Pion double charge exchange in a composite-meson model

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The pion double charge exchange amplitude is evaluated in a composite-meson model based on the four-quark interaction. The model assumes that the mesons are two-quark systems and can interact with each other only through quark loops. To evaluate the meson exchange current contribution, the form factors of the two-pion decay modes of the ρ, σ, and f_0 mesons have been used in the calculations. The contribution of the four-quark box diagram has been taken into account as well as a contact diagram. The contributions of the ρ, σ, and f_0 mesons increase the forward scattering cross section, which depends weakly on the energy.

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I. INTRODUCTION

Double charge exchange (DCX) of pions on nuclei occupies a particular position among all known nuclear reactions. It is unique because through the reaction one can obtain nuclei for which the Z component of the isospin differs by two units from that of the original nuclei. This is possible by double isospin flip of the pion, whose isospin is equal to unity. The existence of DCX for pions was predicted by de Shalit, Drell, and Lipkin in 1961 [1]. Experimentally this process was discovered in the Laboratory of Nuclear Problems at the JINR in 1963 [2]. During the 45 years after its discovery the pion double charge exchange reaction has generated a significant amount of theoretical and experimental work. Progress in the theoretical and experimental studies of the DCX reactions has been reflected in review papers of Backer and Batusov [3] in 1971, Jibuti and Kezerashvili [4] in 1985, Gibbs and Gibson [5] in 1987, Clement [6] in 1992, and Johnson and Morris [7] in 1993.

In DCX at least two nucleons must participate to conserve the electric charge. For this reason, this reaction is more sensitive to the two-nucleon effects, manifested here in the first order, than reactions in which there is no need to consider two nucleons in the first order and in which the effects of two-nucleon dynamics are manifested indirectly. Therefore, the pion DCX can give direct information on the two-nucleon aspect of nuclear dynamics such as the short-range two-nucleon correlation and the meson exchange current.

The most important problem of DCX is the mechanism of the reaction. At present there exist various conceptions of the DCX mechanism of π mesons on nuclei. Because the incident pion energy is below the pion-production threshold, normally, the reaction is dominated by the sequential mechanism, in which the incoming pion undergoes two sequential single charge exchange scatterings on nucleons within a nucleus. In the region of energies around the resonance, analysis of the reaction is very complicated. This is due to the strong distortion of the pion waves at resonance on the one hand and a variety of mechanisms that play a significant role on the other. Explaining the energy dependence of DCX has led to a diversity of proposed mechanisms, including the successive delta interaction mechanism [8,9], the meson exchange current (MEC) mechanism [10,11], the six-quark bag mechanism [12], absorption mechanisms [13], dibaryon mechanisms [14], assuming the production of the hypothetical d' dibaryon, a resonance with baryon number $B = 2$ in the pNN subsystem, and others involving more than two nucleons.

The energies at which the contribution of the dominant sequential mechanism is very small and pion distortion is probably negligible offer the best grounds for the investigation of some exotic mechanisms, such as those involving meson exchange currents, for which the contribution, although small, is not expected to decrease significantly with energy. These low values of the cross section, produced by the mechanism that dominates the reaction below the pion-production threshold and at resonance, open the possibility for alternative mechanisms such as the MEC to be revealed. The MEC mechanism, in which the incoming pion scatters with a virtual pion of opposite charge in the "cloud" surrounding the target nucleon of the nucleus and is itself absorbed on another nucleon, was first proposed by Germond and Wilkin [10] and consists of the assumption that the incident pion is scattered on the off-shell pion exchanged by the nucleons within the nucleus and the DCX takes place at the $\pi\pi$ vertex. The pole diagram in Fig. 1(a) corresponds to that mechanism. Later, Robilotta and Wilkin [11] introduced an additional diagram shown in Fig. 1(b) and concluded that the MEC effects would be small for an analog DCX because this diagram partially cancels the contribution of the pole term and, as a result, reduces the effects of MEC in the reaction. The MEC issue has been revived in Refs. [15–17] using the Lovelace-Veneziano model [18] and in Refs. [19–28] based on an effective Lagrangian method. There were some disagreements and interesting controversy [29,30] about whether the contact term contributes to the DCX reaction. Jiang and Koltun [25] resolved this problem.

