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Contribution of the Δ(1232) to the (e, e′p) reaction along with Coulomb distortion effects

K.S. Kim[1,a], M.K. Cheoun[2,b], S.W. Hong[1], and Y. Chung[3]

[1] BK21 Physics Research Division and Institute of Basic Science, Sungkyunkwan University, Suwon, 440-746 Korea
[2] ICUNSF, Building 139-1, Seoul National University, Seoul, 150-741, Korea
[3] Department of Physics, Yosu National University, Yosu, 550-250, Korea

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Abstract. The Δ-resonance contribution has been included in the $(e, e'p)$ reaction along with Coulomb distortion effects. We treat the resonance via a non-relativistic Δ current operator and use a Dirac Hartree single-particle model for the ground-state single-particle wave function and a relativistic optical model for the knocked-out proton wave function. It is assumed that the π-meson created by the virtual photon is absorbed in the target nucleus following the production of a Δ-resonance. Our DWBA calculation shows that the Δ-resonance contribution to the $(e, e'p)$ reaction cross-section is 10–15% for an energy of 250 MeV transfered to the proton knocked out of the s-shell of ^{40}Ca, in the parallel and perpendicular kinematics.

PACS. 24.90.+d Other topics in nuclear reactions: general – 25.30.-c Lepton-induced reactions

1 Introduction

Electron scattering has been used as a useful tool for the study of nuclear structures and their properties. Since inclusive (e, e') experiments provide information only about the general nuclear structure, exclusive $(e, e'p)$ experiments have been done recently to obtain a clue regarding which orbitals of the target nucleus participate in the reaction. It means that one can study the single-particle motion inside the nucleus and test different nuclear models for nuclear wave functions, in particular, independent particle models.

For instance, one can extract spectral functions for a given shell in the target nucleus with respect to the momentum transfer and the energy transfer. The structure functions give us information about the nucleons in the nucleus through a comparison with experimental data. The comparison, however, needs a scale factor called a spectroscopic factor, which stands for an occupation number related to the probability of removing a nucleon at a given shell state. In the simplest independent particle model the value of the factor is 0 or 1.

Actually, the value deduced in such a way deviates from its 0 or 1 for a given nuclear model because the residual interactions exist after the conversion of the nucleon-nucleon interactions into a mean-field potential. Therefore, a precise estimate of the spectroscopic factor is desirable to test the characteristics of the given nuclear model. But there are still many ambiguities to be pinned down before conclusions for the spectroscopic values can be drawn due to several effects, such as medium effect, current operators, and so on [1,2]. The effect of the two-body current studied in this paper is one of the sources of ambiguities.

Using these exclusive $(e, e'p)$ and inclusive (e, e') reactions, many previous papers [3–11] have reported on interesting results, particularly in the dip region located between the quasi-elastic and the Δ production peaks. In this region, the one-body process which governs the quasi-elastic region does not dominate the cross-section. For instance, it accounts for only 20–30% of the experimental (e, e') cross-section in ^{12}C at a momentum transfer of $q = 400$ MeV/c and energy transfer of $\omega = 200$ MeV [9].

Therefore, the two-body process, in particular, mediated by internal pions, becomes competiting with the one-body process in the dip region. This region, thus, could be a desirable one for the investigation of the two-body process effects. The pion exchange current contributes to these reactions through the propagation of the nucleon (regular pion exchange) and the Δ-resonance inside nucleus. The Δ-resonance contribution, which has been studied by many authors, is thought to be significant in the $(e, e'p)$ reaction. The regular pion exchange has been also investigated extensively as a possible contribution of meson exchange current (MEC) in the electron scattering. Most of the calculations were based on the impulse approximation (IA) with additional contributions, such as the above regular pion exchange and the Δ-resonance. The

[a] e-mail: kyungsik@color.skku.ac.kr
[b] e-mail: cheoun@phya.snu.ac.kr

IA has three important ingredients, wave functions for initial and final nuclei, electro-magnetic current operators, and final-state interactions due to the Coulomb and the strong interactions. Since the wave functions exploited in the IA are usually constructed from independent particle models, they do not contain the pion and the Δ-resonance as degrees of freedom. Therefore, in the framework of the IA one needs to explicitly take the contributions of the regular pion exchange and the Δ-resonance currents into account.

