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Реакция двойной перезарядки пионов на ядрах при низких энергиях

Реакция двойной перезарядки пионов на ядрах может рассматриваться как эффективный инструмент для изучения взаимодействия пи-мезона с двухнуклонной системой, имеющей изоспин $T=1$. В настоящем докладе обсуждается современное состояние теории реакции двойной перезарядки при низких энергиях.

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Pion-Double-Charge Exchange Reaction at Low Energies

The pion-nucleus double-charge exchange (DCX) reaction can be considered as a laboratory to study the pion interaction with the two-nucleon system of the isospin $T=1$. In this report, we discuss the current status of the DCX theory at low energies.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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1 Introduction

The DCX reaction is very attractive from the theoretical point of view because the pion must interact with two nucleons in the nucleus. It makes this reaction to be a good probe for nucleon-nucleon correlations in the nucleus and, on the other hand, DCX provides us with the possibility to study the pion interaction with the pair of nucleons of the total isospin $T = 1$.

The differential cross section of DCX is very small ($\sim 1\,\mu b/sr$) in comparison with the differential cross section of the elastic scattering(which is measured in mb/sr), and of SCX ($\sim 10 - 10^2\,\mu b/sr$). First DCX reaction was observed by the Dubna group [1] in 1963, and the situation with DCX up to 1970 has been reviewed in [2]. Pion beams of sufficient intensity to measure small DCX cross sections became available in 1970$'s$ at the meson factories. Starting from 1976 DCX cross sections to discrete nuclear states were measured. The results of the experimental and theoretical study of the pion-nucleus DCX reaction can be found in the review articles [3],[4] and in the proceedings of the topical workshops [5],[6]and [7]. In the present paper, we discuss the current status of DCX at low energies (T_π about $50\,MeV$).

Interest in DCX reactions increased in 1984 as a result of measurements of the cross sections for the reaction $^{14}C(\pi^+,\pi^-)^{14}O$ at $50\,MeV$ [8]. Prior to these measurements it was believed that the mechanism of the DCX to DIAS (double-analog state) reaction is dominated by two subsequent SCX processes through the isobar-analog state (analog route (AR) transition), i.e.

$$\pi^+ + {}^{14}C(g.s.) \rightarrow \pi^0 + {}^{14}N(E^* = 2.3\,MeV) \rightarrow \pi^- + {}^{14}O(g.s.). \qquad (1)$$

Here, the nuclei $^{14}C(g.s.)$, $^{14}N(E^* = 2.3\,MeV)$ and $^{14}O(g.s.)$ are the members of the isotopic triplet.

If the AR mechanism (1) is dominant one would expect a quite small cross section at forward angles because the SCX to IAS at $50\,MeV$ has a pronounced minimum in the differential cross section at forward angles [12]. This is caused by the destructive interference between the πN s- and p-waves at this energy. But, the $50\,MeV$ experimental data [8], [10] showed the DCX cross section to be large ($\sim 4\,\mu b/sr$) at 0°, and is forward peaked. Moreover, the DIAS cross section at $50\,MeV$ is larger than the cross sections at higher energies which are generally less than $1\,\mu b/sr$. These exciting results stimulate a theoretical study of DCX at low energies.

The DCX to DIAS reaction is very attractive from the theoretical point of view for two reasons. First, this reaction is the isoelastic process (it much simplifies a theoretical analysis) and, second, it gives us a very good possibility to study the pion interaction with the pair of nucleons of the isospin 1.

2 The πNN Dynamics in DCX

In this section, we discuss possible mechanisms of DCX at the two nucleon level which are shown in Fig.1. The results of all calculations presented in this section are calculated in the plane wave approximation.

