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Energy dependence of the $^{12,14}\mathrm{C}(p,\pi^-)^{13,15}\mathrm{O}_{\mathrm{g.s.}}$ reactions in a two-nucleon model

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Based on a two-nucleon pion-production model, we have calculated the cross sections and the analyzing powers for the reactions $^{12,14}\mathrm{C}(p,\pi^-)^{13,15}\mathrm{O}_{\mathrm{g.s.}}$ near and above the delta resonance, which are accessible with the present experimental facilities. As the incident energy increases, the cross section becomes sharply forward peaked and the asymmetry changes its sign for ^{12}C. The asymmetry for ^{14}C stays positive throughout. We have also calculated the energy dependence of the forward cross section assuming the energy-independent normalization factor. [S0556-2813(98)06705-3]

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I. INTRODUCTION

The proton-induced pion-production reaction (p,π) has been extensively studied over the past two decades [1–4]. Around the beginning of the 1980's, $(\vec{p},\pi^-)$ experiments have been carried out with the 200 MeV polarized proton beam at Indiana University Cyclotron Facility (IUCF). It was found that the low-lying high-spin states are selectively excited for medium heavy nuclei [5–11]. Also, the cross sections and the asymmetries in the ground-state transitions $^{12,13,14}\mathrm{C}(\vec{p},\pi^-)^{13,14,15}\mathrm{O}_{\mathrm{g.s.}}$ were found to exhibit a clear isotope dependence [12]. For the reactions $^{13,14}\mathrm{C}(\vec{p},\pi^-)^{14,15}\mathrm{O}_{\mathrm{g.s.}}$, the observed angular distributions of the cross sections are quite similar and their ratio $d\sigma(^{14}\mathrm{C})/d\sigma(^{13}\mathrm{C})$ is about 2, which corresponds to the neutron occupation number in the valence $p_{1/2}$ orbit. Furthermore a striking sign change between the analyzing powers of the reactions $^{12}\mathrm{C}(\vec{p},\pi^-)^{13}\mathrm{O}_{\mathrm{g.s.}}$ and $^{13,14}\mathrm{C}(\vec{p},\pi^-)^{14,15}\mathrm{O}_{\mathrm{g.s}}$ was observed. These experimental evidences led us to believe that the (p,π^-) reaction proceeds dominantly through two-nucleon process $p+n\rightarrow p+p+\pi^-$ in the near threshold region.

Several theoretical works have been done so far. For the stretched-state transitions, the distorted-wave Born approximation (DWBA) calculations with the two-nucleon mechanism succeeded in explaining the overall features of the angular distribution of the cross section and the asymmetry [13–16] and also the reaction spectra [17,18]. On the other hand, in the case of ground-state transitions, the above mentioned experimental results are very difficult to reproduce quantitatively. Two-nucleon model calculations have been done [19,20], but the theoretical value of the cross section for ^{14}C falls off too rapidly at backward direction and the sign of the asymmetry for ^{12}C disagrees at backward direction. Further calculation has been carried out by including the core-polarization effect [21] which was shown to reduce the absolute value of the cross section slightly for both ^{12}C and the ^{14}C but little affects the asymmetry. The DWBA calculation for the ground-state transitions is not successful for the carbon isotopes contrary to the case of stretched-state transitions in the medium heavy nuclei.

To clarify the reaction mechanism, we think it important to study the energy dependence of the reaction cross section and the asymmetry for these ground-state transitions. In the near-threshold region, the two-nucleon process is complicated because of the interference between the s- and p-wave rescattering contribution. At higher-energy region, the s-wave rescattering contribution becomes less important.