It is important to mention that all calculations of the contribution of the MEC based on the effective Lagrangian formalism are performed in the lowest significant order that includes the contribution of the "trees" diagram and no pionic or baryonic closed-loop diagrams are included. The tree diagrams correspond to the Born approximation for $\pi\pi$ scattering, and their contribution is defined by the first term of the expansion of the $\pi\pi$ amplitude in terms of $1/F_\pi^2$.

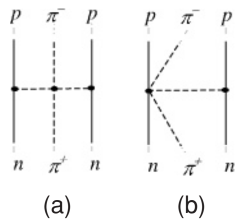

FIG. 1. Diagrams corresponding to the MEC mechanism in the Born approximation: (a) pole diagram and (b) contact diagram.

The subject of this article is the magnitude of the contribution of the MEC mechanism to the DCX reaction based on the composite-meson model. The model assumes that the mesons are two-quark systems and can interact with each other only through quark loops. We are considering the contributions of the diagram shown on the left side in Fig. 2, where the shaded vertex box corresponding to $\pi\pi$ scattering can be described at the quark level and includes the quark diagrams that successfully describe $\pi\pi$ scattering, as well as the contact diagram in Fig. 1(b). This approach allows us to include terms representing σ, f_0, and ρ mesons and find the contribution of these resonances to the MEC mechanism. The contribution of some diagrams, namely the diagram representing the ρ meson, is proportional to $(1/F_\pi^2)^2$. We calculate the energy dependence of the forward scattering amplitude for the DCX and examine its interplay with more conventional mechanisms of the DCX.

II. PION DCX AMPLITUDE

Let us consider the diagram shown on the left side in Fig. 2, one of the diagrams which describes the pion DCX on two nucleons through the MEC mechanism. The shaded vertex block corresponds to the $\pi\pi$ interaction. Therefore, we can construct the amplitude for the process $\pi^+ nn \to \pi^- pp$ using the amplitude for $\pi\pi$ scattering. The amplitude corresponding to this graph is

$$T = (i\sqrt{2}g)^2 \frac{\overline{u}_n(p_{1\mu})\gamma_5\tau_- u_n(p'_{1\mu})\overline{u}_p(p_{2\mu})\gamma_5\tau_- u_p(p'_{2\mu})}{\left(q_{1\mu}^2 - m_\pi^2\right)\left(q_{2\mu}^2 - m_\pi^2\right)} \times M_{\pi^+\pi^-}(k_{i\mu}, q_{1\mu}; q_{2\mu}, k_{f\mu}), \quad (1)$$

where g is the πN coupling constant, m_π is the pion mass, $p_{1\mu}$ and $p_{2\mu}$, $p'_{1\mu}$ and $p'_{2\mu}$ are the four-momenta of the nucleons, $k_{i\mu}$ and $k_{f\mu}$ are the four-momenta of the pions in the initial and final states, respectively, and $q_{1\mu}$ and $q_{2\mu}$ are the four-momenta of virtual mesons. In Eq. (1) $M_{\pi^+\pi^-}$ is the transition matrix element for the $\pi^+\pi^- \to \pi^+\pi^-$ process.

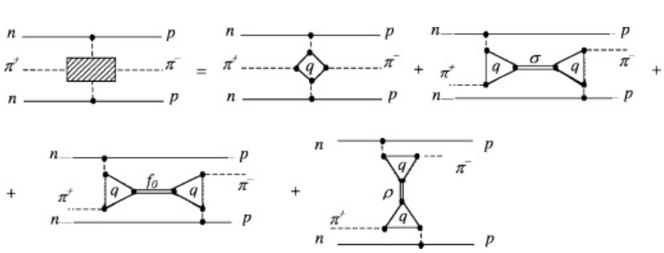

FIG. 2. The quark structure of the MEC diagram.

We assume that the nucleons within the nuclei are nonrelativistic particles. Taking this fact into account, we can rewrite Eq. (1) in the nonrelativistic limit as

$$T = (i\sqrt{2}g)^2 \frac{(\boldsymbol{\sigma}_1 \cdot \mathbf{q}_1)(\boldsymbol{\sigma}_2 \cdot \mathbf{q}_2)}{4m^2} \frac{M_{\pi^+\pi^-}(k_{i\mu}, q_{1\mu}; q_{2\mu}, k_{f\mu})}{\left(\mathbf{q}_1^2 + m_\pi^2\right)\left(\mathbf{q}_2^2 + m_\pi^2\right)}, \quad (2)$$

where m is the mass of the nucleon, $\mathbf{q}_1 = \mathbf{p}'_1 - \mathbf{p}_1$, and $\mathbf{q}_2 = \mathbf{p}'_2 - \mathbf{p}_2$. Thus, we can find the cross section for the pion DCX reaction on a nucleus assuming the MEC mechanism through the $\pi\pi$ scattering by calculating the transition matrix from the amplitude (2) using the nuclear wave functions for initial and final states.