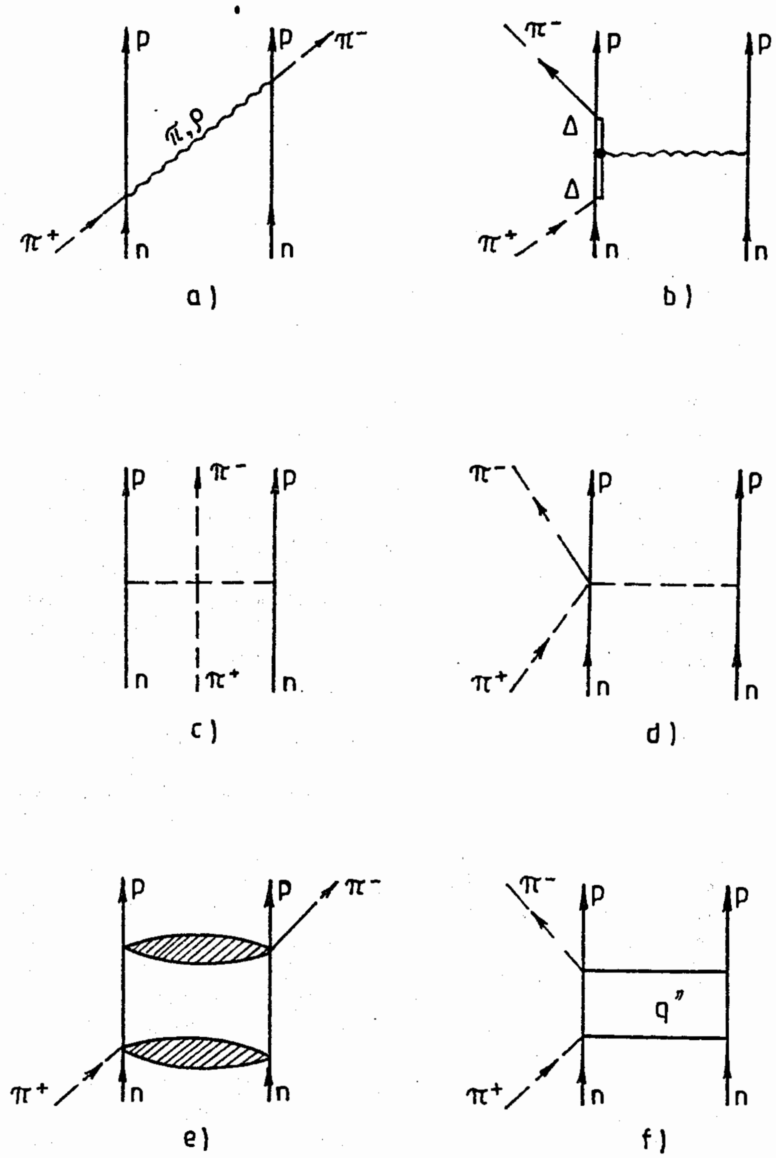

Figure:1 Diagrams for DCX mechanisms

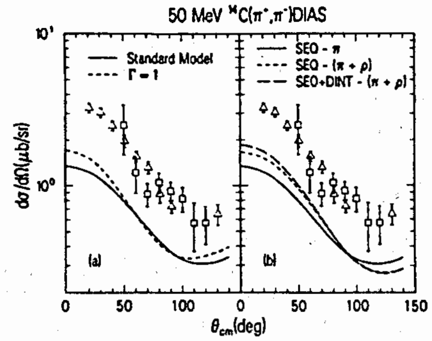

Figure 2: Plane-wave DCX angular distributions at $50\,MeV$: (a) Standard model ($SEQ-\pi$) with and without ($\Gamma = 1$) the short-range correlation function, (b) $SEQ-\pi$, $SEQ-(\pi+\rho)$, and $DINT$. Data from Refs. [8]-[11]. Figure is from Ref. [13].

