Spin effect of antiproton-nucleus inelastic scattering

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If the antiproton optical potential includes the spin orbit interaction term, the $A(\overline{p},\overline{p}')A^*$ inelastic scattering not only can excite the normal parity states, but also can excite the abnormal parity states. It also induces a polarization $P_f(\theta)$ at the inelastic scattering. In the framework of DWIA, we derive and calculate the inelastic scattering cross section and $P_f(\theta)$ for the $^{12}\mathrm{C}(\overline{p},\overline{p}')^{12}\mathrm{C}^*$ with 2^+, 3^-, and 1^+ states at antiproton energies of 46.8 and 179.7 MeV. Our model fit well the available experimental data. The 46.8 MeV measurement of the inelastic differential cross section to the 1^+ abnormal parity state can be explained by a spin orbit term. Such a term generates a sizable inelastic scattering polarization. [S0556-2813(99)06310-4]

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I. INTRODUCTION

The nuclear force depends not only on the relative separation of the two nucleons, but also on their intrinsic degrees of freedom, such as their spin, their charge, etc. The spin orbit coupling has been introduced into the optical potential in order to describe the polarization phenomena in the elastic scattering of particles with spin [1]. However, the study of medium-energy antiproton-nucleus interactions in terms of the optical potential is a topic of current interest [2]. It can be seen from the data [3–7] that the differential cross sections reveal a pronounced diffractive behavior. These data already provide evidence for the strong-absorptive aspect of the $\overline{p}$-nucleus interaction.

One then expects the free antinucleon-nucleon force to have a spin-orbit component that is confirmed by meson-exchange calculations [8]. The real part of the spin-orbit force is of relatively short range and relatively small (two-pion exchange or vector meson exchange). So at small momentum transfer (small angle) the polarization is small. Because of the G parity going from the nucleon-nucleon force to the antinucleon-nucleon force (real part) there is some cancellation of ρ and ω spin-orbit contribution [10] which is further argument why the spin-orbit interaction has been very often neglected.

Nevertheless the polarization $P_f(\theta)$ has been measured [9] in the elastic antiproton nucleus scattering. In the experimental spectrum of inelastic scattering of antiproton on even-even nucleus, there are spin flip states of the target nucleus, in addition to the excited normal 2^+ and 3^- states. If the spin of the target nucleus flips, according to DWIA, the antiproton-nucleus optical potential should have some spin orbit interaction term as it does derive from the free antinucleon-nucleon force.

The paper is organized as follows. In Sec. II the antiproton optical potential including the spin orbit term is defined, thereby the differential cross section and polarization $P_f(\theta)$ of the antiproton-nucleus system are derived. In Sec. III the results for the $^{12}\mathrm{C}(\overline{p},\overline{p}')\mathrm{C}^{12*}$ reaction are calculated. The last section contains a discussion.

II. THE OPTICAL POTENTIAL OF THE $\overline{p}$-NUCLEUS INTERACTION WITH THE SPIN ORBIT TERM

In the framework of DWIA, the optical potential of the $\overline{p}$-nucleus interaction with the spin orbit term is given by

$$U^{(\mathrm{opt})}=V(r)+iW(r)+\left(\frac{\hbar}{mc}\right)^2(\vec{\sigma}\cdot\vec{l})\frac{1}{r}\frac{d}{dr}[V_{so}(r)+iW_{so}(r)], \tag{1}$$

where $\vec{\sigma}$ is the Pauli matrices, $\vec{l}$ the operator of angular momenta, and m the nucleon mass. Then the $\mu\equiv JL$ subwave of the distorted wave $x_\mu^{(+)}(\vec{k}\cdot\vec{r}),x_\mu^{(-)}(\vec{k}\cdot\vec{r})$ [superscript $(+)$ $((-))$ indicates the incoming (outgoing) waves] satisfies the following equation:

$$\left[\frac{d^2}{dr^2}+k^2-\frac{L(L+1)}{r^2}-\frac{2m}{\hbar^2}(U^{(\mathrm{opt})}+V_c(r))\right]x_{JL}(kr)=0, \tag{2}$$

