Meson Exchange Currents in Pion Double Charge Exchange at High Energies

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Abstract

In this letter we study the high energy behavior of the forward differential cross section for the $^{18}O(\pi^+,\pi^-)^{18}Ne$ double charge exchange reaction. We have evaluated the sequential and the meson exchange current mechanisms. The meson exchange current contribution shows a very weak energy dependence and becomes relevant at incident pion kinetic energies above 600 MeV.

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Pion double charge exchange (DCX) has generated a significant amount of theoretical and experimental work in the last years [1, 2]. The main reason is its special sensitivity to the two-nucleons wave function because, in contrast to most nuclear reactions, which are dominated by one-nucleon mechanisms, DCX needs at least two nucleons to take place.

Up to now, most of the research has concentrated in the region of energies around the Δ resonance or below it. At these energies, the analysis of the reaction is very complicated. This is due to the strong distortion of the pion waves at resonance and the diversity of mechanisms that play a significant role : successive deltas [3, 4], meson exchange currents (MEC)[5, 6, 7, 8], absorption mechanisms [9, 10], and many others. Normally, the reaction is dominated by the sequential mechanism (SEQ), in which the incoming pion undergoes two sequential single charge exchange (SCX) scatterings.

A recent DCX calculation, which included only the SEQ mechanism, has been performed for incident pion energies up to 1.4 GeV[11]. It is shown there that the angular cross section at forward angles decreases above 600 MeV, reaching a first dip at 700 MeV and a second, very pronounced, at 1300 MeV. These very low values of the cross section, produced by the mechanism which dominates the reaction at resonance, open the possibility for alternative mechanisms to show up. The clear discrepancies observed between the experimental results on inclusive DCX at high energies and the predictions of a sequential charge exchange model[12] tend to confirm these expectations.

In this paper, we report a new DCX calculation including meson exchange currents (fig. 1b,c) in addition to the SEQ mechanism (fig. 1a). MEC in DCX reactions were first studied by Germond, Robilotta and Wilkin [5]. They found a small contribution to the cross section in the Δ resonance region. Many other calculations [6, 7, 8] have followed their pioneering work, studying also the low energy region, and finding, in all cases, that MEC processes were small compared to the SEQ mechanism. However, the amplitude of the MEC diagrams considered in this paper depends very weakly on the energy of the incoming pion. Thus, one can expect these mechanisms to become important at high energies, in the regions where the SEQ process presents a dip.

Our approach is essentially the same as in ref.[11]. We calculate the cross section for the $^{18}O(\pi^+,\pi^-)^{18}Ne$ reaction using the Glauber model of multiple scattering. Assuming that the DCX process takes place in the valence neutrons, whereas the core (^{16}O) is only responsible for the distortion of the pion waves, the amplitude for the DCX reaction can be written as

$$F(\mathbf{q}) = \frac{ik}{2\pi}\int d^2b\, e^{i\mathbf{q}\mathbf{b}}\,\Gamma_{DCX}(\mathbf{b})\,\Gamma_{DIS}(\mathbf{b}), \tag{1}$$

where $\mathbf{b}$ is the impact parameter, k the incident pion momentum, and $\mathbf{q}$ the momentum transfer. Both k and $\mathbf{q}$ are in the laboratory system. In Eq. (1), Γ_{DIS} is the distorted profile given by

$$\Gamma_{DIS}(\mathbf{b}) = \left\langle {}^{16}O\right| \prod_{i\in core}(1-\Gamma^s(\mathbf{b}-\mathbf{s}_i))\left|{}^{16}O\right\rangle, \tag{2}$$

where Γ^s is the isoscalar profile function. The quality of the approximation implicit in eq. (1), where the profile is factorized into a DCX and a distortion piece was discussed in refs. [4, 8].

We evaluate Γ_{DIS} following the method explained in ref.[13]. We obtain

$$\Gamma_{DIS} = (1 - \Gamma)^{16}, \tag{3}$$

with

$$\Gamma = \frac{1}{2\pi i k_{cm}} \int d^2q\, e^{-i\mathbf{qb}}\, S(q) f^s(q), \tag{4}$$

where k_{cm} is the pion momentum in the πN c.m. system, $f^s(q)$ is the non-spin-flip isoscalar scattering amplitude (also in the πN c.m. system), and $S(q)$ the ^{16}O nuclear form factor, obtained by the Fourier transform of the nuclear density.