2.1 The SEQ Mechanism

Many theoretical efforts have been devoted to clarify the role of the conventional sequential mechanism (SEQ-π) depicted in Fig.1(a), when two successive single-charge scattering of a pion by two nucleons takes place [13] - [17]. One can summarize the results for the SEQ-π mechanism (calculated in the plane wave approximation) as follows: (a) The calculated differential cross sections reproduce qualitatively the angular distributions and underestimate them by more than a factor of two. Only in [15] a quantitative description of the DCX scattering data in the plane wave approximation has been obtained. (b) The plane wave results for SEQ- π are sensitive to the nuclear structure [14], [13], to the short range correlation effects [13], to the range of the pion-nucleon form factors [13], [16] and to uncertainties in the Δ-N interaction [13] (especially within the framework of the Δ-hole model [14]).

To illustrate these conclusions we present in Fig.2 the results of calculations [13] of the DCX cross section for $^{14}C(\pi^+,\pi^-)^{14}O$ at $50\,MeV$. From Fig.2 it follows that

(1) The omission of the short range $N-N$ correlations increases the calculated cross section. The effect depends on the value of the pion cutoff parameter(Λ) of the pion-nucleon form factor which determines the off-shell behavior of the πN amplitude: the largest effect of about 30 % has been obtained for $\Lambda = 6fm^{-1}$ which corresponds to the value of the cutoff mass parameter usually used in the OBE model of the NN-potential. For the values of $\sim 2fm^{-1}$, which are obtained from a separable potential model fits to the πN scattering data, the effect of the short range $N-N$ correlations is negligible for SEQ-π. The standard Model in Fig.2 corresponds to $\Lambda = 6fm^{-1}$.

(2) The addition of the SEQ-ρ gives qualitatively the same but an opposite effect as compared to the effect of short range $N-N$ correlations , i.e. it increases the cross section.

(3) The contribution of the on-shell $\Delta - N$ interaction process (DINT) (Fig.1(b)) is relatively small. In [13] it has also been shown that the process involving (off-shell)

Δ_{33} components in the nuclear wave function is negligible at low energies.

It is important to stress that these conclusions are refereed to the calculations which have been performed with the πN cutoff $\Lambda = 6fm^{-1}$. For the soft values like $\approx 2fm^{-1}$ all effects are nearly washed out.

2.2 The MEC Mechanism

One of the nonconventional processes which might contribute to DCX is the meson-exchange-current mechanism (MEC) which is explained in Fig.1(c,d). The first calculations in the resonance region have been done in [25], where the MEC effect in DCX was shown to be negligible. The role of this mechanism at low energies has been discussed in several recent papers [19], [29] , [21], [22], [24], [23]. General consideration of the MEC contribution to DCX which is based on chiral symmetric effective Lagrangians has been done in [29] , [21], [22], where some constraints on the contribution of meson exchange currents to DCX at low energies have been obtained,

$$| F_{DCX}(MEC) | \leq 10^{-2} fm, \qquad (2)$$

This estimate gives for the cross section the value of an order of 1 μb.

In [19], the MEC contribution has been calculated using the chiral Weinberg Lagrangian. The results for DCX to DIAS from ^{14}C at 50 MeV are shown in Fig.3.

From Fig.3 it follows that the MEC mechanism increases the result for SEQ [13] by as much as 100%. The MEC amplitude is purely real and at 50 MeV was found [13] to be $-.73 \times 10^{-2}$ (which is an agreement with the estimation (1)) and it interferes constructively with the real part of the SEQ amplitude. For much heavier nuclei such as the Ca isotopes, the MEC effect was found to be a much smaller fraction of the sequential process. One can expect the decreasing of the MEC contribution to sequential process with increasing atomic mass because the average distance between the two valence nucleons involved in DCX is larger for larger nuclei.

The role of the MEC mechanism in DCX on $^3H, ^3He$ and ^4He in the energy range from 0.1 to 1.7 GeV has been considered in [23]. The conclusion of this paper was that the SEQ mechanism is dominant at energies below $\sim 300\, Mev$, and at higher energies the contribution of the MEC mechanism becomes more and more important.