For example, the Gent group in Belgium [2,12,13] took a non-relativistic model for the $(e,e'p)$ reaction. Their calculation, based on the Hartree-Fock (HF) approach, made use of the random phase approximation (RPA) with the two-body current and made comparison with the experimental data from NIKHEF [14]. They included the electron Coulomb distortion by using the effective momentum approximation (EMA). The RPA among these effects makes a considerable contribution to the reduced cross-section at high missing momentum. But, the electron Coulomb effect was comparable to that of the two-body current. Many effects like particle-hole interactions in RPA, the two-body process effects due to the pion exchange, such as the MEC and the Δ-resonance current, the final-state interactions, and so on are equally important. In particular, the Δ plays an important role in the transverse nuclear response.

On the other hand, in the quasi-elastic region, many theoretical calculations [15–22] of the $(e,e'p)$ reaction have been carried out in the framework of the distorted-wave Born approximation (DWBA) exploiting a relativistic optical model for the outgoing proton and a relativistic Dirac-Hartree single-particle model for the target nucleus in the presence of the electron Coulomb distortion. If we note that these models rely on the relativistic mean-field theories and these theories contain the mesons as the fundamental building blocks, the DWBA for these reactions does not necessarily need to consider the regular pion exchange contribution. But the Δ-resonance should be explicitly included in the two-body process because the resonance was not included in the construction of the relevant wave functions. In these calculations, it turns out that the Coulomb distortion plays non-negligible roles even without the Δ-resonance. The Coulomb distortion effects are of the order of 30% of the cross-section for ^{208}Pb, so in the dip region the effects should be distinguished in order to investigate the two-body process effects.

In this paper we add the Δ part of the two-body current to the relativistic single-particle model in the dip region where one expects larger contributions than in the quasi-elastic peak. That is, we extend our previous calculations [18,20] by adding a non-relativistic Δ current operator and investigate explicitly the contribution of the $\Delta(1232)$ current to the $(e,e'p)$ reaction cross-section in the dip region, and we also include electron Coulomb distortion effects. In sect. 2, we briefly introduce the two-body current operator and apply it to the $(e,e'p)$ reaction by using the Dirac-Hartree single-particle wave function [23] for the bound state and the relativistic optical model [24] for the proton knocked out. In sect. 3, we calculate the contribution of the $\Delta(1232)$ current for the $2s_{1/2}$, $1d_{3/2}$, and $1d_{5/2}$ shells of ^{40}Ca. Conclusions are given in sect. 4.

2 Theoretical formalism

In the plane-wave Born approximation (PWBA), the cross-section for the exclusive $(e,e'p)$ reaction with a polarized incident electron beam can be written as

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}E_\mathrm{f}\mathrm{d}\Omega_\mathrm{f}\mathrm{d}\Omega_p} = \frac{pE_p}{(2\pi)^3}\sigma_\mathrm{M}[v_\mathrm{L}R_\mathrm{L} + v_\mathrm{T}R_\mathrm{T} + \cos 2\phi_p v_\mathrm{TT}R_\mathrm{TT} + \cos\phi_p v_\mathrm{LT}R_\mathrm{LT} + h\sin\phi_p v_{\mathrm{LT}'}R_{\mathrm{LT}'}] \ , \quad (1)$$

where σ_M is the Mott cross-section and R_L, R_T, R_TT, R_LT, and $R_{\mathrm{LT}'}$ are the longitudinal, transverse, transverse-transverse, longitudinal-transverse, and polarized longitudinal-transverse structure functions, respectively. The factors v_L, v_T, etc. depend on the electron kinematics [18]. E_f and Ω_f are the energy and the solid angle of the final electron, ϕ_p is the azimuthal angle of the outgoing proton measured with respect to the electron scattering plane, and h is the helicity of the initial electron. The momentum and the energy of the outgoing proton are p and E_p. In the full DWBA calculation by using a partial-wave expansion, it is not possible to separate the cross-section into a sum of bilinear products of the electron kinematics and the outgoing proton's azimuthal angle [16]. According to ref. [18], however, it is possible to treat the Coulomb distortion in an approximate way that not only has very good agreement with the full DWBA calculations, but also allows the separation of the cross-section into terms containing structure functions [21,22] which are closely related to the plane-wave structure functions. For this calculation we use the approximate method of including Coulomb distortion which is a very close approximation to the full DWBA result.