where $V_c(r)$ is the Coulomb potential. In DWIA, the T-matrix elements of inelastic scattering may be written as

$$\langle \vec{k}'_{\bar{P}}, f|T|i, \vec{k}_{\bar{P}}\rangle = \langle x^{(-)}_{\mu'} \phi_{J_f M_f}(A)|S|\phi_{J_i M_i}(A) x^{(+)}_{\mu}\rangle, \quad (3)$$

where

$$S = \sum_{j=1}^{A} t_{\bar{p}}(j) \quad (4)$$

is the operator of $\bar{p}$-nucleon interaction in the nucleus, $t_{\bar{p}}(j)$, the two-body collision matrix in the approximation of DWIA and $\sigma_{J_i M_i}(A)$, $\sigma_{J_f M_f}(A)$ are the wave functions of the initial and the final nucleus, respectively. Due to the wave function of antiproton distorted by the spin orbit force, its spin orientation may be changed, therefore the $\mu \neq \mu'$ matrix elements in Eq. (3) are not zero. In order to simplify the matrix element, the T-matrix element may be written as

$$\langle \vec{k}'_{\bar{p}}, f|T|i, \vec{k}_{\bar{p}}\rangle = \langle \vec{k}'_{\bar{p}}|t_{\bar{p}N}|\vec{k}_{\bar{p}}\rangle F^{\mu'\mu}_{M_f M_i}(\theta), \quad (5)$$

where $\langle \vec{k}'_{\bar{p}}|t_{\bar{p}N}|\vec{k}_{\bar{p}}\rangle$ is the two-body t matrix element in the $\bar{p}$-nucleus center-of-mass system and

$$F^{\mu'\mu}_{M_f M_i}(\theta) = \sum_{LM} \hat{J}_i D_L(j'l'jl) C^{J_f M_f}_{J_i M_i L M} S^{M_{\mu'\mu}}_{j'l'jl}(\theta), \quad (6)$$

$$S^{M_{\mu'\mu}}_{j'l'jl}(\theta) = \sum_{L_b} \beta^{M_{\mu'\mu}}_{j'l'jlL_b} P^{\mu-M-\mu'}_{L_b}(\theta), \quad (7)$$

$$\beta^{M_{\mu'\mu}}_{j'l'jlL_b} = \frac{\sqrt{4\pi}}{k_{\bar{P}} k'_{\bar{P}}} \sum_{J_a J_b L_a} (i)^{L_a - L_b} \hat{L}_a \hat{L}_b \hat{J}_b w\left(J_b \frac{1}{2} L L_a; L_b J_a\right) \cdot C^{L_a 0}_{L_b 0 L 0} \cdot C^{J_a \mu}_{L_a 0 1/2 \mu} \cdot C^{J_b \mu - M}_{L_b \mu - M - \mu' 1/2 \mu'} \cdot C^{J_a \mu}_{J_b \mu - M L M} \cdot I^{j'l'jl}_{J_a L_a J_b L_b} \times \sqrt{\frac{(L_b - |\mu - M - \mu'|)!}{(L_b + |\mu - M - \mu'|)!}}, \quad (8)$$

$$I^{j'l'jl}_{J_a L_a J_b L_b} = \int dr\, x^{(-)*}_{J_b L_b}(k'_{\bar{P}} r) \varphi^*_{l'j'}(r) \varphi_{lj}(r) x^{(+)}_{J_a L_a}(k_{\bar{P}} r), \quad (9)$$

$$D_L(j'l'jl) = \sum_j B^*_{J_{j'}} B_{J_j} \hat{l}\hat{l}' \hat{j}\hat{j}' W(j 1/2 L j'; l j') W(J_i J L j'; j J_f) \cdot C^{L0}_{l'0l0}, \quad (10)$$

