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Core-polarization effects in pion single-charge-exchange reaction on *p*-shell nuclei

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We have studied the first-order core-polarization effects in pion single-charge-exchange reactions from polarized ^{15}N and ^{13}C under the distorted-wave impulse approximation. It is shown that the reaction cross section and also the asymmetry are moderately affected by the core polarization. [S0556-2813(96)04207-0]

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Experiments of the pion single-charge-exchange (SCX) reactions on ^{15}N and ^{13}C have been carried out from the viewpoint of studying the isovector spin-dependent interaction of pions in nuclei [1,2]. Recently, an experiment using the polarized ^{13}C target has been performed and the asymmetry has been measured [2]. In the SCX reactions from polarized spin-$\frac{1}{2}$ nuclei, the right-left asymmetry comes from an interference between pion-nucleus spin-independent and spin-dependent amplitudes of the isovector type. In the case of pion elastic scattering, the spin-independent isoscalar interaction dominates and hence the observed asymmetry takes somewhat small values, while in the case of SCX reactions of pion, the measured asymmetry is fairly large, reflecting the importance of the spin-dependent interaction.

Recently, several theoretical works for the SCX reactions have been done by using the shell-model wave function within $0p$ configurations [3,4] or within $(0+2)\hbar\omega$ space [5–7]. Kamalov *et al.* [5] studied these reactions and have pointed out the importance of the nuclear configurations outside $0p$ model space. Concerning the $2\hbar\omega$ configurations outside $0p$ shell, Hicks *et al.* determined the $(1p_{1/2}0p_{1/2}^{-1})$ component in the wave function of ^{13}C from the fit to the $M1$ form factor at large momentum transfer [8]. They obtained about 12% admixture of the $(1p_{1/2}0p_{1/2}^{-1})$ component, which is too large from the viewpoint of the nuclear shell model. Then Bennhold and Tiator [9] reduced it to 6% from the analysis of the (γ,π^-) reaction. Kamalov *et al.* [5] used this wave function and have shown that the theoretical results are considerably affected by the admixture of the $2\hbar\omega$ component. Bennhold *et al.* [6] used the $(0+2)\hbar\omega$ shell-model wave function by Wolters *et al.* [10] for ^{15}N. As is already known, this wave function gives a narrow $M1$ form factor and is unsatisfactory for the description of the $M1$ form factor for p-shell nuclei. Bennhold *et al.* used this wave function for the SCX reaction on ^{15}N at low energy. Recently, Bydzovsky *et al.* [7] also studied the (π^+,π^0) and (p,n) reactions on ^{13}C by using the same $(0+2)\hbar\omega$ shell-model wave function of Wolters *et al.* [10]. Since it fails to reproduce the experimental $M1$ form factor of ^{13}C, they replaced the spin-dependent part of the nuclear matrix elements by the phenomenological $0\hbar\omega$ wave function by Tiator and Wright [11]. Thus all of these calculations do not use the fully consistent wave function with the experimental $M1$ form factor. Since the asymmetry comes from interference between spin-independent and spin-dependent amplitudes, we should use a nuclear wave function which is at least consistent with the charge and magnetic form factors.

It is well known that the core polarization plays an important role for the $M1$ form factor of the $0p$-shell nuclei [12–18] and multi-$\hbar\omega$ components are necessary to explain it. For ^{13}C, Suzuki *et al.* [18] showed that the first-order core polarization largely enhances the isovector $[Y_0\times\sigma]^1$ component and changes the sign of its contribution at $q\geqslant 1.4$ fm^{-1}, while it little affects the $[Y_2\times\sigma]^1$ component. The $M1$ form factor of the ^{12}C and ^{13}C were consistently explained mainly by the effects of first-order core polarization. The experimental $M1$ form factor of ^{15}N is also reproduced by including the core polarization and the exchange-current contribution [17,19]. In the pion SCX reactions, only the isovector component is relevant to the Born amplitude and hence we expect larger core-polarization effects in SCX reactions than in the elastic scattering.

The purpose of the present work is to calculate the effects of first-order core polarization on the reaction cross section and the asymmetry for pion SCX reactions from polarized ^{15}N and ^{13}C and to compare them with the experimental data. Above the delta-resonance region, the core-polarization effects for the cross section have also been studied by Oset *et al.* for ^{14}C [20].