The experiments at the higher-energy region have been carried out at TRIUMF for the $^{13}\mathrm{C}(p,\pi^-)^{14}\mathrm{O}$ and $^{13}\mathrm{C}(p,\pi^+)^{14}\mathrm{C}$ reactions [22]. They measured the energy dependence of the cross section leading to isobaric analog states at a fixed four-momentum transfer. For the (p,π^+) reaction, the delta peak was observed which is quite similar to that seen in $p+p\rightarrow d+\pi^+$ reaction. Unlike the case of (p,π^+) reaction, the cross section for (p,π^-) seems to decrease with the increase of the incident energy and the delta peak seems to be absent. They argued that these reactions may proceed through nonresonant two-body processes. Also they suggested the possible two-step processes involving pion single charge exchange in (p,π^-). But, the data points are limited and no theoretical works have been done so far, and quantitative discussion is difficult. We also expect that the experiments of these reactions will be carried out with the high-quality proton facility at Research Center for Nuclear Physics (RCNP) in Osaka. Motivated by these observations, we have carried out theoretical calculations of the cross section and the asymmetry for the ground-state transitions based on a conventional two-nucleon model at higher energy. The present two-nucleon model succeeded in explaining the overall excitation spectra of the (p,π^-) reactions in medium heavy nuclei. For the ground-state transitions in carbon isotopes, this model is not so successful probably due to the pronounced large momentum and angular momentum mismatch in the ground-state transitions in light nuclei. Hence the precise prediction is difficult and we have to assume the overall energy-independent normalization factor. Our aim, here, is the prediction of the overall trends around the delta region. Our results exhibit smooth delta peak and seem to contradict the available experimental data.

The present paper is organized as follows. In Sec. II, we describe the two-body pion-production model adopted in the

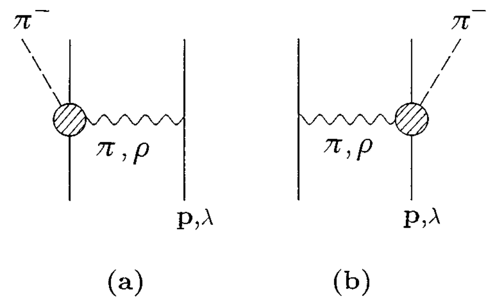

FIG. 1. Two-nucleon pion-production processes assumed in the present calculations for (p,π^-) reactions. The solid line denotes nucleons with **p**, λ being the incident momentum and the spin projection. The wavy line denotes the π and ρ exchanges and the dashed line represents the outgoing negative pion.

present work. The results of our calculations are shown in Sec. III. A summary and conclusions are given in Sec. IV.

II. PION-PRODUCTION MODEL

We consider the two-nucleon pion-production processes as shown in Fig. 1. We take into account the s- and the p-wave rescattering diagrams with π and ρ exchange. The amplitude for the p-wave rescattering diagrams is given by

$$M_{ij}^{(p)}=\frac{f_\pi^*}{m_\pi}(\mathbf{S}_j\cdot\mathbf{k})(-)^\alpha\mathbf{T}_j^{-\alpha}[V_\pi(q)+V_\rho(q)]D_\Delta, \quad (1)$$

where D_Δ is the Δ propagator, and V_π and V_ρ are given by

$$V_\pi(q)=\frac{f_\pi(q^2)f_\pi^*(q^2)}{m_\pi^2}(\boldsymbol{\sigma}_i\cdot\mathbf{q})(\mathbf{S}_j^\dagger\cdot\mathbf{q})\times(\boldsymbol{\tau}_i\cdot\mathbf{T}_j^\dagger)\frac{-1}{(2\pi)^3(\mathbf{q}^2-q_0^2+m_\pi^2)}, \quad (2)$$

and

$$V_\rho(q)=\frac{f_\rho(q^2)f_\rho^*(q^2)}{m_\rho^2}(\boldsymbol{\sigma}_i\times\mathbf{q})(\mathbf{S}_j^\dagger\times\mathbf{q})\times(\boldsymbol{\tau}_i\cdot\mathbf{T}_j^\dagger)\frac{-1}{(2\pi)^3(\mathbf{q}^2-q_0^2+m_\rho^2)}. \quad (3)$$