with $\hat{l} \equiv \sqrt{2l+1}$. $L_a J_a, L_b J_b$ are the numerical values of the distorted subwave, l_j and $l'j'$ are the orbital angular momenta and the total angular momenta of the excited nucleon in the target nucleus, respectively. J is the total angular momentum of the excited target nucleus. $D_L(j'l'jl)$ is a factor related to nuclear structure, B_{J_j} is the numerical values related to J and j, W and C are Clebsch-Gordan coefficients, $I^{j'l'jl}_{J_a L_a J_b L_b}$ is the integral of the distorted subwave and the radial wave function of the excited nucleon, $P^{|m|}_l(\theta)$ is Legendre function. μ, μ' are spin values of the antiproton at the initial and the final states. Using density matrix theory, the density after scattering is given by

$$\rho_f = F \rho_i F^+, \quad (11)$$

F is the matrix of corresponding to Eq. (6). It is the matrix element of the state space of the magnetic component, ρ_i is the initial state density matrix. If the initial state magnetic component is not anisotropic, then

$$\rho_i = \frac{1}{2} \frac{1}{2J_i + 1} I, \quad (12)$$

where I is the unit density matrix, thus, the differential cross section of antiproton-nucleus inelastic scattering is given by

$$\left(\frac{d\sigma}{d\Omega}\right)_{f,i} = \frac{k'_{\bar{P}}}{k_{\bar{P}}} \frac{k_{\bar{P}N}}{k'_{\bar{P}N}} \left(\frac{AE'}{E}\right)^2 \left(\frac{d\sigma}{d\Omega}\right)_{\bar{P}N \to \bar{P}N} I_0(\theta), \quad (13)$$

TABLE I. Antiproton-^{12}C optical potential parameters.

$E_{\bar{P}}$ MeV	V_0 MeV	W_0 MeV	R_v fm	R_I fm	a_v fm	a_I fm	V_{so} MeV	W_{so} MeV	R_s fm	a_s fm
46.8	−20	−111	2.29	2.4	0.52	0.54	−6.6	−6.6	2.52	0.56
179.7	−41	−217	2.577	2.0	0.52	0.52	−4	−4	2.15	0.571

where

$$I_0(\theta)=\frac{2J_f+1}{2}\sum_{LM\mu\mu'}\frac{1}{(2L+1)}|D_L(j'l'jl)|^2|S^{M\mu'\mu}_{j'l'jl}(\theta)|^2, \tag{14}$$

and $(d\sigma/d\omega)\overline{p}N\rightarrow\overline{p}N$ is the free two-body differential cross section, E' is the total energy of the two-body system, E is the total energy of the scattering system, and $k_{\overline{P}},k_{\overline{P}N},k'_{\overline{P}},k'_{\overline{P}N}$ are the incident and the outgoing momentas of the antiproton, respectively.

For even-even nuclei, $J_i=0$, then $L=J_f$. The polarization transfer from the state $\varphi_{jl}(\vec{r})$ to the state $\varphi_{j'l'}(\vec{r})$, may be written as

$$P_f(\theta)=\frac{\mathrm{Im}\sum_M(S^{*M(1/2)1/2}(\theta)S^{M-(1/2)1/2}(\theta)+S^{*M(1/2)-1/2}(\theta)S^{M-(1/2)-1/2}(\theta))}{\sum_{\mu\mu'}|S^{M\mu'\mu}_{j'l'jl}(\theta)|^2}. \tag{15}$$

III. DIFFERENTIAL CROSS SECTION AND POLARIZATION

Using Eq. (13) and Eq. (15), we calculate the differential cross section and the polarization of inelastic scattering. The optical potential that includes the spin orbit term is given by the Woods-Saxon formula

$$V(r)+iW(r)=V_0\frac{1}{1+e^{(r-R_v)a_v}}+iW_0\frac{1}{1+e^{(r-R_I)/a_I}}, \tag{16}$$

$$V_{so}(r)+iW_{so}(r)=V_{so}\frac{1}{1+e^{(r-R_s)/a_s}}+iW_{so}\frac{1}{1+e^{(r-R_s)/a_s}}, \tag{17}$$