The scattering amplitude in the analog SCX reaction from a spin-$\frac{1}{2}$ nucleus is given as a sum of isovector spin-nonflip and spin-flip pion-nucleus amplitudes $f(\theta)$ and $g(\theta)$,

$$\mathcal{F}(\theta)=f(\theta)+ig(\theta)\boldsymbol{\sigma}\cdot(\hat{\mathbf{k}}_i\times\hat{\mathbf{k}}_f). \tag{1}$$

Here $\hat{\mathbf{k}}_i$ ($\hat{\mathbf{k}}_f$) is a unit vector directed to the momentum of the incident (outgoing) pion. The asymmetry Ay(θ) is given as an interference between these amplitudes $f(\theta)$ and $g(\theta)$ as

$$\mathrm{Ay}(\theta)=\frac{2\,\mathrm{Im}(fg^*)\sin\theta}{|f|^2+|g|^2\sin^2\theta}. \tag{2}$$

Let us define the multipole density operator $\mathcal{O}$ as

$$\mathcal{O}=\sum_i \frac{\delta(r-r_i)}{r^2}[Y_L(\hat{\mathbf{r}}_i)\otimes\sigma_i^{(S)}]^J\boldsymbol{\tau}_i^{(k)}; \tag{3}$$

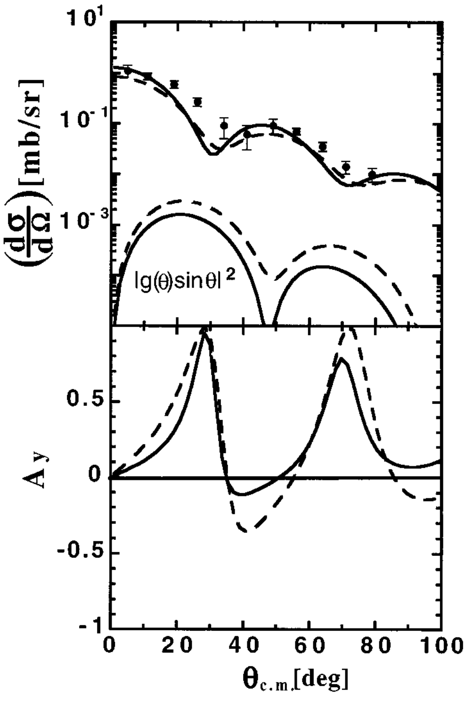

FIG. 1. Cross section and the asymmetry for the pion SCX reaction $^{15}N(\pi^+,\pi^0)^{15}O(IAS)$ at $T_\pi = 165$ MeV. We have used the pion-nucleus optical potential which fits the π-^{15}N elastic scattering data. The solid and dashed lines present the results with and without core-polarization effects. For the cross section, the contribution from the spin-flip amplitude $|g(\theta)\sin\theta|^2$ is also shown. The experimental data are taken from Ref. [1].

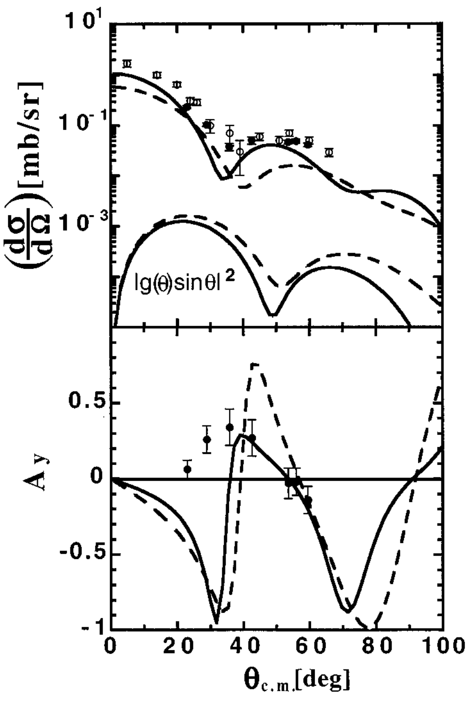

FIG. 2. Cross section and the asymmetry for the pion SCX reaction $^{13}C(\pi^+,\pi^0)^{13}N(IAS)$ at $T_\pi = 163$ MeV. The solid and dashed lines have the same meaning as in Fig. 1. The experimental data are taken from Ref. [1] for $T_\pi = 165$ MeV and from Ref. [2] for $T_\pi = 163$ MeV.