From the aforesaid it follows that DCX can be considered as an effective tool for study the meson exchange current effects in nuclear physics. It should be noted that the pion Lagrangian is not completely specified since the chiral symmetry is broken, and the MEC effect is very sensitive to the value of the chiral symmetry-breaking parameter ξ (see Fig.3)

2.3 The Absorption Mechanism

There are several arguments in favor of the importance of the absorption channel in DCX which is shown schematically in Fig.1(f). First, it is known that pion absorption has a strong effect on elastic scattering both at low energies and at resonance. Second, it is also known that a fraction of pions is absorbed by two nucleons of total isospin 1 (see, e.g. [28]). Third, it has been argued that the absorption mechanism might be responsible for the shift of the first minimum in the differential cross section to smaller angles at resonance energies [26],[18].

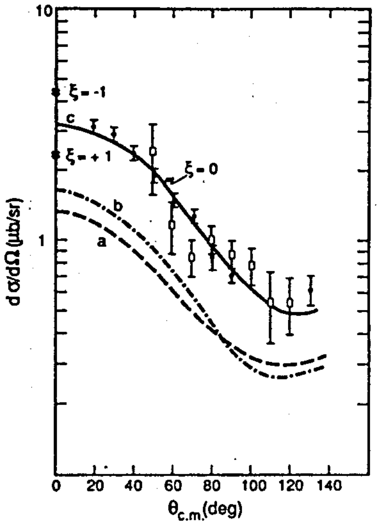

Figure 3: Angular distribution for DCX to DIAS from ^{14}C at 50 MeV with and without the meson currents: (a) $SEQ - \pi$, (b) $SEQ - (\pi + \rho)$, (c) full sequential (b) plus MEC effects. The crosses show the effect on the zero-degree cross section of changing ξ from -1 to 1. Figure is from Ref. [19].

In [27] the absorption contribution to the DCX amplitude has been evaluated consistently with the present knowledge of the pion absorption problem. The guiding principle in [27] was to connect the DCX absorption amplitude with the absorption part of the optical potential. The results for the reaction $^{14}C(\pi^+, \pi^-)^{14}O$ at 50 MeV are shown in Fig.4. The conventional mechanism has been taken from [13] and we have added to it coherently the absorption amplitude. The absorption mechanism is smaller than the conventional at small angles since one has partial interference between s and p-wave absorption mechanisms. At larger angles, the conventional and absorption mechanisms are comparable. The interference between the conventional and absorption mechanisms is constructive and enhances appreciably the results with respect to those of the conventional, or sequential, mechanism. The final results are closer to the experimental ones but one should have in mind that there is no the pion distortion in the results.

Around the resonance the effects are globally very small but the approximately destructive interference leads to a small shift of the first diffraction minimum in $^{18}O(\pi^+, \pi^-)\, DIAS$ at $T_\pi = 164\, MeV$, which is not sufficient to explain the experimental data.

The effect of the absorption mechanism, like the one of the exchange currents, decreases with increasing A due to the fact that the processes involve the contribution of short range forces. We can see this qualitatively by evaluating the effects of the

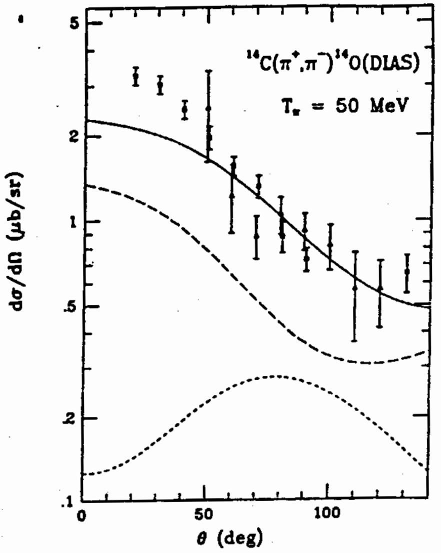

Figure 4: Differential cross section for $^{14}C(\pi^+,\pi^-)DIAS$ at $50\,MeV$. Long dashed line : $SEQ-(\pi+\rho)$ [13]. Short dashed line: absorption mechanism. Solid line : sum of two. Figure is from Ref.[27].

exchange currents in ^{16}O, which are smaller than in ^{14}C, although the structure of the wave function is also partly responsible.