III. PION DCX AMPLITUDE IN THE COMPOSITE-MESON MODEL

Equation (2) involves the $\pi^+\pi^-$ scattering amplitude. The transition amplitude for the $\pi^+\pi^- \to \pi^+\pi^-$ process is the linear combination of the $\pi\pi$ amplitudes with the definite isospin

$$M_{\pi^+\pi^-} = \tfrac{1}{3}T^0 + \tfrac{1}{2}T^1 + \tfrac{1}{6}T^2. \quad (3)$$

The isotopic amplitudes T^0, T^1, and T^2 correspond to the states with total isospin 0, 1, and 2 and are the linear combinations of the invariant amplitudes $A(s,t,u)$, where s, t, and u are the standard Mandelstam variables. We can get the corresponding coefficients by expressing amplitudes in the t channel through amplitudes in the s channel, using the crossing symmetry. The transition amplitude for the $\pi^+\pi^- \to \pi^+\pi^-$ process can be expressed through the invariant amplitudes $A(s,t,u)$ as

$$M_{\pi^+\pi^-} = A(s,t,u) + A(t,s,u). \quad (4)$$

In the composite-meson model the MEC diagram on the left side in Fig. 2 can be represented by the sum of diagrams. To do that, the shaded vertex box corresponding to $\pi\pi$ scattering can be considered at the quark level and includes the quark diagrams that successfully describe $\pi\pi$ scattering. Indeed, in the model of the composite mesons $\pi^+ = u\overline{d}$ and $\pi^- = d\overline{u}$ are two-quark systems, and we can assume that the interaction of the mesons with each other takes place only through quark loops. Following these assumptions and considering only the single-loop approximation, we can expand the diagram on the left side in Fig. 2 as shown. The inner blocks between the nucleon lines in Fig. 2 show all diagrams that contribute to the $\pi\pi$ scattering amplitude and successfully describe the $\pi\pi$ scattering lengths. The first quark-box diagram actually corresponds to the pole diagram in Fig. 1(a) for $\pi\pi$ scattering and, as we will show, part of its contribution proportional to $1/F_\pi^2$ represents the Born approximation in the effective Lagrangian method. The choice of the other diagram is based on the probability of the two-pion decay of mesons: $\rho(770) \to \pi\pi$, $\sigma(600) \to \pi\pi$, and $f_0(980) \to \pi\pi$. Therefore, the quark-box diagram of $\pi\pi$ scattering and the diagrams with ρ, σ, and f_0 mesons in the intermediate states should play the main role for the process $\pi^+ nn \to \pi^- pp$ in the model of the MEC. The inner quark blocks of the diagrams in Fig. 2 can be easily obtained from the Lagrangian [31]

$$L = \overline{Q}\left[i\hat{\partial} - m_q + \frac{m_q}{F_\pi}(\sigma \sin\alpha + f_0\cos\alpha + i\gamma_5\tau\pi) + \frac{g_\rho}{2}\tau\boldsymbol{\rho}\right]Q, \tag{5}$$

where Q is the quark field, m_q is the mass of the quark, g_ρ is the decay constant of the ρ meson, and α is the mixing angle. Thus, for calculations of the contributions of the diagrams in Fig. 2 we need to know all effective coupling constants and express them in terms of two decay constants g_ρ and F_π of the $\rho \to 2\pi$ and $\pi \to \mu\overline{\nu}$ decays. We shall impose a natural requirement that on the mass shell the form factors of the processes should coincide exactly with the corresponding physical coupling constants. The form factor for the $\rho \to 2\pi, \sigma \to 2\pi$, and $f_0 \to 2\pi$ decays can be obtained from the Lagrangian (5) following Ref. [31], and finally we can find the contribution of the inner part of the diagrams in Fig. 2:

$$A(s,t,u) = -\frac{m_\pi^2}{2F_\pi^2} + 4\frac{m_q^2}{F_\pi^2}\left[\frac{1-(m_q/4\pi F_\pi)^2}{(2\pi F_\pi)^2} + \frac{4m_q^2\sin^2\alpha}{m_\sigma^2(m_\sigma^2 - s)} + \frac{4m_q^2\cos^2\alpha}{m_{f_0}^2(m_{f_0}^2 - s)}\right]s + g_\rho^2\left[\frac{s-u}{m_\rho^2 - t}\left(1 + \frac{t-m_\rho^2}{8\pi^2F_\pi^2}\right)^2 + \frac{s-t}{m_\rho^2 - u}\left(1 + \frac{u-m_\rho^2}{8\pi^2F_\pi^2}\right)^2\right]. \tag{6}$$