From Ref. [2], we found that using the optical potential parameters obtained by fitting the elastic experimental data in the inelastic case at the same incident energy, the experimental data are fitted very well. Therefore, in this paper using the results of Ref. [2], the antiproton-nucleus optical potential parameters are listed in Table I. We are also using the $\overline{p}N$ two-body forward scattering amplitude

$$t_{\overline{P}N}=\frac{ik\sigma_{\overline{p}N}(1-i\varepsilon)}{4\pi}, \tag{18}$$

where $\sigma_{\overline{p}N}$ is the total cross section of the two-body systems, ε is the ratio of the real-to-imaginary $\overline{p}-N$ amplitudes, which is neglected in the calculation due to the strong annihilation phenomena in the antiproton-proton collision. We use for $\sigma_{\overline{p}N}$ values obtained in Ref. [11] from a Glauber

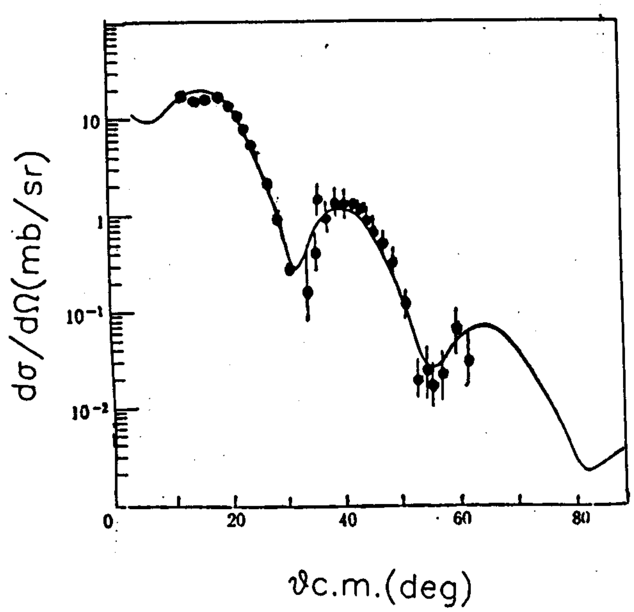

FIG. 1. The differential cross sections for the ^{12}C($\overline{p},\overline{p}'$)^{12}C* ($2^+$, 4.44 MeV) reaction at $E_{\overline{p}}$=179.7 MeV. The solid curve shows the calculated results, the experimental points are from Ref. [7].

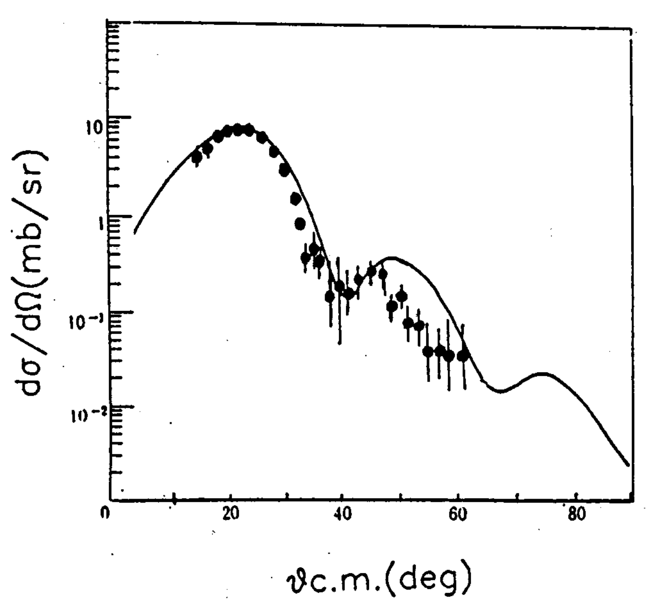

FIG. 2. As in Fig. 1, but for the ^{12}C($\overline{p},\overline{p}'$)^{12}C* ($3^-$, 9.6 MeV) reaction.

