMENTS

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