Substituting Eq. (6) into Eq. (4), for the $\pi^+\pi^- \to \pi^+\pi^-$ amplitude we get

$$\begin{aligned} M_{\pi^+\pi^-} = &-\frac{m_\pi^2}{F_\pi^2} + \frac{m_q^2}{(\pi F_\pi)^2}\left[\frac{s+t}{F_\pi^2} - \frac{m_q^2}{(4\pi F_\pi)^2}\frac{s+t}{F_\pi^2}\right] \\ &+ \frac{4m_q^2}{F_\pi^2}\left\{\frac{4m_q^2}{m_\sigma^2}\left(\frac{s}{(m_\sigma^2 - s)} + \frac{t}{(m_\sigma^2 - t)}\right)\sin^2\alpha \right. \\ &\left. + \frac{4m_q^2}{m_{f_0}^2}\left(\frac{s}{(m_{f_0}^2 - s)} + \frac{t}{(m_{f_0}^2 - t)}\right)\cos^2\alpha\right\} \\ &+ g_\rho\left\{\frac{t-u}{m_\rho^2 - s}\left(1 + \frac{s-m_\rho^2}{8\pi^2F_\pi^2}\right)^2 \right. \\ &\left. + \frac{s-u}{m_\rho^2 - t}\left(1 + \frac{t-m_\rho^2}{8\pi^2F_\pi^2}\right)^2\right\}. \end{aligned} \tag{7}$$

In Eq. (7) the mixing angle α can be determined from $\Gamma_{f_0\to 2\pi} = 26$ MeV and it is $\alpha = 17^\circ$ if $m_q = 280$ MeV [32], and the decay constant g_ρ of the ρ meson is given by $g_\rho^2/4\pi \approx 3$. It is important to mention that the contribution of the quark-box diagram to the scattering amplitude depends on the undetermined parameter, whose value was fixed in [31] so that the experimental value of the pion-pion scattering length a_0^2 is obtained. Equation (7) shows the transition amplitude for the $\pi^+\pi^- \to \pi^+\pi^-$ process and is used for the calculation of the amplitude (2) for the pion DCX reaction on a nucleus.

IV. RESULTS AND DISCUSSION

Let us compare the MEC amplitude evaluated in the composite-meson model given by Eq. (7) with one obtained in the Born approximation using the Weinberg Lagrangian [33]:

$$M^W_{\pi^+\pi^-} = -\frac{m_\pi^2}{F_\pi^2} + \frac{s+t}{F_\pi^2}. \tag{8}$$

Equation (8) corresponds to the $\pi\pi$ vertex in Fig. 1(a). It is easy to see that the constant term in Eq. (7) is the same as in Eq. (8). The term in the square brackets is caused by the quark-box diagram and inclusion of the so-called q^2 terms in the quark-box diagrams, and it is partially proportional to $(1/F_\pi^2)^2$. As shown in Refs. [34,35], the inclusion of the q^2 terms leads to convergent integrals and appreciably improved the description of electromagnetic meson radii and $\pi\pi$ scattering lengths. The factor in front of the square brackets $m_q^2/(\pi F_\pi)^2 = 1$ for $F_\pi = 89.2$ MeV and $m_q = 280$ MeV and a variation of this factor is insignificant when the pion decay constant varies from 87 to 93 MeV. Therefore, the constant term and the first term in the square brackets in Eq. (7) give the Weinberg transition amplitude for the $\pi^+\pi^- \to \pi^+\pi^-$ process in the Born approximation. The last four lines of Eq. (7) introduce the contribution of the ρ, σ, and f_0 mesons into the MEC mechanism. The two terms in Eq. (7) related to the mixing angle α represent the contribution of the σ and f_0 mesons. The last term that follows the factor g_ρ is the contribution of the ϱ meson. The contribution of the ϱ meson has the terms that are also proportional to $(1/F_\pi^2)^2$. After substitution of Eq. (7) into Eq. (3) one can separate the part that corresponds to the amplitude of the pole diagram in Fig. 1(a) for the process $\pi^+nn \to \pi^-pp$ in the Born approximation for the Weinberg Lagrangian:

$$T_1 = \frac{g^2}{4m^2}\frac{2}{F_\pi^2}\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{q}_1)(\boldsymbol{\sigma}_2\cdot\mathbf{q}_2)(2\mathbf{q}_1\cdot\mathbf{q}_2 - \mathbf{q}_1^2 - \mathbf{q}_2^2 - 2m_\pi^2)}{(\mathbf{q}_1^2 + m_\pi^2)(\mathbf{q}_2^2 + m_\pi^2)}. \tag{9}$$

Let us now consider the other diagram that describes the MEC in the DCX process. Chiral symmetry requires consideration of both diagrams in Fig. 1. We can find the contribution of the contact diagram in Fig. 1(b) by using the Lagrangians

$$\begin{aligned} L_{NN\pi} &= \frac{g}{2m}\overline{\psi}\gamma^\mu\gamma_5\tau\psi\cdot(\partial_\mu\pi), \\ L_{NN\pi\pi\pi} &= -\frac{g}{2m}\frac{1}{4F_\pi^2}\overline{\psi}\gamma^\mu\gamma_5\tau\psi\cdot(\partial_\mu\pi)\pi^2 \end{aligned} \tag{10}$$

for the $NN\pi$ and $NN\pi\pi\pi$ vertices. The amplitude for the contact diagram of Fig. 1(b) for the process $\pi^+nn \to \pi^-pp$ can be calculated by the same way as Eq. (2) using standard methods and in the nonrelativistic limit is given by

$$T_2 = -\frac{g^2}{4m^2}\frac{2}{F_\pi^2}\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{q}_1)[\boldsymbol{\sigma}_2\cdot\mathbf{q}_1 - \boldsymbol{\sigma}_2\cdot\mathbf{q}_2]}{(\mathbf{q}_1^2 + m_\pi^2)}. \tag{11}$$

The sum of Eqs. (9) and (11) gives the the contribution of the quark-box diagram, including only terms proportional to $1/F_\pi^2$ and the contact diagram and is the same as the sum of contributions of the pole [Fig. 1(a)] and contact [Fig. 1(b)] diagrams in the Born approximation

$$T^B = \frac{g^2}{4m^2}\frac{2}{F_\pi^2}\frac{(\boldsymbol{\sigma}_1\cdot\mathbf{q}_1)(\boldsymbol{\sigma}_2\cdot\mathbf{q}_2)\left(2\mathbf{q}_1\cdot\mathbf{q}_2-\mathbf{q}_1^2-m_\pi^2\right)-(\boldsymbol{\sigma}_1\cdot\mathbf{q}_1)(\boldsymbol{\sigma}_2\cdot\mathbf{q}_1)\left(\mathbf{q}_2^2+m_\pi^2\right)}{\left(\mathbf{q}_1^2+m_\pi^2\right)\left(\mathbf{q}_2^2+m_\pi^2\right)}. \tag{12}$$

Equation (12) shows that there is a cancellation between the contributions of the quark-box diagram and the contact diagram. Such cancellation has been observed earlier in Refs. [11] and [25] for the pole and contact diagrams in the effective Lagrangian method. Thus, Eq. (12) represents the contribution of the contact diagram in Fig. 1(b) and part of the contribution of the quark-box diagram in Fig. 2, which is proportional to $1/F_\pi^2$. The rest of the contribution of the quark-box diagram is proportional to $(1/F_\pi^2)^2$ and represents the deviation from the Born approximation.