2.4 The 6q Exotic

To explain a large, forward-peaked cross section in the low-energy DCX, a mechanism in which the pion interacts with six quark clusters (Fig.1(f)) in a nucleus has been considered in [33] and [36].

In [33], the pion interaction with 6 quark bag states, which are specified by the quantum numbers $T=0$, $J^P=1^+, 2^+$ has been considered. It has been shown that a $\sim 6\%$ probability for a 6q cluster provides a large and forward peaked cross section for DCX at $50\,MeV$. The same qualitative effect has been found in [36], where it is supposed that the pion interaction with the $2N$-system goes through a formation of the narrow dibaryon $d' : T=0$, $J^P=2^-$. The negative parity of this dibaryon allows the only decay mode to the πNN channel.

In [34], within the same framework as in [33], Miller calculated the DCX excitation function $(d\sigma(0^\circ)/d\omega)$ at higher energies of $300-500\,MeV$, and predicted the peak at about $450\,MeV$ which is due to a $580\,MeV$ 6q-bag state $T=0$, $J^P=2^+$. Later, the experimental data [37] did not confirm this prediction. On the other hand, it has been shown [35] that the SEQ model reproduces these data well.

At present, the situation with the 6q mechanism in DCX is very unclear because the cited above calculations contain free parameters such as a six quark formation probability, the coupling constants to exotic nuclear states, and others. The results of [35] showed the importance of a careful study of more conventional mechanisms in DCX which have been described in the foregoing subsections.

3 Pion Distortion Effects

The effect of a pion distortion for the SEQ-π mechanism has been studied in several papers [11], [14]-[17]. The pion distortion comes about both from the distortion of in- and out-going pion (external distortion) as well as from the distortion of intermediate pion (internal distortion). In the Bleszynsky-Glauber paper [15] it has been noted that the pion distortion effect at low energies is of no importance and can be neglected. A strong pion distortion effect (external + internal) has been found in [14] and [11]. In the last two papers, by turning on the pion distortion, the plane wave results are magnified by a factor of two. In these papers also it has been pointed out that the main effect comes from the distortion of the intermediate pion. Turning off the internal distortion decreases strongly the cross section. On the other hand in [17] it has been noted that the inclusion of the internal distortion generally decreases the calculated cross sections. The effect of external distortion within the framework of the DWIA-approximation has recently been studied in [16] and the authors claimed that the distortion of the external pion considerably changes the plane wave angular distribution, increasing the cross sections at forward angles and decreasing them at large angles. From the above it follows that so far the situation with the pion distortion effect is controversial.

In [38] the effects of the external pion distortion for isoelastic charge exchange scattering (within the framework of the isospin invariant optical model) have been considered. An approximated method of taking into account the distortion based on the separable expansion of the optical potential in momentum space is developed. This method provides a simple procedure to calculate the distortion effects for SCX and DCX pion isoelastic scattering channels for given partial wave channels.

The distorted wave T-matrix ($\mathcal{T}^{DW}$) is related to the plane wave T-matrix ($\mathcal{T}^{PW}$) as

$$\mathcal{T}_\alpha^{DW}(k_f,k_i;E)=\gamma_\alpha^{DW}(k_f,k_i)\mathcal{T}_\alpha^{PW}(k_f,k_i;E) \tag{3}$$

where

$$\gamma_\alpha^{DW}(k_f,k_i)=(1-k_fF_\alpha(k_f)\xi_\alpha(k_f))(1-k_iF_\alpha(k_i)\xi_\alpha(k_i)) \tag{4}$$

and

$$\xi_\alpha(k)=\frac{1}{\pi\epsilon_{\pi A}(k)}\int_0^\infty\frac{q^2dq}{2\pi^2}[\frac{\alpha(q)}{g_\alpha(k)}]^2\frac{1}{E(k)-E(q)+i\delta} \tag{5}$$