The DCX profile function (Γ_{DCX}) will be the sum of Γ_{SEQ} and Γ_{MEC}, the profiles for the sequential and the meson exchange currents mechanisms, respectively. For the SEQ mechanism (fig. 1a) we find

$$\Gamma_{SEQ} = -\sum_{m_1,m_2} \frac{(-1)^{5-m_1-m_2}}{3} \Big\langle 1d_{5/2} m_1 \Big| \Gamma^v \Big| 1d_{5/2} m_2 \Big\rangle \Big\langle 1d_{5/2} - m_1 \Big| \Gamma^v \Big| 1d_{5/2} - m_2 \Big\rangle, \tag{5}$$

where we use harmonic oscillator wave functions with a parameter $\alpha^2 = 0.32\text{fm}^{-2}$, and

$$\langle nljm | \Gamma^v | n'l'j'm' \rangle = \frac{1}{2\pi i k} \int d^2q\, e^{-i\mathbf{qb}} f^v(\mathbf{q}) \langle nljm | e^{i\mathbf{qs}} | n'l'j'm' \rangle. \tag{6}$$

Here, $f^v(q)$ is the isovector part of the πN amplitude, obtained using the SAID code [14]. We have included partial waves up to $l = 6$.

The MEC profile is given by

$$\Gamma_{MEC}(\mathbf{b}) = \frac{1}{2\pi i k} \int d^2q\, e^{-i\mathbf{qb}} F(\mathbf{q}), \tag{7}$$

where $F(\mathbf{q})$ is calculated in the framework of chiral perturbation theory (ChPT) at tree level with baryons (nucleons) incorporated[15]. In the present work we restrict ourselves to the leading order in ChPT but, at energies above the Δ resonance, higher orders could be also important, as well as the explicit inclusion of resonances such as the $\rho(770)$.

For this process, the set of relevant lagrangians is the following:

$$\begin{aligned}
\mathcal{L}_{NN\pi} &= -\frac{f}{\mu} \bar{\psi} \gamma^\mu \gamma_5 \boldsymbol{\tau} \psi \cdot (\partial_\mu \boldsymbol{\phi}), \\
\mathcal{L}_{NN\pi\pi\pi} &= \frac{1}{6 f_\pi^2} \frac{f}{\mu} (\bar{\psi} \gamma^\mu \gamma_5 \boldsymbol{\tau} \psi) \cdot [(\partial_\mu \boldsymbol{\phi}) \boldsymbol{\phi}^2 - \boldsymbol{\phi} (\partial_\mu \boldsymbol{\phi} \cdot \boldsymbol{\phi})], \\
\mathcal{L}_{\pi\pi\pi\pi} &= \frac{1}{6 f_\pi^2} [(\partial_\mu \boldsymbol{\phi} \cdot \boldsymbol{\phi})^2 - \boldsymbol{\phi}^2 (\partial_\mu \boldsymbol{\phi})^2 + \frac{1}{4} \mu^2 \boldsymbol{\phi}^4].
\end{aligned} \tag{8}$$

Here, f_π is the pion decay constant ($f_\pi = 92.4 MeV$), μ is the pion mass and $f = 1.02$. From these lagrangians we obtain two terms, the so-called pion pole term (fig 1b) and contact term (fig 1c). The amplitude corresponding to the contact term is give by the formula:

$$F_{CT} = \frac{1}{3}\frac{1}{(2\pi)^4}\frac{1}{f_\pi^2}\left(\frac{f}{\mu}\right)^2 \int d^3p \sum_{m_1,m_2} \frac{(-1)^{5-m_1-m_2}}{6} \left\langle 1d_{5/2}m_1 \middle| \boldsymbol{\sigma}(2\mathbf{p}+\mathbf{q})\, e^{i(\mathbf{p}-\mathbf{q})\mathbf{x}} \middle| 1d_{5/2}m_2 \right\rangle \left\langle 1d_{5/2}-m_1 \middle| \boldsymbol{\sigma}\mathbf{p}e^{-i\mathbf{p}\mathbf{y}} \middle| 1d_{5/2}-m_2 \right\rangle \frac{1}{\mathbf{p}^2+\mu^2} \left(\frac{\Lambda^2-\mu^2}{\Lambda^2+\mathbf{p}^2}\right)^2, \quad (9)$$

and the amplitude of the pole term is

$$F_{PT} = \frac{2}{3}\frac{1}{(2\pi)^4}\frac{1}{f_\pi^2}\left(\frac{f}{\mu}\right)^2 \int d^3p \sum_{m_1,m_2} \frac{(-1)^{5-m_1-m_2}}{6} \left\langle 1d_{5/2}m_1 \middle| \boldsymbol{\sigma}\mathbf{p}e^{-i\mathbf{p}\mathbf{x}} \middle| 1d_{5/2}m_2 \right\rangle \left\langle 1d_{5/2}-m_1 \middle| \boldsymbol{\sigma}(\mathbf{p}-\mathbf{q})e^{i(\mathbf{p}-\mathbf{q})\mathbf{y}} \middle| 1d_{5/2}-m_2 \right\rangle \frac{(2\mu^2+\mathbf{p}\mathbf{q}-\mathbf{p}^2)}{(\mathbf{p}^2+\mu^2)((\mathbf{p}-\mathbf{q})^2+\mu^2)} \left(\frac{\Lambda^2-\mu^2}{\Lambda^2+\mathbf{p}^2}\right)\left(\frac{\Lambda^2-\mu^2}{\Lambda^2+(\mathbf{p}-\mathbf{q})^2}\right). \quad (10)$$

For the cutoff parameter we take $\Lambda = 1.3 GeV$. It should be always taken into account that the contact term and pole term contributions might differ from each other for different representations of the pion field leading to different sets of lagrangians[7]. The only magnitude that has physical meaning is the sum of these two amplitudes.