Here, we use the static form of the πNN vertex. We have neglected the nucleon recoil terms. For a consistent treatment of the relativistic effects, relativistic formulation such as that of Ref. [23] is necessary but these are beyond the scope of the present study. The transition spin and isospin operators are denoted by **S** and **T**, respectively. We assume the following form for the form factors:

$$f_{\pi,\rho}(q^2)=f_{\pi,\rho}\frac{\Lambda_{\pi,\rho}^2-m_{\pi,\rho}^2}{\Lambda_{\pi,\rho}^2-q_0^2+\mathbf{q}^2},$$

$$f_{\pi,\rho}^*(q^2)=f_{\pi,\rho}^*\frac{\Lambda_{\pi,\rho}^{*2}-m_{\pi,\rho}^2}{\Lambda_{\pi,\rho}^{*2}-q_0^2+\mathbf{q}^2}. \quad (4)$$

For the s-wave rescattering diagrams, we use the phenomenological interaction Hamiltonian of Koltun and Reitan [24],

$$H_1=4\pi\frac{\lambda_1}{m_\pi}\boldsymbol{\Phi}^2, \quad H_2=4\pi\frac{\lambda_2}{m_\pi}\boldsymbol{\tau}\cdot(\boldsymbol{\Phi}\times\boldsymbol{\Pi}), \quad (5)$$

where $\boldsymbol{\Phi}$ and $\boldsymbol{\Pi}$ are the pion field operator and its conjugate, respectively. We assume the off-shell extrapolation of the coupling strengths λ_1 and λ_2 due to Maxwell *et al.* [25]:

$$\lambda_1(t)=-\frac{1}{2}m_\pi\left(a_{\rm sr}+a_\sigma\frac{m_\sigma^2}{m_\sigma^2-t}\right), \quad (6)$$

$$\lambda_2(t)=\lambda_2\frac{m_\rho^2}{m_\rho^2-t}, \quad (7)$$

where t is the four momentum transfer in the πN t channel. We adopt the values $a_{\rm sr}=-0.23m_\pi^{-1}$, $a_\sigma=0.22m_\pi^{-1}$, and $m_\sigma=4.2m_\pi$ [25]. The coupling strength λ_2 is calculated from the experimental pion-nucleon phase shifts of Arndt *et al.* [26]. The corresponding s-wave rescattering amplitude is given by

$$M_{ij}^{(s)}=8\pi\frac{f_\pi(q^2)}{m_\pi}(\boldsymbol{\sigma}_i\cdot\mathbf{q})\left[\frac{\lambda_1}{m_\pi}(-)^\alpha\tau_i^{-\alpha}-\frac{\lambda_2}{m_\pi^2}\frac{q_0+\omega_k}{2}\times i(\boldsymbol{\tau}_i\times\boldsymbol{\tau}_j)^{-\alpha}(-)^\alpha\right]\frac{-1}{(2\pi)^3(\mathbf{q}^2-q_0^2+m_\pi^2)}. \quad (8)$$

The effects of the two-nucleon correlation are taken into account phenomenologically according to the method of Oset and Weise [27] with a correlation function of the form

$$\Omega(r)=1-j_0(m_c|\mathbf{r}_1-\mathbf{r}_2|), \quad (9)$$

where we take the ω meson mass for m_c. The $V_{\pi,\rho}(q)$ in Eqs. (2) and (3) are replaced by $V_{\pi,\rho}^c$ as

$$V_{\pi,\rho}(q)\to V_{\pi,\rho}^c(q)=\int e^{i\mathbf{q}\cdot\mathbf{r}}V_{\pi,\rho}(\mathbf{r})\Omega(r)d\mathbf{r}. \quad (10)$$

The amplitudes $M^{(p)}$ and $M^{(s)}$ in Eqs. (1) and (8) are sandwiched by the initial and final nuclear wave functions and the proton and the pion distorted waves. The detailed form of the operators and the expressions for the cross section and the analyzing power are found in Ref. [14].