Here α denotes the quantum numbers of a given partial channel such as: the orbital angular momentum (l), total angular momentum (I), isospin (T), etc.; $F_\alpha(k)$ is the π-nucleus elastic scattering amplitude; $\epsilon_{\pi A}(k)=k^2/[2\pi^2dE(k)/dk]=k\bar{\omega}/2\pi^2$ is the

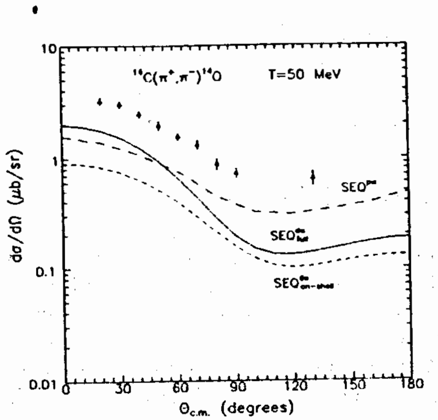

Figure 5: Differential cross section for $^{14}C(\pi^+,\pi^-)DIAS$ at $50\,MeV$. Dashed line: $SEQ-(\pi+\rho))$ [13] in the plane wave approximation, and the solid line is for external pion distortion calculations. Figure is from Ref.[38]

density of the scattered states, and $\bar{\omega}$ is the reduced pion-nucleus mass. For the isoelastic scattering $k_i = k_f$.

The distortion factor (4) is expressed in terms of the pion-nucleus form factors $g_\alpha(q)$

$$g_L(k) = k^L e^{-k^2/4\alpha}(1-\beta_1\frac{k^2}{4\alpha}-\beta_2(\frac{k^2}{4\alpha})^2) \qquad (6)$$

which are obtained by applying the separable approximation method following Bateman [43] for the optical potential which well describes the low energy $\pi - A$ interaction.

There is a number of different optical potentials that equally well describe the low energy $\pi - A$ interaction [39]-[42]. It is shown yet [40] that all these potentials are closely related to the Kisslinger potential. This globally parameterized potential is given by

$$\frac{-2\bar{\omega}}{4\pi}U(r) = b_{eff}\rho(r) - c_{eff}\vec{\nabla}\rho(r)\vec{\nabla} + c_{eff}\frac{\bar{\omega}}{2M}\vec{\nabla}^2\rho(r) \qquad (7)$$

where $\rho(r)$ is the nuclear density, and b_{eff} and c_{eff} are the complex energy dependent parameters. The parameters $\beta_{1,2}$ of the pion-nucleus form factors are expressed in terms of these parameters.

In Fig.5 we present the results of our calculations of the differential cross section for DCX to DIAS for ^{14}C using U_2^{SEQ} taken from [13]. The plane-wave result is given by the dashed line. The on-shell external distortion (short-dashed line) decreases substantially the plane wave angular distribution over the whole range of the scattering angles. Turning on the off-shell distortion (solid line) changes qualitatively the plane wave result, increasing it at forward angles and decreasing at large angles. The same qualitative effect of the external distortion has been obtained in [16] (DWIA approximation).

4 Conclusion

From the results presented in this review it follows that there is number of competing processes , such as the SEQ, MEC and absorption mechanisms which contribute to DCX at low energies. There is large sensitivity of the results to the quantities involved in the process, which makes it possible to study the $N-N$ correlations in nuclei and the πNN dynamics by the DCX reaction [20]. We also showed that the pion external distortion is very important and changes the plane-wave angular distributions qualitatively at large angles. To be able to collect all pieces together and compare systematically the theory with the experimental data, we have to clarify the effect of intermediate distortion of a pion (π^o) in SEQ-π (Fig.1(a)), which is under investigation now.

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