In Refs. [21,22] it was shown that the contributions from both diagrams in Fig. 1 for the forward scattering DCX reaction is not significant for incident pion energy up to 350 MeV. Later in Ref. [28], the authors showed that the contributions of the pole diagram and contact diagram quite smoothly depend on the incident pion energy up to 1400 MeV and are important at high energy. To establish the order of the magnitude of the MEC contribution in the composite-meson model, let us calculate the forward scattering cross section for the ^{18}O$(\pi^+,\pi^-)^{18}$Ne reaction for incident pion energy from 600 to 1400 MeV and compare the contribution of the MEC evaluated in the composite-meson model based on the four-quark interaction with the calculations in the Born approximation, as well as with the dominant sequential mechanism. For forward scattering $\mathbf{q}_1=\mathbf{q}_2\equiv\mathbf{q}$ and Eq. (12) becomes

$$T^B = -\frac{g^2}{4m^2}\frac{2}{F_\pi^2}\frac{2(\boldsymbol{\sigma}_1\cdot\mathbf{q})(\boldsymbol{\sigma}_2\cdot\mathbf{q})m_\pi^2}{\left(\mathbf{q}^2+m_\pi^2\right)^2}. \tag{13}$$

For simplicity, we use the shell-model wave functions to describe the initial and final nuclear state of ^{18}O and ^{18}Ne. We neglect the contribution of the ^{16}O core to the DCX, assuming that the DCX process takes place on the valence neutrons and the reaction leads to the double isobaric analog state. The wave function of the two odd neutrons in ^{18}O has been used as in Refs. [15,23] with the harmonic oscillator parameter $\alpha^2=0.32\,\mathrm{fm}^{-2}$. Since our main points are to understand the contribution of three $\pi\pi$ resonances ρ,σ, and f_0 to the MEC mechanism, establish the order of magnitude of this contribution. and compare it to the conventional mechanisms, we neglect the distortion of the pion waves, using the plane waves instead. The pion-wave distortion reduces the cross section by about a factor of 2 and most dramatically below 600 MeV; at the above 600 MeV the distortion also reduces the cross section but the energy dependence remains almost the same as without the distortion [36]. Keeping this in mind we calculated the cross section in the plane-wave approximation. In this approximation, integration of Eq. (13) over momentum q in the target can be performed analytically and the result is

$$T^B = \frac{2}{F_\pi^2}\frac{1}{m_\pi}\frac{\partial}{\partial m_\pi}V(r), \tag{14}$$

where

$$V(r) = \frac{1}{4\pi}\left(\frac{gm_\pi}{2m}\right)^2\left\{\frac{1}{3}(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)+\frac{1}{3}S_{12}\times\left[1+\frac{3}{m_\pi r}+\frac{3}{(m_\pi r)^2}\right]\right\}\frac{e^{-m_\pi r}}{r}, \tag{15}$$
$$S_{12} = \frac{3(\boldsymbol{\sigma}_1\cdot\mathbf{r})(\boldsymbol{\sigma}_2\cdot\mathbf{r})}{r^2}-(\boldsymbol{\sigma}_1\cdot\sigma_2)$$

is a one-pion exchange potential. Thus, the sum of contributions of the pole and the contact diagrams in the Born approximation is proportional to the derivative of the one-pion exchange potential with respect to the pion mass. This is equivalent to the sum of the contributions of the quark-box diagram, including only terms proportional to $1/F_\pi^2$ and the contact diagram in Fig. 1(b).

The results of the calculations of the dependence of the differential cross section at zero degrees on the incoming pion kinetic energy for the reaction ^{18}O$(\pi^+,\pi^-)^{18}$Ne are presented in Fig. 3. First, from this figure, we can get a general overview of the energy dependence of the cross section for different mechanisms. Second, Fig. 3 also allows us to understand

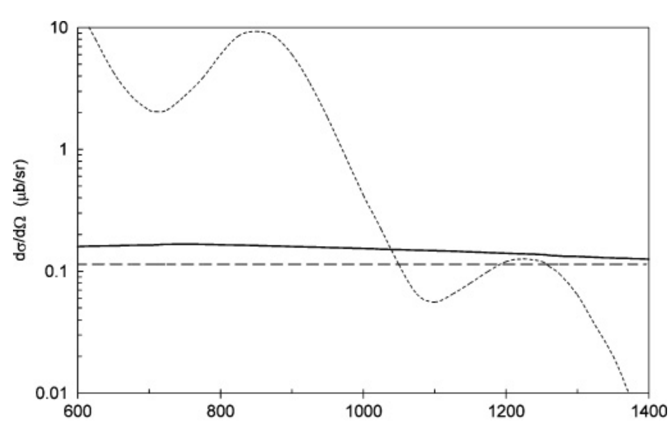

FIG. 3. Forward scattering differential cross section for the reaction ^{18}O$(\pi^+,\pi^-)^{18}$Ne as a function of the incident pion energy. The solid line represents the contribution of the MEC in the composite-meson model with the contact diagram [the sum of diagrams in Figs. 1(b) and 2]. The dashed curve is the contribution of the pole and contact diagrams in the Born approximation and the dotted curve is the result from Ref. [36] for the sequential mechanism.