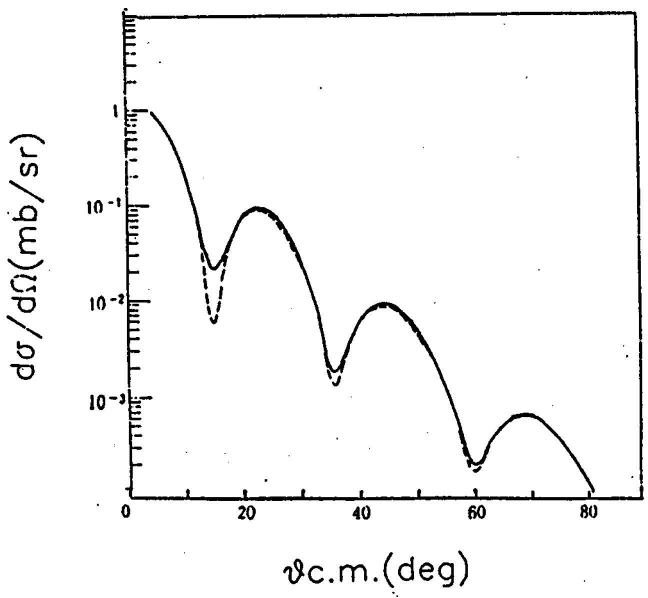

FIG. 3. The differential cross sections for the $^{12}C(\overline{p},\overline{p}')^{12}C^*$ (1^+, 12.7 MeV) reaction at $E_{\overline{p}}=179.7$ MeV. The solid curve shows the total calculated results and the dashed curve expresses the $L=0$, $S=1$ calculated results.

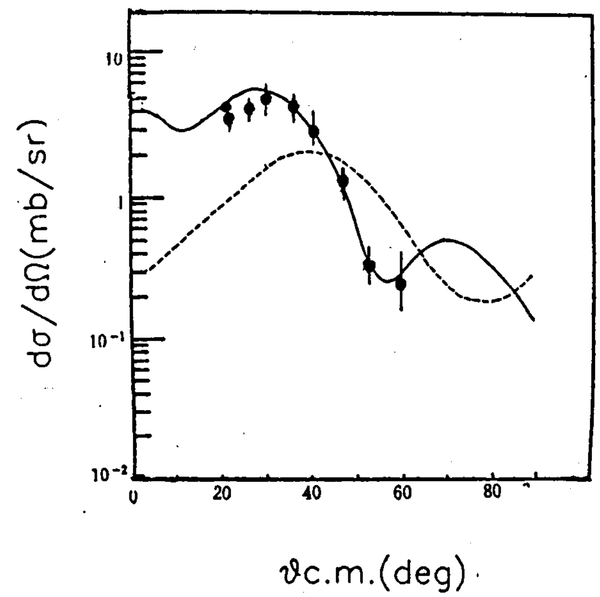

FIG. 4. The differential cross sections for $^{12}C(\overline{p},\overline{p}')^{12}C^*$ (2^+,3^- states) reaction at $E_{\overline{p}}=46.8$ MeV. The solid curve shows the calculated results of the 2^+ state, the dashed curve expresses the calculated results of the 3^- state, and the experimental points are from Refs. [3] and [7].

model analysis of elastic scattering data of $\overline{p}$ on ^{12}C, ^{16}O, and ^{40}Ca at 47 and 179 MeV, i.e., $\sigma_{\overline{p}N}=210$ mb (for 46.8 MeV) and $\sigma_{\overline{p}N}=145$ mb (for 179.7 MeV). It is very important to choose in a proper way the nucleon wave function for calculating the antiproton-nucleus inelastic process. For this reason, in the calculation below we do not use the harmonic oscillator again but use the bound state wave function, which is obtained by solving exactly Eq. (2) with the Woods-Saxon optical potential. We calculate in this way the differential cross section and the polarization of inelastic scattering. There are no other free parameters in our model.

All calculated differential cross sections for $^{12}C(\overline{p},\overline{p}')^{12}C^*$ (the final states are 2^+, 3^-, and 1^+) are given in Figs. 1–6. The ground state of ^{12}C is taken to be the closed $1p_{3/2}$, the 2^+ state is $(p_{3/2}^{-1}p_{1/2})_2$, the 3^- state is $(p_{3/2}^{-1}d_{5/2})$, and the 1^+ state is $(p_{3/2}^{-1}p_{1/2})_1$. These are the main configurations of 2^+, 3^-, and 1^+ states. In Figs. 1 and 2, our results are drawn as solid curves, fit well the experimental data of Ref. [7]. However the differential cross section in the 3^- state (Fig. 2) lies above the data both in the 30 and 50° regions. In Ref. [7] the fit to the 3^- overshoots also the data, mainly in the 50° region. A reason for this disagreement is the possible existence of a vibrational state.