In order to calculate the contribution of the Δ-resonance to the dip region, we use the non-relativistic $\Delta(1232)$ current operator [13] given by

$$\hat{J}^{(2)}_{\Delta,\ \text{non-rel.}}(\mathbf{q},\ \mathbf{k}_1,\ \mathbf{k}_2) = \frac{2if_{\gamma N\Delta}f_{\pi N\Delta}f_{\pi NN}}{9m_\pi^3(M_\Delta - M_N - \omega - \frac{i}{2}\Gamma_\Delta)} \times\Bigg\{\Big[-(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z\frac{(\boldsymbol{\sigma}_2\cdot\mathbf{k}_2)}{k_2^2+m_\pi^2}(\boldsymbol{\sigma}_1\times\mathbf{k}_2)\times\mathbf{q} + 4(\boldsymbol{\tau}_2)_z\frac{(\boldsymbol{\sigma}_2\cdot\mathbf{k}_2)}{k_2^2+m_\pi^2}(\mathbf{k}_2\times\mathbf{q})\Big] + [1\longleftrightarrow 2]\Bigg\}, \quad (2)$$

where the Δ width $\Gamma_\Delta(\omega)$ was extracted from the formula given by Oset *et al.* [25]. The values of the coupling constants are $f^2_{\gamma N\Delta} = 0.014$, $\frac{f^2_{\pi N\Delta}}{4\pi} = 0.37$, and $\frac{f^2_{\pi NN}}{4\pi} = 0.079$. The Δ- and π-meson form factors are given by the following forms [26]:

$$F_{\gamma N\Delta} = \frac{1}{\left(1-\frac{k_\mu^2}{707000}\right)^2}\,, \qquad F_{\pi N\Delta} = \frac{1}{\left(1-\frac{k_\mu^2}{690000}\right)^2}\,,$$

where k_μ^2 is in units of MeV^2. For the πNN form factor, a monopole form $(\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 - k_\mu{}^2)$ with $\Lambda_\pi = 1200$ MeV is taken. $\mathbf{k}_1$ and $\mathbf{k}_2$ are the momenta transferred through the pion to nucleons 1 and 2, respectively. We briefly repeat an explanation of each term in eq. (2) [27]. The first bracket corresponds to the case where the photon interacts with nucleon 1 followed by Δ propagation which decays into the outgoing proton and an internal pion absorbed by nucleon 2. The first term in the bracket corresponds to a spin-flip of nucleon 1. The second corresponds to the non-spin-flip reaction and dominates over the first term due to the factor 4. Moreover, if we consider isospin, the first term survives only for the case of charged-pion exchange between the nucleons, while the second term allows for π^0 exchange. Therefore, the π^0 exchange in the Δ-resonance channel has a comparable contribution to the charged-pion exchange in this $(e,e'p)$ reaction, although it has a smaller Δ decay cross-section than the charged-pion decay. The second bracket stems from the interchange of nucleons 1 and 2, *i.e.*, the virtual photon forms a Δ on nucleon 2 followed by π^+ exchange between the relevant nucleons if the nucleon 1 is knocked out.

To apply the two-body current to the one-body current, we make the following assumptions: 1) the virtual photon emitted by the electron is absorbed by a single nucleon, 2) π^0 and $\pi^\pm$ mesons are exchanged consistently with charge conservation. Furthermore, when the pion is absorbed by the proton, we use momentum conservation at each vertex.

The one-body current is written as

$$J_N^{\mu(1)}(\mathbf{r}) = \langle A-1, p|\hat{J}^{\mu(1)}(\mathbf{q})|A-1, b\rangle = e\bar{\Psi}_p(\mathbf{r})\hat{J}^{\mu(1)}(\mathbf{q})\Psi_b(\mathbf{r}) \ . \quad (3)$$

The $\hat{J}_N^{\mu(1)}(\mathbf{q})$ is the one-body nucleon current operator given by

$$\hat{J}_N^{\mu(1)}(\mathbf{q}) = F_1\gamma^\mu + \frac{i\mu_T}{2M_N}F_2\sigma^{\mu\nu}q_\nu \ , \quad (4)$$

where μ_T denotes the nucleon anomalous magnetic moment and F_1 and F_2 stand for the nucleon form factors which are function *s* of the four-momentum transfer.

The Δ-resonance is formed mainly by the *p*-wave photon as is well known in the $M_{1^+}(3/2)$ amplitude for pion photoproduction. Consequently, one can expect that the proton knocked out from the $s_{1/2}$ state is affected more by the Δ excitation mechanism than protons from the *d* states.

