Spin-flip probability in $^{12}C(\vec{p},\vec{p}\,')^{12}C^*$ at 397 MeV

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Measurements of the spin-flip probability for states in ^{12}C excited by 397 MeV protons are presented. These data are compared with distorted-wave Born approximation and plane-wave calculations using Cohen-Kurath wave functions as well as simpler transition densities. The results are discussed in terms of the implications for nuclear structure as well as the nucleon-nucleon effective interaction.

NUCLEAR REACTIONS $^{12}C(\vec{p},\vec{p}\,')$, spin-flip probability; DWBA, nucleon-nucleon effective interaction.

I. INTRODUCTION

Measurements of differential cross sections and analyzing powers for inelastic proton scattering at medium energies (100–800 MeV) are currently being used to test the nucleon-nucleon (*NN*) effective interaction. Comparisons of the data to theoretical predictions are sensitive to many details of both the transition density and the distorting optical potential. In this paper we report on the first measurement of the spin-flip probability (SFP or S_{nn} in the equations and figures) in inelastic scattering at intermediate energies. As we demonstrate in Sec. III, this observable, which is related to the polarization transfer coefficient D_{nn} by

$$S_{nn}=\tfrac{1}{2}\{1-D_{nn}\}\ ,$$

is much less sensitive to the details of the transition density. Near the maximum in the differential cross section the SFP is primarily sensitive to the *NN* effective interaction and the spin transfer, *S*, to the target. These features make the SFP a promising observable both for testing the *NN* effective interaction and for identifying spin modes of nuclear excitation.

The earliest measurements of SFP's (Ref. 1) used the $(p,p'\gamma)$ technique, which is limited mainly to $0^+\rightarrow 2^+$ transitions where spin transfer is relatively unimportant. Direct measurements of the SFP were later made using a carbon polarimeter[2] at proton energies of 30 to 50 MeV. In that work large SFP's were measured for the 1^+, $T=0$ state in ^{12}C and other unnatural-parity states. Interpretation of data at those energies is complicated because of reaction-mechanism uncertainties. This problem should be less severe at high energies.

In this work data were obtained at a proton bombarding energy of 397 MeV for states in ^{12}C. The measurements were made with the recently developed polarimeter in the focal plane of the high resolution spectrometer (HRS) at the Clinton P. Anderson Meson Physics Facility.[3] In Sec. II we outline the use of the focal-plane polarimeter for our study. We compare the data to theoretical predictions and present possible interpretations in Sec. III.

II. EXPERIMENTAL DETAIL

The use of the HRS focal-plane polarimeter for measurements of the spin-rotation parameter *Q* in elastic scattering at $T_p = 500$ MeV has been described previously.[4] This system is also well-suited to inelastic-scattering studies as it maintains the HRS resolution ($\simeq 100$ keV FWHM) while analyzing all states within the HRS acceptance ($E_x = 6-23$ MeV for these measurements). The extension to inelastic scattering at moderate excitation energies presents the added difficulty of subtracting the polarization effects due to background under the peaks of interest. In the present work, this background was due primarily to broad states of the target in the excitation-energy range of interest and some instrumental background. This is quite different from the beam-related backgrounds described by Besset *et al.*[5] Our method of subtraction involved measuring the background polarization on either side of the peak in excitation energy and the peak-plus-background polarization under the peak. In all cases the polarization of the background did not change significantly from one side to the other.

Given the polarization of the background (P_B) and the polarization of the measured peak-plus-background (P_m), the corrected peak polarization P_{corr} is given by a weighted average,

$$P_{\text{corr}} = \frac{P_m(1+r) - P_B}{r} , \tag{1}$$

where r is the ratio of peak yield to background yield measured over the same interval of excitation as was used in the determination of P_m. This was applied to measurements for both beam polarization orientations P_n^+ and P_n^-. We calculate r^+ and r^- separately since in general they are different, and we assume $|P_n^+| = |P_n^-| = P_n$ to obtain

$$D_{nn} = \frac{(P_{\text{corr}}^+ - P_{\text{corr}}^-) + P_n A_y (P_{\text{corr}}^+ + P_{\text{corr}}^-)}{2P_n} , \tag{2}$$

where A_y is the analyzing power of the reaction. Implicit in Eq. (2) is the assumption that P_{corr} has been corrected for precession of the polarization vector in the HRS dipoles so that it represents the final-state polarization at the target. (At 397 MeV, $\hat{n}$-type polarization at the target precesses by $360° + 23°$, yielding almost maximal sensitivity at the focal plane.)