These results are obtained based on a revised DWUCK [12] computer program. Each partial wave $x_{JL}^{(\pm)}(kr)$ is calculated by the optical potential which includes the spin orbit team. The bound state wave functions $\varphi_{lj}(r)$ are obtained by solving a Schrödinger equation with Woods-Saxon potential, the integration $I_{J_aL_aJ_bL_b}^{j'l'jl}$ is completed, and finally the $S_{j'l'jl}^{M_{\mu'}\mu}(\theta)$ are exactly calculated in the framework of DWIA.

IV. DISCUSSION

Now we investigate the calculated results in two aspects from the nuclear structure concept. On the one hand, the target can be excited to the normal parity states, as 2^+, 3^- states. In these states the spin of the nucleon does not flip in the process. Therefore, no matter whether the optical potential of the distorted wave includes the spin orbit term or not, these states can be excited. However, the polarization $P_f(\theta)$ could be formed only by the optical potential including the spin orbit term, where the orientation of the spin of the outgoing antiproton is not left and right symmetric. In Ref. [13], we found the polarization $P_f(\theta)\equiv 0$ for the central potential.

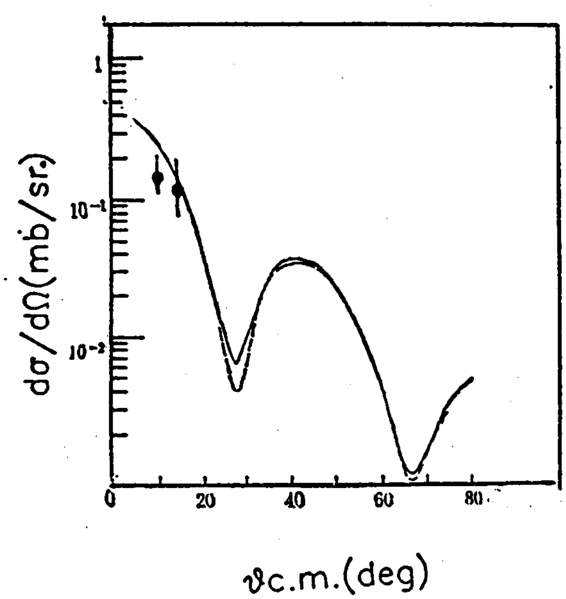

FIG. 5. As in Fig. 3, but at $E_{\overline{p}}=46.8$ MeV. The two experimental points are from Ref. [7].