Within the DWBA scheme, the outgoing-nucleon wave function $\Psi_p(\mathbf{r})$ and the bound-state nucleon wave function $\Psi_b(\mathbf{r})$ are obtained in a relativistic optical model and a relativistic Dirac-Hartree single-particle model, respectively. The outgoing-nucleon wave function is given by

$$\Psi_p(\mathbf{r}) = \sum_{\kappa_p\mu_p} C_{\kappa_p\mu_p} e^{-i\delta_{\kappa_p}} \psi_{\kappa_p}^{\mu_p}(\mathbf{r}) \ , \quad (5)$$

where $\psi_{\kappa_p}^{\mu_p}(\mathbf{r})$ and $C_{\kappa_p\mu_p}$ are given by

$$\psi_{\kappa_p}^{\mu_p}(\mathbf{r}) = \begin{pmatrix} f_{\kappa_p}(r)\chi_{\kappa_p}^{\mu_p}(\hat{\mathbf{r}}) \\ g_{\kappa_p}(r)\chi_{-\kappa_p}^{\mu_p}(\hat{\mathbf{r}}) \end{pmatrix} ,$$

and

$$C_{\kappa_p\mu_p} = \sqrt{\frac{E_p+M}{2E_p}} 4\pi(i)^{\ell_p} C^{\ell_p \ \frac{1}{2} \ j_p}_{\mu_p - s \ s \ \mu_p} Y_{\ell_p}^{\mu_p - s *}(\hat{\mathbf{p}}) \ ,$$

in which $f(r)$ and $g(r)$ are obtained by solving numerically coupled Dirac radial equations. $\chi_{\kappa_p}^{\mu_p}(\hat{\mathbf{r}})$ is the spin angle function [28]. The bound-state wave function has a structure similar to the above outgoing nucleon, but it does not contain an imaginary part.

On the other hand, the two-body current is calculated in the following way:

$$\begin{aligned} J_\Delta^{\mu(2)}(\mathbf{r}) &= \langle A-2, p, b2'|\hat{J_\Delta}^{\mu(2)}(\mathbf{q})|A-2, b, b2\rangle = \\ &e\int \mathrm{d}\mathbf{r}' \int_0^{k_\mathrm{F}} \mathrm{d}\mathbf{k}_i \ \mathcal{A}[\bar{\Psi}_p(\mathbf{r})\bar{\Psi}_{b2'}(\mathbf{r}')] \\ &\times \hat{J}_\Delta^{\mu(2)}(\mathbf{q},\mathbf{k}_i) \ \mathcal{A}[\Psi_{b2}(\mathbf{r}')\Psi_b(\mathbf{r})] \ , \end{aligned} \quad (6)$$

where $\mathcal{A}$ stands for the anti-symmetrization and k_F denotes the Fermi momentum. $\Psi_p(\mathbf{r})$ and $\Psi_b(\mathbf{r})$ are the same wave functions as in eq. (3) and $\Psi_{b2'}(\mathbf{r}')$ and $\Psi_{b2}(\mathbf{r}')$ are undetected particles inside the target nucleus.

As for the bound-state wave functions, $\Psi_{b2}(\mathbf{r}')$ and $\Psi_{b2'}(\mathbf{r}')$, we exploit the plane-wave–like form. Using this analytical form is an effective method to describe the Coulomb distorted Dirac particle in the electron scattering [18,19]. Namely, the comparison of this analytic form to the exact fully distorted wave in the case of the electron scattering does not give any discernible difference in the results. Of course, in case of the nucleon, this form could be questioned because the nucleon inside the nucleus is in the additional vector and scalar potentials due to the strong interactions. But, in this paper, we assume that it is still valid even in the strong interactions. Otherwise, we could not use the momentum conservation in the 3-point vertex of the internal pion and the nucleons. It leads to a formidable task of incorporation of the Δ-resonance in the DWBA method.

Exploiting the momentum conservation at the pion vertex and the orthogonality of the bound wave functions, we can simply integrate over $\mathbf{r}'$ and obtain

$$J_\Delta^{\mu(2)}(\mathbf{r}) = e\mathcal{R}(\mathbf{r}) \int_0^{k_\mathrm{F}} \mathrm{d}\mathbf{k}_i \ [\bar{u}_p\bar{u}_{b2'}] \ \hat{J}_\Delta^{\mu(2)}(\mathbf{q},\mathbf{k}_i) \ [u_{b2}u_b] \ , \quad (7)$$

where $\mathcal{R}(\mathbf{r})$ is a remaining radial integration part and $\hat{J}_\Delta^{\mu(2)}$ is a still fully relativistic Δ current. After this manipulation, we reduce it to a non-relativistic form of eq. (2) using the static approximation for the $\hat{J}_\Delta^{\mu(2)}$ by decomposing the Dirac spinors into the 2-component Pauli spinors as follows [11]:

$$J_{\Delta}^{\mu(2)}(\mathbf{r}) = e\mathcal{R}(\mathbf{r}) \int_0^{k_F} \mathrm{d}\mathbf{k}_i \, [\bar{\chi}_p(\hat{\mathbf{r}})\bar{\chi}_{b2'}(\mathbf{k}_i)] \times \hat{J}_{\Delta,\ \mathrm{non\text{-}rel.}}^{\mu(2)}(\mathbf{q}, \mathbf{k}_i) \, [\chi_{b2}(\mathbf{k}_i)\chi_b(\hat{\mathbf{r}})] \ . \tag{8}$$

We apply this current form to the final continuum state and the bound wave function to calculate the cross-section. Since the π^0 and $\pi^{\pm}$ mesons are exchanged inside the target nucleus, the momenta $\mathbf{k}_1$ and $\mathbf{k}_2$ in eq. (2) are assumed to remain inside the Fermi sphere. Note that the detected final proton is treated by a continuum wave function obtained from the relativistic optical model, while the bound state is described by the single-particle wave function. Thus, the final-state interaction is automatically included in this treatment.

The total nuclear current can be written as

$$J^{\mu} = J_N^{\mu(1)} + J_{\Delta}^{\mu(2)} \ , \tag{9}$$

where $J_N^{\mu(1)}$ is the nuclear current obtained by ref. [18] and $J_{\Delta}^{\mu(2)}$ is the Δ-resonance current. The non-relativistic Δ current is purely transverse, and then it is trivial to obtain $q_{\mu}J_{\Delta}^{\mu(2)} = 0$. But the one-body current is not conserved and the orthogonality may be violated in the $(e, e'p)$ process, because we choose the relativistic Hartree single-particle model for the bound state and the relativistic optical model for the outgoing nucleon. Up to now, there is no more convenient way to describe this knocking-out process. For these reasons, we choose the Coulomb gauge, which is commonly used, to conserve the one-body current, and finally we obtain $q_{\mu}J^{\mu} = 0$.

In the case of the impulse approximation, the meson exchange currents need to be included if the wave functions for the nucleus are constructed in the framework of the independent particle model. However, as already mentioned, we use a relativistic Dirac-Hartree single-particle model for the target nucleus. In particular, our scalar and vector potentials for the bound-state wave functions, $\Psi_b(\mathbf{r})$ in eq. (3), are obtained from the relativistic σ-ω model of Horowitz and Serot [23]. In this model, the mesons are included explicitly as degrees of freedom with the nucleons, so we did not include the meson in the two-body current. The Δ-resonance, however, is not included in our relativistic model for the nucleus. Therefore, we explicitly include the Δ-resonance in our two-body currents.

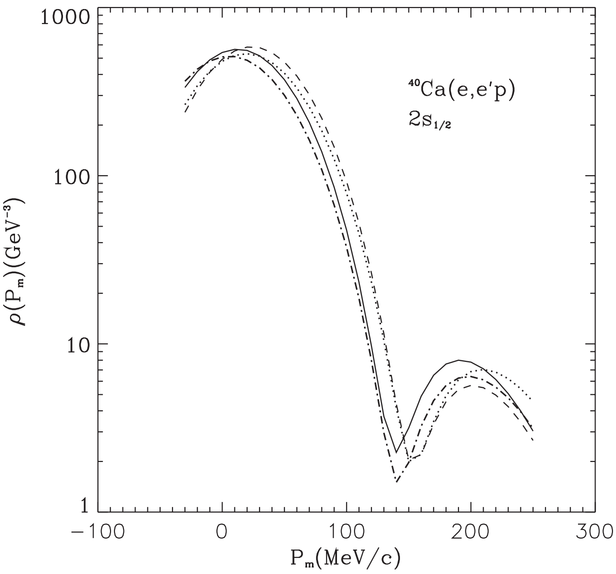

Fig. 1. The reduced cross-sections for knocking out protons from the $2s_{1/2}$-shell of ^{40}Ca in the parallel kinematics. The kinematics are $E_{\mathrm{i}} = 500$ MeV with energy transfer $\omega = 250$ MeV. The dotted and dashed curves show the DWBA results without and with the $\Delta(1232)$ contribution, respectively. The dash-dotted and solid curves show the PWBA results without and with the $\Delta(1232)$, respectively.