An alternative treatment of the background similar to that described by Besset *et al.*[5] was also tested. In this case the background correction was done in the accumulated sums (see Ref. 3 for a definition of these sums) rather than in the polarizations calculated from them. The results of this analysis were identical with those from the analysis described above.

Additional systematic corrections for out-of-plane scatterings at the target were made according to the prescription of Ref. 3. Even though these corrections are largest at small scattering angles they amount to shifts in S_{nn} which are less than 0.01 at all angles considered here.

False asymmetries that are independent of beam polarization affect D_{nn} through the latter term in Eq. (2). In the limit that $A_y = 0$ such effects cancel exactly. We have determined that instrumental false asymmetries are less than 0.01. This value, weighted by the small values of A_y for the unnatural-parity states (≤ 0.3), reduces the systematic uncertainty in S_{nn} due to this term to less than 0.01. Furthermore, D_{nn} was measured for elastic scattering from ^{12}C over the region of the focal plane used for the inelastic measurements. In this case S_{nn} must be zero. Within the uncertainty determined primarily by counting statistics, ± 0.03, all measurements were consistent with zero. Finally, the overall normalization of S_{nn} due to uncertainties in the beam polarization is estimated to be less than 0.01.

Counting statistics for the reported unnatural-parity transitions give errors in S_{nn} of at least 0.05. Therefore, none of the systematic corrections discussed above affect the gross features of the data.

Figure 1 presents spectra obtained at $\theta_L = 8.5°$. The upper spectrum shows the unpolarized cross section versus excitation energy. The lower spectrum is the product of S_{nn} times the differential cross section. Although the natural-parity transitions to the 0^+ and 3^- states stand out in the cross-section spectrum, they do not appear in the $S_{nn} \cdot d\sigma/d\Omega$ spectrum. The $S_{nn} \cdot d\sigma/d\Omega$ plot illustrates one of the unique features of the HRS focal-

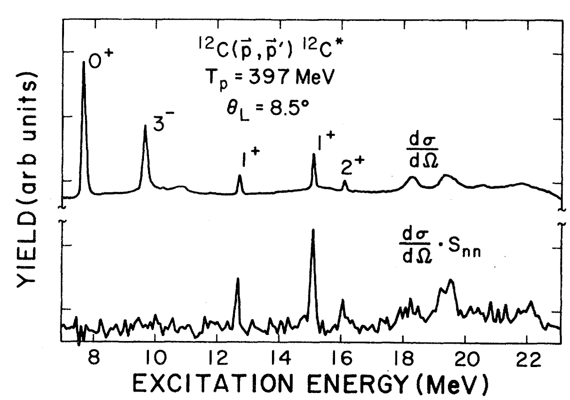

FIG. 1. Histograms of $d\sigma/d\Omega$ (upper) and $d\sigma/d\Omega\ S_{nn}$ as a function of excitation energy for scattering from ^{12}C at $T_p = 397$ MeV and $\theta_{\text{lab}} = 8.5°$.

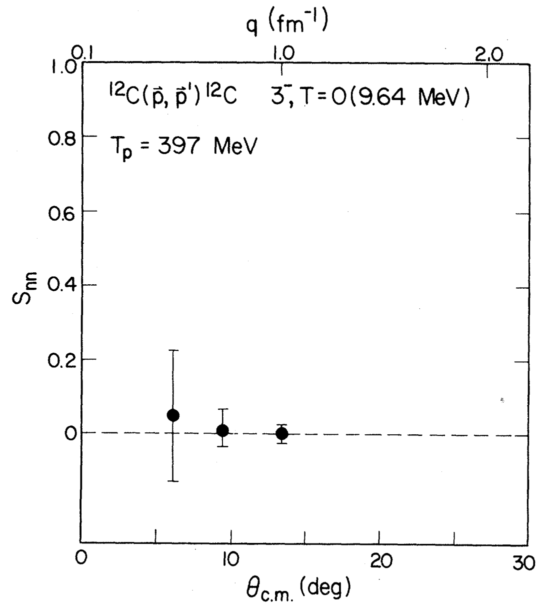

FIG. 2. Spin-flip probability S_{nn} vs center-of-mass scattering angle for the 3^- state (9.64 MeV) in ^{12}C measured at $T_p = 397$ MeV.