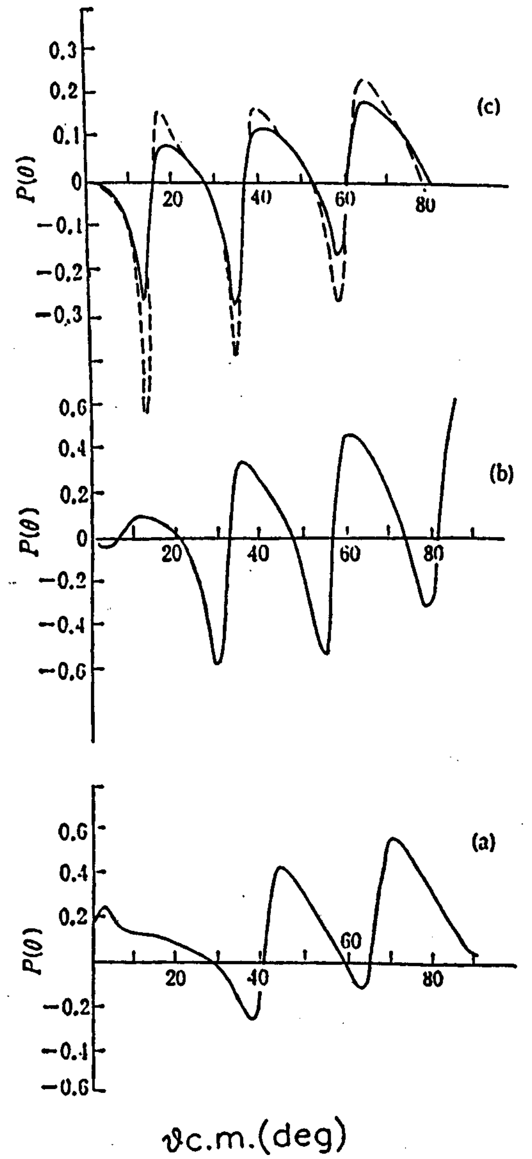

FIG. 6. The polarization $P_f(\theta)$ for $^{12}C(\overline{p},\overline{p}')^{12}C^*$ reaction at $E_{\overline{p}}$=179.7 MeV. (a) The solid curve shows the calculated results of the 3^- states; (b) the solid curve expresses the calculated results for the 2^+ state; (c) the solid curve represents the calculated results of the 1^+ state and the dashed curve shows the calculated results for $L=0$, $S=1$.

From Fig. 6 we found in the 2^+ and 3^- states a sizable polarization as was found in the elastic case in Ref. [13], although the only existing experimental data (Ref. [9] for elastic scattering; there is no data, so far, for inelastic scattering) gives small polarization at small angles. The result has aroused concern among experimentalists.

On the other hand, the target can also be excited to the abnormal parity states, namely, the spin of the nucleon flipped in the process, e.g., $1^+(p_{3/2}^{-1}p_{1/2})_1$ state, where the state of the nucleon was excited from $p_{3/2}$ into $p_{1/2}$, and its spin was changed. For example (Fig. 5), the inelastic differential cross sections in the forward direction only have two data points in the experimental result ($E_P=46.8$ MeV). The calculated results fit the experimental data quite well. It should be pointed out that the excited abnormal parity state is much weaker than the normal parity state—about two orders of magnitude smaller. The reason is that the transition form factor $D_L(j'l'jl)$ for the abnormal parity state is much weaker than that of the normal parity state. Further we analyzed the inelastic scattering of the 1^+ state. In Figs. 3, 5, and 6, the dashed curves show the result only considering an $L=0$ contribution, because $L=0$ is the dominant contribution. The $L=2$ contribution to the differential cross sections is much smaller. It contributes only in the peak and dip of the differential cross section as can be seen in Figs. 3, 5, and 6. On the contrary, if the antiproton optical potential does not include the spin orbit term, the spin of the nucleon does not flip, therefore, the calculation gives $(d\sigma/d\Omega)_{f,i}\equiv 0$.

Antiproton-proton LEAR experiments have shown that polarization observables are quite sizable in the elastic process and also in charge exchange [14]. For free two-body spin 1/2–spin 1/2 scattering the polarization is real, a^*e in terms of *J*. (Bystricky *et al.* amplitudes a, b, c, d, and e [15].) On the other hand, the only contribution to the *e* amplitude comes from a spin-orbit term [16], so if a spin-orbit term is absent one has effectively a zero polarization. Iteration of a tensor term can generate a spin-orbit term [17].

A spin-spin term does induce a nonzero inelastic differential cross section into an abnormal parity state at small angles and the tensor term at large angles [7,17]. On the other hand, the possible importance of the spin-orbit term, in particular at large momentum transfer, has also been considered by Dover *et al.* [18,19].

If one can generate with spin-spin and/or tensor force transition to an abnormal state, there is so far no experimental evidence that a spin-orbit term in $\overline{p}$ nucleus plays an important role. Nevertheless, as seen in Fig. 6, the presence of a spin-orbit term generates a sizable polarization in the inelastic scattering not only to normal 2^+ and 3^- states but also to the abnormal 1^+ state.

At present, the polarization $P_f(\theta)$ [9] in an elastic channel is being measured by CERN, and the abnormal parity states in the inelastic channel have been observed by Garreta *et al.* [3] and Lemaire *et al.* [7]. These experimental data reveal that the spin-orbit term in the antiproton optical potential could play an important role. We hope to see the corresponding experimental data, for example, the polarization $P_f(\theta)$ of the inelastic channel, the differential cross sections of the abnormal parity states, etc., in the near future [20].

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