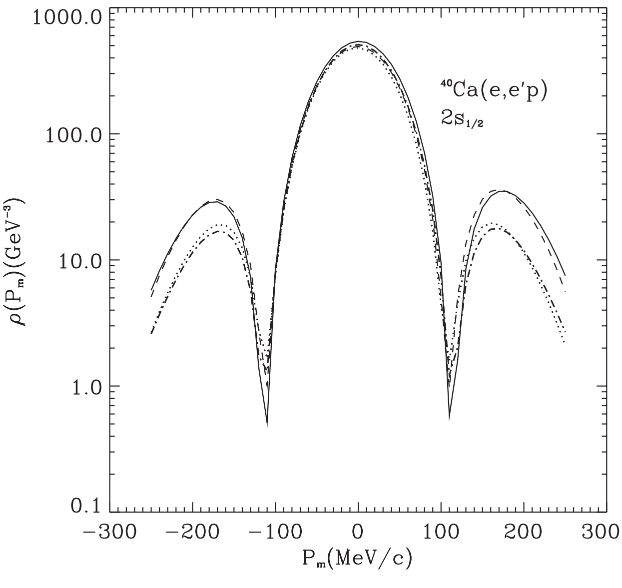

Fig. 2. The same as fig. 1 but with the perpendicular kinematics.

3 Results

In this analysis, we try to calculate the reduced cross-section arising from knocking out a proton from a given shell. This cross-section is related to the probability that a proton in the shell is carrying the missing momentum defined by $\mathbf{p}_{\mathrm{m}} = \mathbf{p} - \mathbf{q}$. The reduced cross-section is generally defined by

$$\rho(p_{\mathrm{m}}) = \frac{1}{pE_p\sigma_{ep}} \frac{\mathrm{d}^3\sigma}{\mathrm{d}E_{\mathrm{f}}\mathrm{d}\Omega_{\mathrm{f}}\mathrm{d}\Omega_p} \ . \tag{10}$$

The off-shell electron-proton cross-section σ_{ep} is not uniquely defined, but we use the form σ_{ep}^{cc1} given by de Forest [29] in all the calculations. There are two kinematical situations commonly used in $(e, e'p)$ experiments. They are the parallel kinematics in which the outgoing-proton momentum $\mathbf{p}$ is along the momentum transfer $\mathbf{q}$ and the perpendicular kinematics where the detected proton makes an angle with respect to the momentum transfer $\mathbf{q}$. Here, the electron energy transfer and the direc-

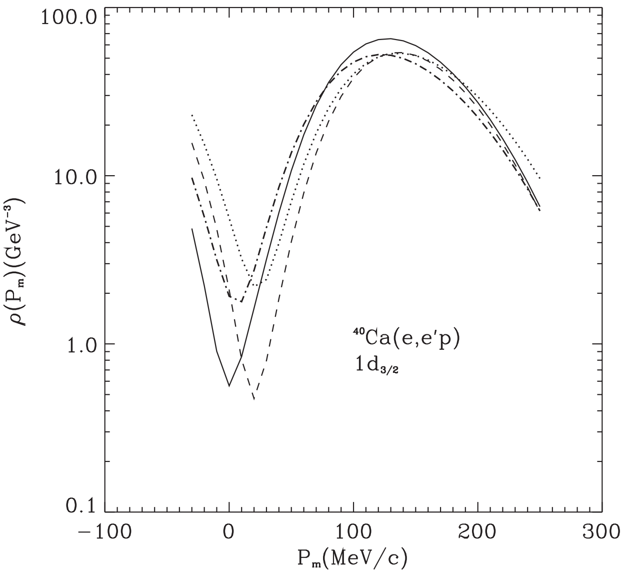

Fig. 3. The same as fig. 1 but for the $1d_{3/2}$-shell.