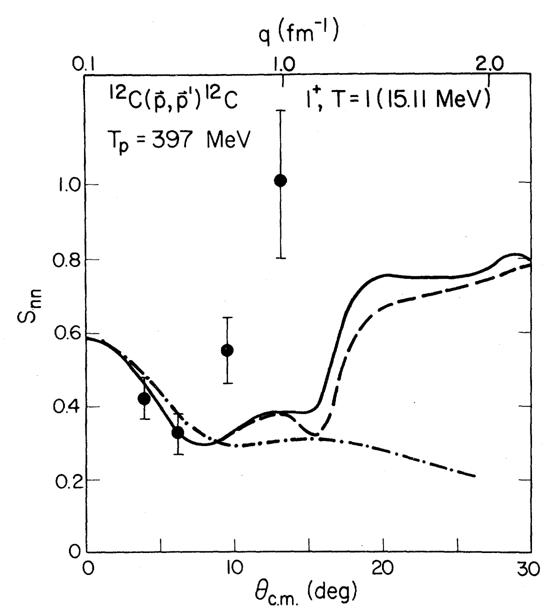

FIG. 3. Spin-flip probability S_{nn} vs center-of-mass scattering angle for the 1^+, $T=1$ state (15.11 MeV) in ^{12}C measured at $T_p = 397$ MeV. The solid curve is the DWBA calculation using the CK wave function and the dashed curve is the DWBA calculation using a pure $p_{1/2}(p_{3/2})^{-1}$ transition density. The dotted-dashed curve is the plane wave result for $LSJ = (011)$.

plane polarimeter, the ability to enhance "spin-flip" strength over a large region of excitation energy. For example, the groups near 18 and 19 MeV probably correspond to 2^- states, rather than 1^- or 2^+ states.

The SFP angular distributions measured for the 3^- $T=0$ (9.64 MeV), 1^+ $T=0$ (12.71 MeV), 1^+ $T=1$ (15.11 MeV), and 2^+ $T=1$ (16.11 MeV) states of ^{12}C are shown in Figs. 2–5. The error bars plotted with the data points represent the statistical uncertainties only.

The large SFP at forward angles observed at low energies for large spin transfer $S=1$ is also observed at intermediate energies. The measured SFP's for the 1^+ and 2^+ states, where $S=1$ is known to be important, are qualitatively very similar. The SFP is large at small angles and then decreases with increasing angle. In contrast, the SFP extracted for the 3^- state, which is dominantly $S=0$, is consistent with zero at all angles (Fig. 2).

III. INTERPRETATION AND COMPARISON WITH THEORY

A. Microscopic DWIA calculations

In the impulse approximation the interaction between the projectile and the target nucleons is given by the free NN interaction. The NN interaction can be written as

$$t^{\text{eff}} = t^{\text{cent}} + t^{LS} + t^{\text{tens}} ,$$

where

$$\begin{aligned} t^{\text{cent}} &= (t^c + t^c_\tau \vec{\tau}_1\cdot\vec{\tau}_2) + (t^c_\sigma + t^c_{\sigma\tau}\vec{\tau}_1\cdot\vec{\tau}_2)\vec{\sigma}_1\cdot\vec{\sigma}_2 , \\ t^{LS} &= (t_{LS} + t_{LS\tau}\vec{\tau}_1\cdot\vec{\tau}_2)(\vec{\sigma}_1+\vec{\sigma}_2)\cdot\hat{n} , \\ t^{\text{tens}} &= (t_T + t_{T\tau}\vec{\tau}_1\cdot\vec{\tau}_2) \\ &\quad \times (3(\vec{\sigma}_1\cdot\hat{r}_{12})(\vec{\sigma}_2\cdot\hat{r}_{12}) - \vec{\sigma}_1\cdot\vec{\sigma}_2) \end{aligned} \tag{3}$$

are the central, spin-orbit, and tensor components, respectively. These t's are related to the fundamental N-N scattering amplitudes in Ref. 6. The interaction used in our calculations was the coordinate-space representation of the antisymmetrized t matrix of Love and Franey.[6] These calculations were performed using a modified version[7] of the code DWBA-70 which treats the knockon exchange terms exactly.