III. RESULTS

The distorted waves for the incident proton are generated by the proton-nucleus optical potential with parameters given by Ingemarsson *et al.* [28] at $T_p=183$, 205 MeV and Jones *et al.* [29] at $T_p=318$, 398 MeV. For these energies, a relativistic treatment of the proton scattering might be necessary but our primary interest here is to study the overall feature of the (p,π^-) reaction and hence we simply use a nonrelativistic optical potential with parameters determined from the fit to the elastic scattering data. To calculate the pion distorted waves, we adopt the optical potential parametrized by Stricker and co-workers [30–32] (MSU potential), which was constructed to describe the low-energy pion-nucleus

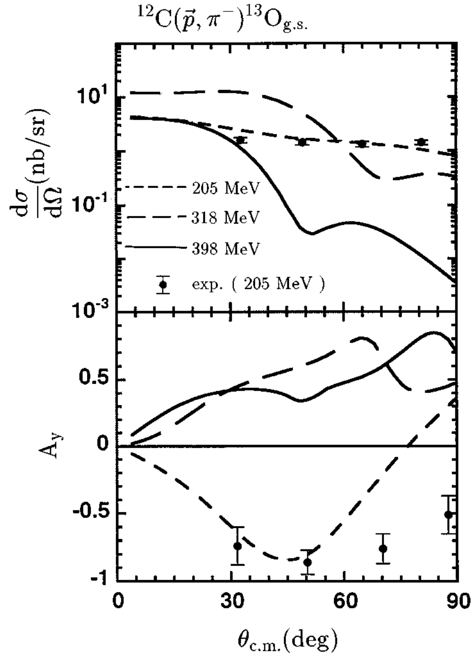

FIG. 2. The cross sections and asymmetries for the reaction $^{12}C(\vec{p},\pi^-)^{13}O_{g.s.}$. The dashed, long dashed, and solid lines correspond to the results with incident proton energies $T_p = 205$, 318, and 398 MeV, respectively. We have multiplied a factor 0.1 for all of these theoretical values. The experimental data are those for the incident energy $T_p = 205$ MeV, which are taken from Ref. [12].

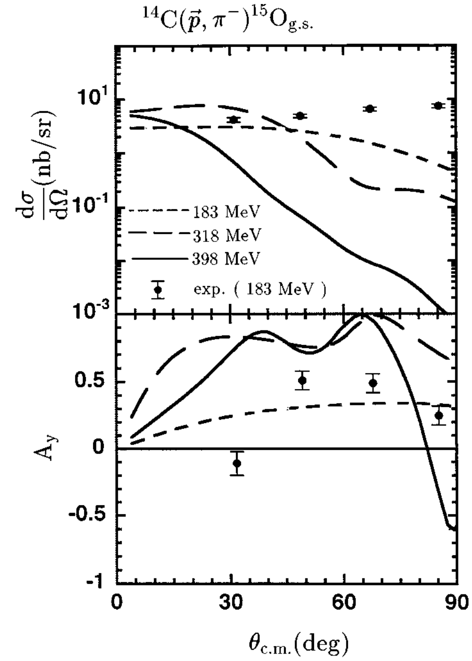

FIG. 3. The cross sections and asymmetries for the reaction $^{14}C(\vec{p},\pi^-)^{15}O_{g.s.}$. The dashed, long dashed, and solid lines correspond to these with the incident proton energies $T_p = 183$, 318, and 398 MeV, respectively. We have multiplied a factor 0.1 for all of these theoretical results. The experimental data are those for the incident energy $T_p = 183$ MeV, which are taken from Ref. [12].