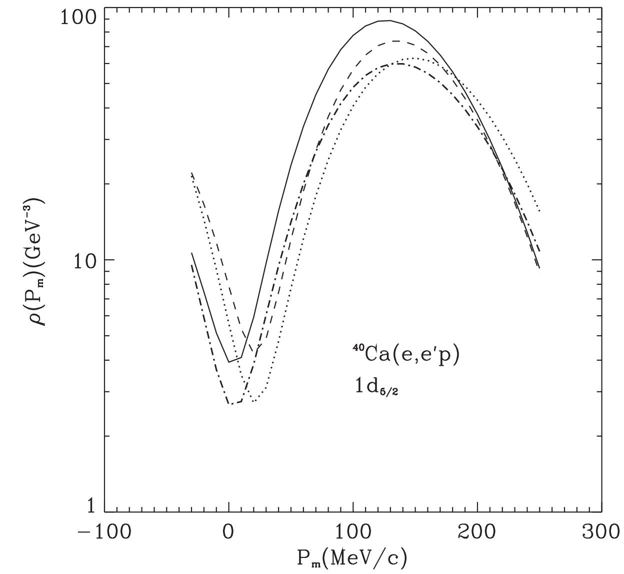

Fig. 5. The same as fig. 1 but for the $1d_{5/2}$-shell.

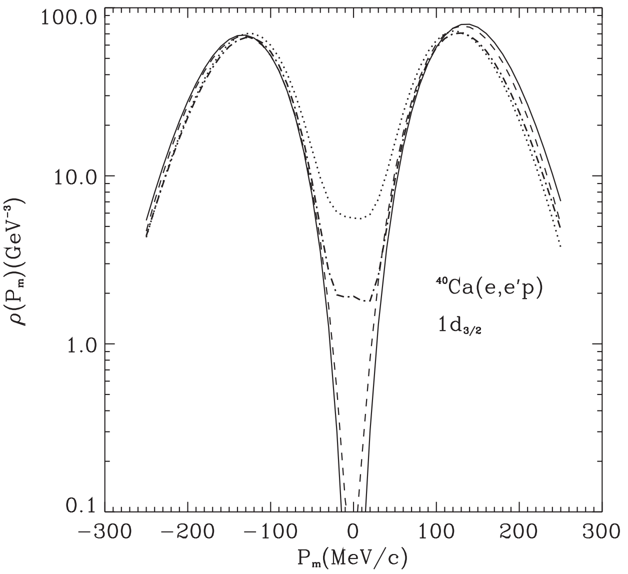

Fig. 4. The same as fig. 2 but for the $1d_{3/2}$-shell.

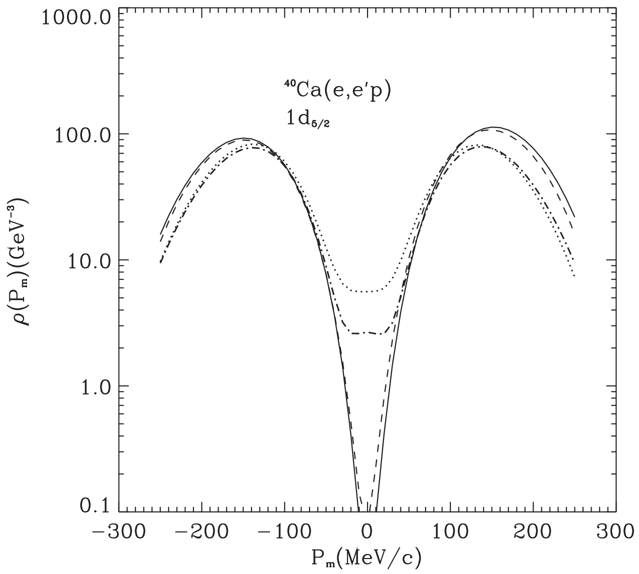

Fig. 6. The same as fig. 2 but for the $1d_{5/2}$-shell.

tion of **q** are fixed. In both kinematics the magnitude of **p**, the outgoing-proton momentum, is normally held at a constant value. All the calculations are carried out in the laboratory frame (target fixed frame).

In figs. 1-6, we show six results for the contribution of the $\Delta(1232)$-resonance to the proton knocked out of the $2s_{1/2}$, the $1d_{3/2}$, and the $1d_{5/2}$ shells of ^{40}Ca in both the parallel and perpendicular kinematics. The incoming-electron energy and the energy transfer are $E_{\rm i} = 500$ MeV and $\omega = 250$ MeV, respectively, in all the cases. Notice that the momentum transfer in the perpendicular kinematics is $|\mathbf{p}| = |\mathbf{q}| = 718.1$ MeV/c and the scattering angle $\theta_e = 144.3°$ over the whole ω region. In all figures, the dotted lines are DWBA results without the Δ contribution, while the dashed lines show DWBA results with the inclusion of the Δ contribution. The dash-dotted lines and the solid lines denote the PWBA results without and with the Δ contribution, respectively, and can be compared to the dotted and dashed lines to see the effects of electron Coulomb distortion.