The one-body density-matrix elements used in the calculations were derived from the $1p$-shell wave functions of Cohen and Kurath.[8] Transition densities were calculated with harmonic oscillator wave

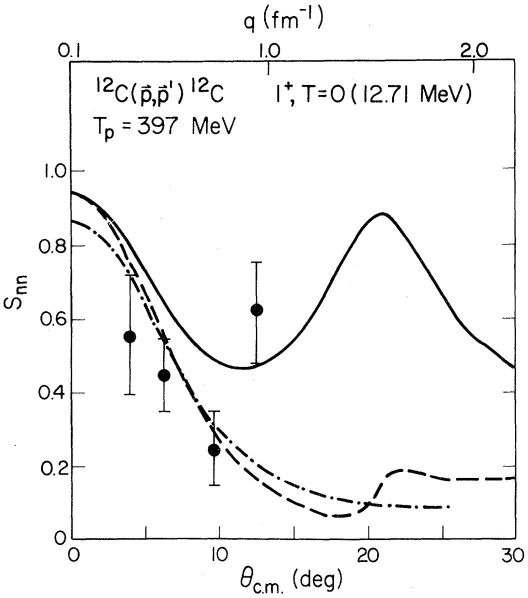

FIG. 4. Spin-flip probability S_{nn} vs center-of-mass scattering angle for the 1^+, $T=0$ state (12.71 MeV) in ^{12}C measured at $T_p=397$ MeV. The solid curve is the DWBA calculation using the CK wave function and the dashed curve is the DWBA calculation for $LSJ=(011)$. The dotted-dashed curve is the plane wave result for $LSJ=(011)$.

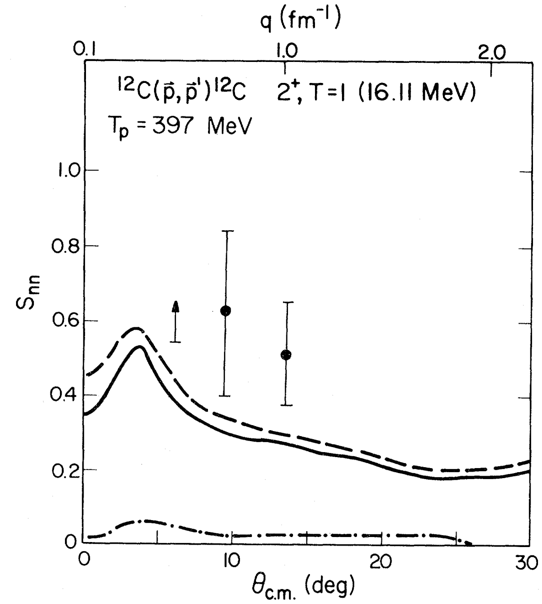

FIG. 5. Spin-flip probability S_{nn} vs center-of-mass scattering angle for the 2^+, $T=1$ state (16.11 MeV) in ^{12}C measured at $T_p=397$ MeV. The solid curve is the DWBA calculation using the CK wave function and the dashed curve is the DWBA calculation using the modified transition density described in Ref. 10. The dotted-dashed curve is a DWBA calculation for $LSJ=(202)$.

functions using oscillator parameters chosen[9] to reproduce the shape of the transverse form factors derived from electron scattering. Correction was made for center-of-mass effects (see Table I). For the 2^+, $T=1$ state an additional wave function was used in which the relative amount of $S=1$ was increased.[10]

The optical potential used was obtained by Jones *et al.*[11,12] through fitting their 398-MeV $\vec{p}+{}^{12}C$ elastic scattering data. An alternative potential, generated by fitting the cross section data of the Saclay group,[13] gave the same SFP's at forward angles with some small differences at larger angles.

B. 1^+, $T=1$ state at 15.11 MeV

The small momentum-transfer properties of the 15.11-MeV 1^+ state are reasonably well described by the Cohen-Kurath (CK) wave functions. The transverse form factor measured in (e,e') is reproduced[9] for $q \leq 1.5$ fm^{-1} with a renormalization factor of 1.3. Furthermore, agreement with the log*ft* values derived from β decay is obtained with no renormalization,[8] and the experimental γ-decay width to the ground state is only about 20% larger than predicted. Our calculation at 397 MeV reproduces the (p,p') cross section data of Jones *et al.*[11] for $q \leq 1.5$ fm^{-1} with no renormalization. The calculation using the CK wave functions (solid curve, Fig. 3) is in very good agreement with the 3.5° and 5.5° data points. Calculations utilizing various harmonic oscillator parameters indicate that at small momentum transfer the SFP is not sensitive to changes in the oscillator parameter. Calculations were also performed for a simple particle-hole $(1p_{1/2}1p_{3/2}{}^{-1})$ configuration (dashed curve in Fig. 3) and for a transition density characterized by

TABLE I. Harmonic oscillator parameters. $\alpha'=(A/A-1)^{1/2}\alpha_{ee'}$.