the relative contributions of the MEC in the composite-meson model based on the four-quark interaction and the contact diagram and those when the ρ, σ, and f_0 mesons are not included. The results of our calculations based on the composite-meson model and contribution of the contact diagram in Fig. 3 are presented by a solid line. They show that the cross section depends weakly on the energy, simply reflecting the weak dependence of the $\pi\pi$ amplitude on the energy. We checked the sensitivity of the calculations to changes of the masses of the σ and f_0 mesons. For the given value of the mixing angle $\alpha = 17^\circ$, the cross section is sensitive to small changes of the σ meson mass and almost did not change with small changes of the f_0 meson mass. For example, changing the σ meson mass from 780 to 700 MeV will change the cross section for about 14%. Let us also mention that the third term of Eq. (7) related to the ϱ-meson contribution, appreciably changes the cross section, showing the importance of the ϱ meson at energies above 600 MeV. The cross section corresponding to the MEC mechanism when the ρ, σ, and f_0 mesons are not included is presented by the dashed line. This cross section, calculated based on the amplitude (14), includes both the pole term as well as the contact term and corresponds to the Born approximation in the effective Lagrangian method. The comparison of these results shows that inclusion of the ρ, σ, and f_0 mesons increases the cross section and their contribution decreases with energy. The cross section for the MEC in the composite-meson model with the contact diagram in Fig. 1(b) is systematically larger by an average of 25% than that in the Born approximation. The dotted curve in Fig. 3 represents the cross section calculated by Alvarez-Ruso [36] in the framework of the formalism of Ref. [28] without the distortion of the pion waves when the DCX occurs through two successive pN charge exchanges on two neutrons obtained with a cutoff parameter of 1.3 GeV. The cross section shows a rapid decrease and a first dip at 700 MeV and a second more pronounced dip at 1100 MeV. At the energy region of the second dip the cross section obtained including the MEC diagrams of Figs. 1(b) and 2 is larger than that for the sequential mechanism and the MEC mechanism becomes significant. At these energies the MEC mechanism with inclusion of the ρ, σ and f_0 mesons dominates in the reaction.

One may be misled by comparing our results with the cross section for the sequential mechanism. At a glance, Fig. 3 gives you a general overview of the energy dependence of the cross section for different mechanisms. Just presenting both calculations in the same figure does not make a proper comparison. The consistent comparison of our results with the sequential mechanism requires having the same form factors with the same cutoff parameter. It is very well known from the literature that the cutoff parameter should be different for s, p, etc. scattering and depends on the energy. Our calculation is done in the approximation of the hard nucleon, which allows us to evaluate the amplitude analytically and get the analytical result (14) that the sum of contributions of the pole and the contact diagrams in the Born approximation is proportional to the derivative of the one-pion exchange potential with respect to the pion mass. The calculation of the cross section for the sequential mechanism includes form factors with monopole cutoff parameter 1.3 GeV. This parameter does not depend on the energy and is the same in the range from 400 to 1400 MeV. It is a rough approximation and this is why we did not use the same form factor in our calculations. However, in a calculation of both theories with the same assumption about form factors it might be expected that the MEC cross section will decrease and the two cross sections at the minimum would be more nearly equal. However, with the inclusion of the form factors the contributions of the ρ, σ, and f_0 mesons in the MEC mechanism still increase the forward scattering cross section. Also let us mention that, as follows from Ref. [28], the interference of the sequential amplitude and MEC amplitude in the Born approximation shifts the second minimum position to low energy, makes it deeper, and increases the cross section at the maximum. We can expect that the same effects might happen when amplitudes for the sequential mechanism and MEC with inclusion of the resonances would be added.

Thus, we can conclude that at the considered energy region the MEC mechanism in the composite-meson model with the contact diagram can reveal much about the pion DCX because it has a substantial contribution and the inclusion of the ρ, σ, and f_0 mesons increases the contribution of the meson exchange currents in the MEC mechanism for the DCX reaction. It is important to mention that the distortion of the pion waves will generally reduce the cross section in the composite-meson model as well as for the MEC in the Born approximation and the sequential mechanism but it will not change the conclusion of the importance of the inclusion of the pion resonances into the MEC mechanism.

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