The dependence of the angular cross section at zero degrees on the incoming pion kinetic energy is presented in fig. 2. Our calculation for the SEQ mechanism (dashed line) uses a new improved set of phase shifts. As a consequence, the results differ in shape, though not in order of magnitude, from those of [11] around 1300 MeV. Using the same phase shifts as in [11] we reproduce their results from 400 MeV to 1400 MeV. The effects of the renormalization of the pion isovector interaction discussed in [11] are not included in our calculation. That renormalization reduces the SEQ cross section and would make MEC even more visible. The SEQ cross section shows a rapid decrease starting at 600 MeV, a first dip at 700 MeV and a second and more pronounced dip at 1100 MeV. The cross section corresponding to the MEC mechanisms is quite flat as a function of energy. This reflects the very weak energy dependence of the amplitudes. In spite of that, the MEC amplitude is too small to produce a very significant enhancement in the cross section. In the region of the first dip, the cross section obtained including MEC and SEQ mechanisms is bigger than the SEQ one by a factor of 2. The inclusive experiments at these energies[12] show a similar, but more pronounced, effect. At 1030 and 1200 MeV both mechanisms are comparable in magnitude. In the first case, the interference causes a strong cancelation, while in the second it is additive. It is important to remark that the strong energy dependence produced by such interference effects would be modified by the inclusion of any other sizable mechanisms, as well as by any modification in the experimental πN phase shifts.

In summary, we have shown in this paper that, because of the small DCX cross section produced by the sequential mechanism at high energies, meson exchange currents processes could show up in this reaction. A simple model for these processes predicts important changes of the cross section above 600 MeV. At these energies, some additional MEC mechanisms involving the ρ meson could be important.

Acknowledgments

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1 Figure Captions

Fig. 1. DCX mechanisms: a) Sequential, b) and c) MEC mechanisms: b) pole term, c) contact term.

Fig. 2. Energy dependence of the forward cross section for $^{18}O(\pi^+,\pi^-)^{18}Ne$. Dashed curve: SEQ mechanism, dashed-dotted line: MEC mechanisms, full line: SEQ + MEC mechanisms.