State	Excitation energy (MeV)	α' (fm^{-1})
1^+, $T=0$	12.71	0.636
1^+, $T=1$	15.11	0.536
2^+, $T=1$	16.11	0.637

values for the orbital angular momentum, the spin, and the total angular momentum transfers of $LSJ=(011)$. These both produced essentially the same SFP as did the full CK wave functions at small q. Therefore, it seems that at small momentum transfers [i.e., near the peak in $d\sigma/d\Omega(q)$] the calculations are sensitive primarily to the relative strengths of the different parts of the NN interaction.

This point is elucidated by a comparison of the full DWIA calculations with the results of the plane-wave approximation[14] for $LSJ=(011)$. The expression for the SFP from Ref. 14, which depends only on the impulse approximation (IA) amplitudes, is

$$S_{nn}=\frac{F^2+E^2}{C^2+B^2+F^2+E^2}\ , \tag{4}$$

where the relationship between the coefficients C, B, E, and F and the t's of Eq. (3) is given in Ref. 6. The dotted-dashed curve in Fig. 3 was generated from Eq. (4) for S_{nn}. The agreement between the DWBA and plane wave results at small momentum transfers demonstrates that the SFP is insensitive to distortion effects in this region. The comparison of the various transition densities previously discussed suggests that the SFP is also largely independent of the details (except for the amount of $S=1$) of the assumed transition density.

An examination of the contributions of the various parts of the NN interaction indicates that the transition to the 1^+, $T=1$ state is mediated by a combination of the central spin dependent and tensor interactions, $t^c_{\sigma\tau}$ and $t_{T\tau}$, with only a very small contribution from the spin-orbit interaction, $t_{LS\tau}$. Hence, our measurements of SFP at forward angles test the relative strengths of $t^c_{\sigma\tau}$ and $t_{T\tau}$. The excellent agreement between this data and the calculations indicates that in this region of q, the relative strengths of $t^c_{\sigma\tau}$ and $t_{T\tau}$ are adequately described in the Love-Franey effective interaction.

Although the distorted-wave calculation qualitatively reproduces the increase in the SFP beyond 7°, it increases more gradually than does the data. At these momentum transfers the predicted SFP is more sensitive to the details of the transition density and the distorting optical potential. Thus, interpretation of the discrepancy in terms of the q dependence of the effective interaction is not straightforward.

C. 1^+, $T=0$ state at 12.71 MeV

The CK wave functions for this state are not well tested by inelastic electron scattering because of its insensitivity to $S=1$, $T=0$ transitions. Interpretation of the existing electron scattering data for this transition is complicated by the known[15,16] isospin mixing with the 1^+, $T=1$ state at 15.11 MeV. A calculation using the harmonic oscillator parameter determined from the (e,e') measurements gives a reasonable fit to the (p,p') cross section data of Jones *et al.*[11] and therefore this oscillator parameter was used in the calculations presented here for the SFP.

The solid curve in Fig. 4 was calculated with the CK wave functions. Although the calculation reproduces the overall trend of the data, the predicted SFP is slightly high at the forward angles and somewhat low at the largest angle. The 12.71-MeV state transition is dominated by the tensor interaction, t_T (through the exchange terms) and the spin-orbit t_{LS} interaction; there is almost no contribution from the weak, central spin-dependent interaction, t^c_σ. The minimum in the predicted SFP at about 10° corresponds to the angle where the contributions of t_{LS} and t_T to the cross section are approximately equal (t_{LS} causes a very small SFP for a pure $S=1$ transition). The depth of the minimum is very sensitive to the relative strengths of t_T and t_{LS}.

The position and depth of the minimum are also somewhat sensitive to the assumed transition density. The SFP at angles greater than 10° is affected very much by the choice of oscillator parameter, while at more forward angles there is little sensitivity to the oscillator parameter. For some transition densities, such as that for a single LSJ, the second peak in SFP almost completely disappears (Fig. 4).

The dashed curve in Fig. 4 corresponds to a transition density with $LSJ=(011)$. The differences between this calculation and that using the full CK wave function [for which $LSJ=(111)$ is dominant] are small for $\theta \leq 7°$. The dotted-dashed curve in Fig. 4, which is the plane wave calculation for this transition, also agrees very well with the DWBA result for the same LSJ. This demonstrates, as was shown for the 15.11-MeV state, that the SFP near the maximum of $d\sigma/d\Omega$ is determined mainly by the impulse approximation amplitudes.