then, the nuclear transition densities $\rho_{LSJ}^{(k)}(r)$ can be calculated under the first-order perturbation as

$$\rho_{LSJ}^{(k)}(r) = \langle \Phi_f | \mathcal{O} | \Phi_i \rangle + \left\langle \Phi_f \left| \mathcal{O} \frac{1}{e} (V_{\mathrm{res}} - U) \right| \Phi_i \right\rangle + \left\langle \Phi_f \left| (V_{\mathrm{res}} - U) \frac{1}{e} \mathcal{O} \right| \Phi_i \right\rangle, \tag{4}$$

where V_{res} is a two-body residual interaction and we have subtracted the one-body Hartree-Fock contribution U which is important for the case of open-shell nuclei [18]. As the $0p$-shell wave function, we adopted the Cohen-Kurath wave function with (8–16) POT two-body matrix elements [21]. As a central part of the residual interaction, we adopted the phenomenological Yukawa-type form with Rosenfeld exchange mixture. For the noncentral part, we used the tensor force of Hamada-Johnstone nucleon-nucleon interaction [22] with cutoff radius $r_c = 0.7$ fm. We use the oscillator length parameter $b = 1.67$ fm for ^{15}N [23] and $b = 1.543$ fm for ^{13}C [18]. We have taken into account the intermediate one-particle–one-hole (1p1h) states up to $12\hbar\omega$ excitation.

We have carried out the distorted-wave impulse approximation (DWIA) calculation of pion SCX reactions from polarized ^{15}N at $T_\pi = 165$ MeV and ^{13}C at $T_\pi = 163$ MeV, leading to the isobaric analog state. The pion distorted waves are generated with the pion-nucleus optical potential by Stricker and co-workers [24–26]. For the absorption parameters B_0 and C_0, we adopted the values determined phenomenologically by Gmitro *et al.* [27]. It is well known that first-order DWIA theory includes too much absorption and the calculated SCX cross section is smaller than the experiment around the delta-resonance region. Much work has been done concerning the possible higher-order corrections to the pion optical potential in the SCX reaction [28–33]. Since we focus our attention on core-polarization effects, we simply adjusted the s- and p-wave parameters of the pion-nucleus optical potential to fit the experimental data of elastic scattering for ^{15}N. The results are shown in Fig. 1 for ^{15}N at $T_\pi = 165$ MeV. As is seen, the core polarization enhances the cross section at the forward direction and the cross section is shifted slightly to the forward direction. If we use the first-order optical potential, the absolute values of the cross section decrease about a factor 1.6, while the angular distribution is almost unaltered.

We have also calculated the SCX cross section for ^{13}C. The experimental data for the elastic scattering π^+-^{13}C are not available at $T_\pi = 163$ MeV, and hence we used the impulse values for the potential parameters. The results are shown in Fig. 2. The core-polarization effects are almost the same as in the case of ^{15}N. Since we used the impulse values for the pion potential parameters, the cross section is smaller than the experiment. We can see fairly large core-polarization effects even at the forward direction. This situation is in contrast with the case of the elastic scattering [34]. Obviously, the core polarization for SCX reaction is absent at the forward direction in the plane-wave impulse approximation (PWIA) and it is induced by pion distortion effects. Our result of the asymmetry for ^{13}C is similar to that of Ref. [4]. It is interesting to note that the asymmetries for ^{15}N and

^{13}C have opposite signs. This is due to the fact that the dominant configurations for these nuclei are proton-hole and neutron-particle components, respectively.

In the present paper, we have studied core-polarization effects for the SCX reactions on ^{15}N and ^{13}C. We used the nuclear wave function which is consistent with the charge and magnetic form factors. The core polarization moderately affects the angular distribution for both the cross section and the asymmetry but it is not so large as to change the overall pattern of the asymmetry. Even if we take into account the core polarization, the discrepancy between theory and experiment still remains for the asymmetry. This indicates that the DWIA treatment is insufficient, which has been already pointed out for the absolute value of the cross section [28–33]. Further study of the reaction mechanism is necessary for a thorough understanding of the SCX reactions.

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