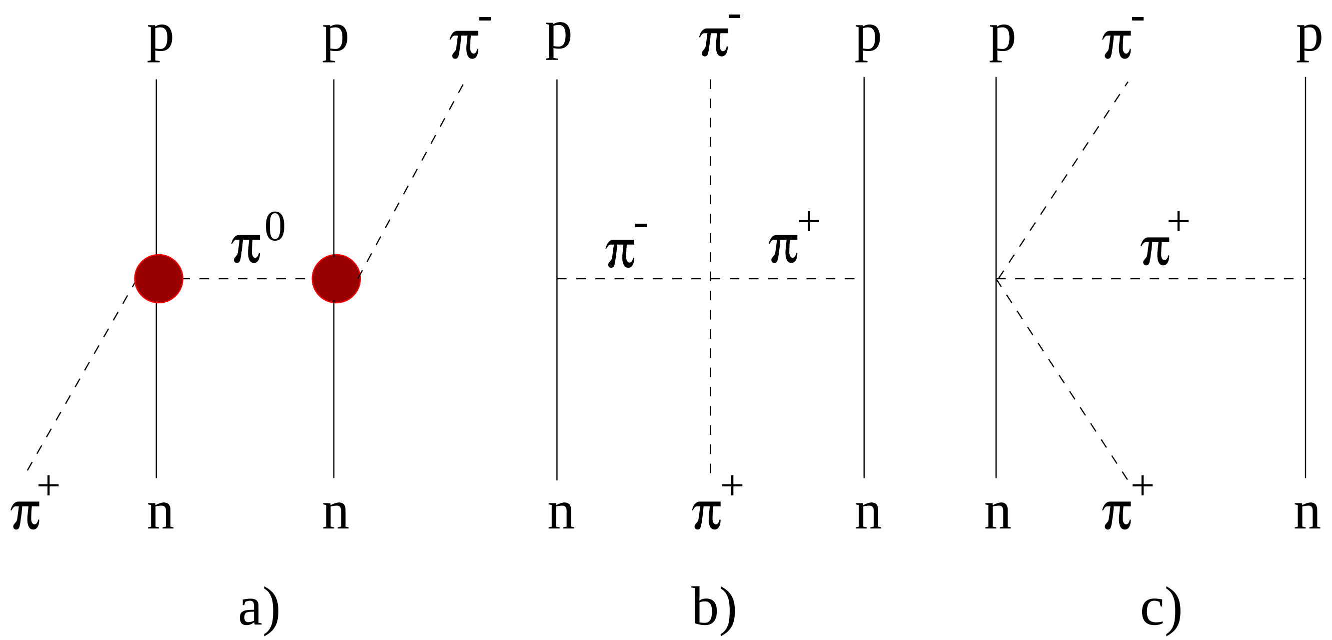
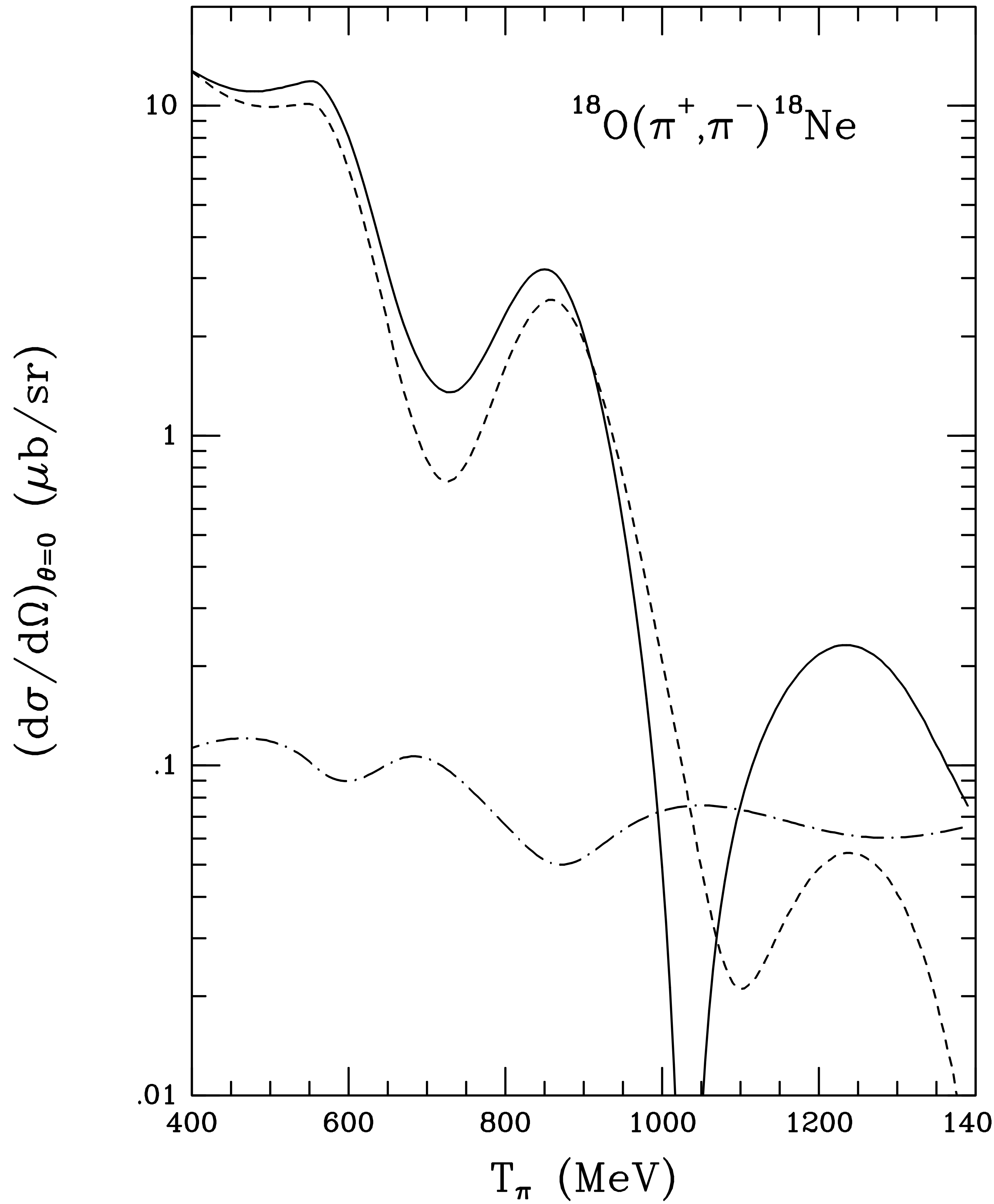


Fig 1

Fig 2.


$^{18}O(\pi^+,\pi^-)^{18}Ne$
10
1
.1
.01
400
600
800
1000
1200
1400
$(d\sigma/d\Omega)_{\theta=0}$ (μb/sr)
T_π (MeV)