The discrepancy between the data and the theoretical prediction at the forward angles indicates that there might be problems with the t_T and t_{LS} parts of the force. Although the calculation using the simple transition density comes closer to the data at 8.5°, it gives poorer agreement with the 12° point and also a poorer fit to the shape of the cross section data. This indicates that the problems at forward angles cannot be solved by modifications of the transition density but require changes to the force. Problems in t_{LS} have previously been indicated by Hoffmann *et al.*[17] from an analysis of *p*-nucleus scattering data.

D. 2^+, $T=1$ state at 16.11 MeV

The CK wave functions for this transition predict the spectroscopic amplitude for $S=1$ to be large. The solid curve in Fig. 5, which was calculated using the CK wave functions, reproduces the general trend of the data but it is uniformly too low. It is known, however, that the CK wave functions for the 2^+, $T=1$ state are not very successful in predicting the transverse form factor[18] measured in (e,e'). Therefore we have calculated the SFP (dashed curve, Fig. 5) using a transition density[10] having $S=0$ and $S=1$ contributions separately scaled to concurrently reproduce the longitudinal and transverse form factors obtained from (e,e'). This scaling increased the ratio of $S=1$ to $S=0$ in the transition density, a feature reflected by an overall increase in the predicted SFP. The importance of $S=1$ in this transition is illustrated by the dotted-dashed curve in Fig. 5, which corresponds to a transition density with $LSJ=(202)$. The calculated SFP is near zero at all q values. This calculation shows the sensitivity of the SFP to the relative strengths of the $S=1$ and $S=0$ amplitudes.

This state is excited through a combination of t_τ^c, $t_{\sigma\tau}^c$, and $t_{T\tau}$. Note that t_τ^c cannot contribute to unnatural-parity transitions such as that to the 15.11-MeV state. If one accepts the $S=0$ to $S=1$ ratio as determined by the (e,e') measurements and further assumes that $t_{\sigma\tau}^c$ and $t_{T\tau}$ as given by Love and Franey have the correct relative strengths from the 15.11-MeV state data, then the SFP measurements for the 16.11-MeV state would indicate that t_τ^c is too strong relative to $t_{\sigma\tau}^c$ and $t_{T\tau}$. It should be noted, however, that the SFP for the 1^+, $T=1$ state in the region where the 2^+, $T=1$ data exist is also larger than predicted by the DWIA. Therefore, these data might also indicate some deficiency in the q dependence of $t_{\sigma\tau}^c$ or $t_{T\tau}$.

IV. SUMMARY

We have presented measurements of the spin-flip probability for intermediate-energy inelastic proton scattering. The reactions studied in ^{12}C include unnatural-parity transitions to the 1^+, $T=0$ (12.71 MeV) and $T=1$ (15.11 MeV) states and natural-parity transitions to the 3^- $T=0$ (9.64 MeV) and 2^+ $T=1$ (16.11 MeV) states. The 1^+ and 2^+ transitions exhibit large SFP at forward angles; in contrast, the SFP of the collective 3^- state is consistent with zero. Comparisons of DWBA calculations with simple equations from plane-wave predictions demonstrate that near the maximum in $d\sigma/d\Omega$ the SFP is sensitive mainly to the nucleon-nucleon interaction and the amount of $S=1$ in the transition density. At larger angles, $\geq 10°$, the SFP is more sensitive to the details of the wave functions. In this region it should be possible to extract nuclear structure information.

Comparisons of the data with the theoretical predictions for the 1^+, $T=1$ state indicate that the relative strengths of the central spin dependent and tensor interactions are correct at small q but may have problems at larger q. The large q data for the 2^+, $T=1$ state are also consistent with problems in the force in this range. The agreement between the calculations and the data for the 1^+, $T=0$ state at small angles is poorer than for the 1^+, $T=1$ state. The insensitivity of the SFP to the transition density at these angles makes it likely that the discrepancy is due to inaccuracies in the relative strengths of the spin orbit and tensor interactions.

These measurements have demonstrated that for transitions having large $S=1$ components the SFP is large, and that for transitions that involve mostly $S=0$ the SFP is small. Low q measurements of the SFP appear to be an ideal tool for testing the effective nucleon-nucleon interaction because they are insensitive to many of the effects that produce ambiguities in comparison of absolute cross sections with model predictions.

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