elastic scattering. For the s- and p-wave potential parameters, we use impulse values calculated from the experimental pion-nucleon phase shifts [33]. For the absorption parameters B_0 and C_0, we use the values of Gmitro *et al.* [34]. They assume the first-order optical potential supplemented by the phenomenological ρ^2 terms which simulate the pion absorption and the higher-order effects. The coefficients B_0 and C_0 for these ρ^2 terms were determined from the fit to the experimental data of the pion-nucleus elastic scattering. They obtained the energy-dependent parameters which are close to the values of the MSU potential in the low-energy region. Though they use a different form for the off-shell extrapolation of the pion-nucleon scattering amplitude from that of MSU, we expect that the results for (p,π^-) are not too sensitive to the detailed off-shell behavior of the pion-nucleon scattering amplitude as shown in Ref. [14]. For the nuclear wave functions, we use the $0p$-shell model wave functions with the effective two-body interaction of Hauge and Maripuu [35]. The Cohen-Kurath wave function [36] gives almost the same results. In the following calculations, we neglected the s-wave rescattering contribution for incident proton energies larger than 250 MeV.

In Figs. 2 and 3, we show the results of the cross section and the asymmetry for the ground-state transitions $^{12}C(\vec{p},\pi^-)^{13}O_{g.s.}$ and $^{14}C(\vec{p},\pi^-)^{15}O_{g.s.}$, respectively. In the near-threshold region, our theoretical values overestimate the experimental cross section around forward direction by an order of magnitude and, in these figures, we have multiplied a factor of 0.1 to the theoretical values of the cross section. The present two-nucleon model reproduces the experimental flat angular distribution of the cross section near threshold but fails to explain the absolute values of the cross section. The present results are slightly different from those in Refs. [19,21], since we use different parameters for the pion optical potential. As seen in Figs. 2 and 3, the calculated cross sections rapidly decrease at large angle with the increase of the incident proton energy, which is due to the larger momentum transfer to the nucleus. At forward direction the cross section smoothly increases near the delta resonance, which is a consequence of the assumed two-body process through the delta.

Near threshold, our calculation correctly reproduces the observed isotopic sign change of the asymmetry at forward direction as seen in Figs. 2 and 3. Qualitatively, the sign change of the asymmetry is considered to come from the difference of the single particle orbit of the struck neutron in the two-body process $\vec{p}+n \rightarrow pp+\pi^-$; $p_{3/2}$ neutron for ^{12}C and $p_{1/2}$ neutron for $^{14,13}C$ [12]. Vigdor *et al.* attempted to give qualitative explanation of this sign change but their naive semi-classical consideration leads to opposite signs for the asymmetry [37]. It is interesting to note that the asymmetry for $^{12}C(\vec{p},\pi^-)^{13}O_{g.s.}$ becomes positive at higher energy and then the asymmetry for both of the $^{12,14}C(\vec{p},\pi^-)^{13,15}O_{g.s.}$ reactions takes positive values at high energy.

Considering the high-q nature of the (p,π^-) reaction, it is difficult to precisely predict the absolute value of the cross section, especially for the ground-state transitions. Even for the stretched-state transition in medium heavy nuclei, where we expect better momentum and angular momentum matching, we need energy-dependent normalization factors 3.3 ($T_p = 166$ MeV) and 1.4 ($T_p = 205$ MeV) to reproduce the forward cross sections $^{48}Ca(p,\pi^-)^{49}Ti(\frac{19}{2}^-$:4.38 MeV) as was shown in Ref. [15]. Previously, we have calculated the