As shown in figs. 1 and 2, in the DWBA calculation the contributions of the Δ are about 10% in the parallel kinematics and about 3% in the perpendicular kinematics for the case of the proton knocked out of the $2s_{1/2}$ orbit around the first peak. As is seen in figs. 3 and 4, however, the effect on the $1d_{3/2}$ orbit is about 3% in the parallel kinematics and 4% on the left and right peak positions in the perpendicular kinematics. In addition, figs. 5 and 6 show that the effects of the Δ on the $1d_{5/2}$ orbit are around 10% in the parallel kinematics and around 5% on the left peak and 10% on the right peak in the perpendicular kinematics. The Δ effect on the $2s_{1/2}$ orbit for both the parallel and perpendicular kinematics does not affect the positions of maxima and minima. The Δ effect on the $1d_{3/2}$ and $1d_{5/2}$ orbits for both kinematics produces only a small amount of shift. In the parallel kinematics, the contribution of the Δ increases with higher missing momentum $|\mathbf{p}_{\rm m}|$ (small momentum transfer $|\mathbf{q}|$ as can be seen in eq. (2)). In the perpendicular kinematics where the momentum transfer is fixed, the role of the Δ becomes more important with higher missing momentum. In the PWBA calculations, the role of the Δ on the $2s_{1/2}$ orbit has similar effects as in the DWBA calculations. But the Δ contribution to the d orbits appears different from that to the s orbit, which means the electron Coulomb distortion affects the Δ current although the distortion is not large in the dip region. In particular, the effect of the electron Coulomb distortion on the $1d$ orbits is smaller than that on the $2s$ orbit at the $p_{\rm m} > 0$ maximum positions.

From these results we see that although the effect on the d orbits looks more significant, the Δ contribution to the $2s_{1/2}$ orbit is actually larger in magnitude (see the scale of the y-axis in the figures). The reason may be related to the following: The relative angular momenta needed between the virtual photon and the bound nucleons are 1 and 0 for $2s_{1/2}$ and $1d_{3/2}$, respectively, to form the propagating Δ since the total angular momentum of the Δ is 3/2 and the Δ contribution arises mainly from $l = 1$. Therefore, the Δ contribution is larger for the s-shell than for the d-shell. Note that the ratio of the Δ contribution to the $1d_{2/5}$ orbit is also as important as that to the $2s_{1/2}$ orbit.

Although we have not examined more deeply bound orbits, we may deduce that the contribution of the $\Delta(1232)$ for inner orbits is larger than for outer orbits, since the nuclear density is larger deep inside the nucleus. Thus, if one consider all the nucleons, the total contribution of the Δ via this process may be somewhat larger than 10%–15%. This process, together with other processes where the pions exit the nucleus, will contribute to the (e, e') cross-section by about 20% in this kinematics range. Furthermore, in the dip region, we find that the effect of electron Coulomb distortion is about 7% for ^{40}Ca on each orbit in both kinematics consistently with ref. [30].

4 Conclusion

In summary, we have included the Δ-resonance contribution to the reduced cross-section for the reaction $(e, e'p)$ around the dip region ($\omega = 250$ MeV) as a function of the missing momentum. We have examined the cases in which the proton is knocked out from different shells. In the dip region, the Δ effects are considerably increased for higher missing momentum $p_{\rm m}$ and are almost 10% around the first peak in both kinematics for a proton knocked out of the $2s_{1/2}$ orbit. The size of the Δ effects on the first peak is only 3–5% for protons knocked out of the $1d_{3/2}$ orbit and about 10% for protons from the $1d_{5/2}$ orbit in ^{40}Ca. The reason why the Δ contribution in the s-shell is larger than in the d-shells depends on the relative momenta between the virtual photon and the bound nucleons. The size of the Δ contribution to the $(e, e'p)$, especially in the parallel kinematics, depends on the momentum transfer at a given initial electron energy and becomes larger with higher missing momentum. The effects of the electron Coulomb distortion for ^{40}Ca are comparable to the effects of the Δ current for these kinematics.

In conclusion our present calculations in the dip region show the possibility to treat the two-body current operator in a single-particle model in a simple way and thereby add it to the single-body current for the $(e, e'p)$ reaction. Our calculation includes electron Coulomb distortion and the final-state interaction of the outgoing proton. We find a relatively large Δ contribution to the $(e, e'p)$ reaction in the dip region. We believe this approach will be useful in analyzing $(e, e'p)$ experiments in the dip region and that it can be extended to the analysis of (e, e') reactions.

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