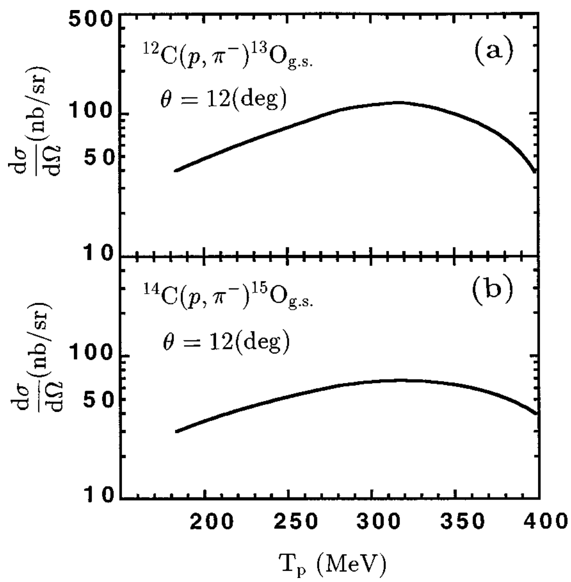

FIG. 4. The calculated differential cross sections for the reactions (a) $^{12}\mathrm{C}(p,\pi^-)^{13}\mathrm{O}_{\mathrm{g.s.}}$ and (b) $^{14}\mathrm{C}(p,\pi^-)^{15}\mathrm{O}_{\mathrm{g.s.}}$ at an angle $\theta = 12°$ as a function of the incident proton energy T_p.

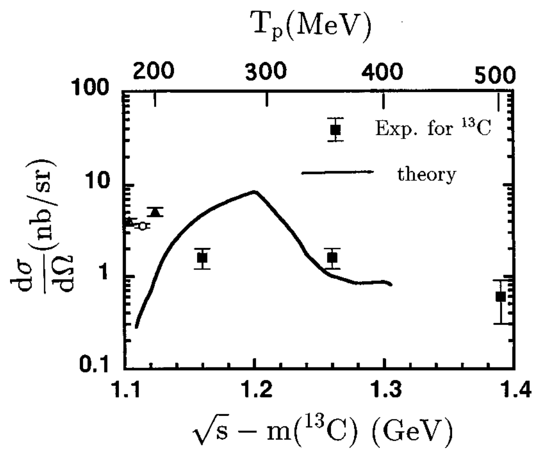

FIG. 5. The differential cross section as a function of the center-of-mass energy $\sqrt{s}-m(^{13}\mathrm{C})$ at a fixed four-momentum transfer $t=0.50\ \mathrm{GeV}^2/c^2$. The experimental data are taken from various sources: ■ (Ref. [22]), ○ (Ref. [12]), △ (Ref. [38]), and ▲ (Ref. [39]). The solid line represents our theoretical values multiplied by a factor 0.1. In the upper part, we provide the incident proton energy for easy comparison to the previous figures.

first-order core-polarization effect and have shown that it reduces the cross section by about a factor of 2 over all angular direction but little affect the asymmetry [21]. Even if we consider the core-polarization effect, there still remains the descrepancy about a factor 5. The absolute values of the cross section are sensitive to the choice of the imaginary part of the pion-nucleus optical potential. To minimize the ambiguity, we have used the potential parameters which reproduce the pion-nucleus elastic scattering which is sensitive to the optical potential around the on mass shell. Regarding the off-shell part of the optical potential, we have previously examined the off-shell dependence of the pion-production cross section in Ref. [14]. Though we only examined limited range of the cutoff mass and also only tested the case of Gaussian form factors, the cross section is not too sensitive to the off-shell part of the optical potential.

To see the energy dependence of the forward cross sections, we show, in Fig. 4, the cross section at an angle $\theta = 12°$. The calculated cross section increases with the incident proton energy and has a smooth peak around $T_p = 320$ MeV corresponding to the intermediate delta resonance. Here, we assumed the energy-independent overall normalization factor 0.1. As mentioned above, the core polarization reduces the cross section over almost all angular range by a factor 2. Even if we consider the core polarization there still remains a descrepancy about a factor 5 at the low-energy region. Our present results and the following discussions are invalidated if this normalization factor is strongly energy dependent. In order to compare with the available experimental data, we show the differential cross section for ^{13}C in Fig. 5 as a function of center-of-mass energy $\sqrt{s}-m(^{13}\mathrm{C})$ at a fixed four momentum transfer $t=0.5\ \mathrm{GeV}^2/c^2$ [22]. The experimental values are those for ^{13}C and the theoretical values are obtained from those of ^{14}C by multiplying a factor 0.5 in order to take into account the number of valence neutrons. We could not calculate the cross section for large $\sqrt{s}-m(^{13}\mathrm{C})$ since we do not have appropriate potential parameters for the proton. Here, we have multiplied a normalization factor 0.1 to the theoretical values. The low-energy data corresponds to the cross section at backward direction and, since the theoretical value of the cross section decreases too rapidly at backward direction [19–21], our results underestimate the low-energy cross section.

Contrary to our results, the experimental (p,π^-) cross section seems to have no peak around the delta resonance. For positive pion production process $p+p \to p+n+\pi^+$, the dominant channel is $pp(^1D_2) \to N\Delta(^5S_2) \to NN(^3S_1) + \pi^+(p\ \text{wave})$, where s-wave intermediate $N\Delta$ and final NN states are involved. For negative pion production, short-range nature of the (p,π^-) process also favors the relative s state for final two protons $(^1S_0)$. If we assume the dominant final $pp(^1S_0)$ channel and also the orbital angular momentum of pion 0 or 1, only $N\Delta(^3P_0)$ intermediate state is allowed [20]. The analysis of the analyzing power data leading to (p,π^-) continuum state together with the phase-shift analysis of the $\pi^- pp(^1S_0) \to pn$ angular distribution extracted from the $^3\mathrm{He}(\pi^-,pn)n$ data suggest that the reaction proceeds $\pi^- pp(^1S_0) \to np(^3D_1 T=0)$ [40,41], where intermediate $N\Delta$ state is forbidden. Though the final two proton channel $pp(^1S_0)$ is believed to dominate the reaction process, the role of delta resonance in (p,π^-) reaction is not clear and the nonresonant process might dominate the (p,π^-) leading to ground states [20]. In the ground state transition of $^{12,14}\mathrm{C}(p,\pi^-)^{13,15}\mathrm{O}_{\mathrm{g.s.}}$, large angular momentum transfer to the target nucleus is hard to accommodate because the final nucleus has low spin. The alternative possible processes for the (p,π^-) reaction are discussed in Ref. [22]. In the present calculation, we have assumed that the reaction proceeds dominantly through delta resonance and our DWBA calculation predicts a smooth peak around the delta resonance. These results seem to contradict the experimental data. The available data points are limited and it is hoped that the (p,π^-) experiment of the ground-state transitions will be carried out in near future and shed some light to the understanding of the still unclear reaction mechanism of the ground-state (p,π^-) reactions especially the role of delta resonance in (p,π^-) reactions.

IV. SUMMARY AND CONCLUSIONS

The (p,π^-) reaction theory with the two-nucleon mechanism was successful in describing the overall features of the stretched-state transitions in medium heavy nuclei in the near-threshold (p,π^-) reactions. On the other hand, the ground-state transitions in the carbon isotopes were not fully understood. From the theoretical and experimental studies [20,22], it is argued that the ground-state transition might proceed through the nonresonant channel. In the threshold region, the reaction mechanism is complicated due to the interference between s- and p-wave rescattering contributions. Near and above the delta resonance region, the s-wave rescattering contribution becomes less important. In the present work, we have extended our full-range DWBA calculations of the ground-state transitions of the carbon isotopes $^{12,14}\mathrm{C}(\vec{p},\pi^-)^{13,15}\mathrm{O}_{\mathrm{g.s.}}$ to higher-energy regions assuming the dominant delta processes. At higher energies, the theoretical cross sections are sharply forward peaked due to the larger momentum transfer to the nucleus. Also, the asymmetry changes its sign around the delta resonance for $^{12}\mathrm{C}$. Our model calculation predicts a peak in the forward cross section around the delta resonance. Here we assumed an energy independent normalization factor. We have also compared our results with the experimental data of TRIUMF at a fixed four momentum transfer. Our results seem to contradict these experimental data. For the better understanding of the underlying reaction mechanism especially for the role of delta resonance in the (p,π^-) reactions, it would be interesting to study these reactions experimentally at higher-energy region in detail. We hope that the experiments of these reactions will be carried out in the near future.

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