# Possible manifestations of a narrow dibaryon resonance in the interaction of pions with nuclei

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(Submitted 28 December 1990)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 3, 132–135 (10 February 1991)

The possibility of describing the cross section for double elastic charge exchange of pions with nuclei at low energies by means of a resonant contribution of a dibaryon state is discussed.

Recent measurements[1] of $\pi^+ \to \pi^-$ charge exchange at $^{14}C$ at low energies have revealed certain structural features in the plot of the cross section $d\sigma(\vartheta = 0)/d\Omega$ versus the energy of the incident pion, $T_\pi = E_\pi - m_\pi$. According to the standard model (a sequential charge exchange with two nucleons),[2] there should be a rounded dip at $T_\pi = 20$–$80$ MeV in the cross section for a zero angle. This dip would result from a destructive interference of $S$ and $P$ waves. A peak has been found experimentally at $T_\pi \approx 40$–$50$ MeV. So far, we have no explanation for this effect on the basis of the standard interpretation.[1,2] There are also indications[1] of a peak at the same $T_\pi$ in the charge exchange $\pi^+ \to \pi^-$ at $^{18}O$ and $^{12}C$.

Let us examine the possibility of explaining the peak in the cross section $d\sigma(\vartheta = 0^0)/d\Omega$ as resulting from the existence of a comparatively narrow dibaryon, a basic property of which is the absence of a decay into $NN$. Such a dibaryon ($d'$) has been predicted in specifically this energy region in a QCD-string model with $LS$ coupling.[3] Its quantum numbers would be $T = 0$, $J^P = 2^-$, and the only decay mode would be $NN\pi$. Other estimates put its mass 60 MeV higher.[4]

The dibaryon $d'$ could contribute to the elastic charge exchange $\pi^+ \to \pi^-$ if the initial and final nuclei contained admixtures of $6q$ states with the quantum numbers $nn$ and $pp$ (Fig. 1). The resonant contribution to the cross section is

$$\frac{d\sigma_R(\vartheta = 0^0)}{d\Omega} = \frac{(2l_\pi + 1)^2}{4k^2} \frac{\Gamma_+ \Gamma_-}{(E - E_0)^2 + \Gamma^2/4} P_{6q}^2 , \tag{1}$$

where $\Gamma_+$ and $\Gamma_-$ are the partial decay widths of $d'$ for the decay into $nn\pi^+$ and $pp\pi^-$, $\Gamma_+/\Gamma = \Gamma_-/\Gamma = 1/3$, and $P_{6q}$ is the probability for the admixture of $6q$ states in the nucleus. This probability is determined primarily by the probability for the transition $NN \to 6q(J^P = 0^+, T = 1)$. This transition might occur if the resultant spin of the two nucleons were $S = 0$, and the relative orbital angular momentum $l = 0$ (the formation of $6q$ states with $T = 1$ and $J^P \neq 0^+$ is suppressed by the centrifugal barrier). Since $J(d') = 2$, we have $l_\pi = 2$.

The role of an admixture of $6q(0^+)$ states in the double charge exchange of pions with nuclei has been discussed previously,[5] but without consideration of resonant contributions (such as $d'$).

The probability $P_{6q}$ in (1) depends on the wave function of the nucleus. A charge

  

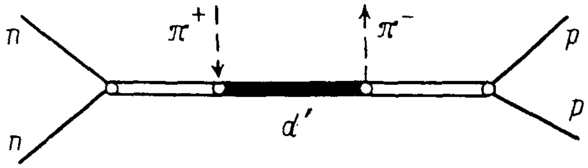


FIG. 1. Diagram of resonant double charge exchange of pions.

exchange with $^{14}C$ accompanied by a transition to the doubly analog nucleus $^{14}O$ could generate transitions from $p_{3/2}$ and $p_{1/2}$ shells. The pair of nucleons involved in the process should have a total angular momentum $J = 0$. The expansion in $J$ for an arbitrary pair of nucleons with $j_1 = j_2$ in the $p$ shell is

$$|j_1 j_2> = |1/2,\ 1/2> = |1/2,\ 1/2, J = 0>,$$

$$|j_1 j_2> = |3/2,\ 3/2> = \frac{1}{\sqrt{6}}|3/2,\ 3/2,\ J = 0> + \sqrt{\frac{5}{6}}|3/2,\ 3/2,\ J = 2> . \quad (2)$$

To pursue this calculation, we need to transform to the relative coordinates $\vec{r} = \vec{r}_1 - \vec{r}_2$ and to the center-of-mass coordinates $\vec{R} = (\vec{r}_1 + \vec{r}_2)/2$. To express the states $|j_1 j_2, J = 0\rangle$ in terms of $\vec{r}$ and $\vec{R}$, we should go over from $jj$ coupling to an $LS$ coupling scheme and then make use of the Moshinsky transformation coefficients.[6,7] Skipping the details, we write the result:

$$|j_1 j_2,\ J = 0> = \sum_{\lambda, S} \tilde{\lambda}\tilde{S}\tilde{j}_1\tilde{j}_2 \begin{Bmatrix} l_1 & s_1 & j_1 \\ l_2 & s_2 & j_2 \\ \lambda & S & J \end{Bmatrix} \sum_{\mu S_z} C^{00}_{\lambda\mu S S_z} |S, S_z>$$

$$\times \sum_{nlNL} < nl,\ NL,\ \lambda | n_1 l_1,\ n_2 l_2,\ \lambda > |nl,\ NL,\ \lambda > . \quad (3)$$

Here $nl$ and $NL$ are quantum numbers which characterize the relative motion of the nucleons and the motion of their center of mass, respectively, $\lambda$ is the resultant angular momentum, $\mu$ is its projection, $\vec{\lambda} = \vec{l}_1 + \vec{l}_2 = \vec{l} + \vec{L}$, $\tilde{\lambda} = \sqrt{2\lambda + 1}$, etc. For an oscillator potential we would have

$$|nl,\ NL,\ \lambda\mu> = \sum_{mM} C^{\lambda\mu}_{lmLM} R_{nl}(r/\sqrt{2}) R_{NL}(R\sqrt{2}) Y_{lm}(\vartheta, \varphi) Y_{LM}(\theta, \phi), \quad (4)$$

where $R_{nl}(r)$ are the radial wave functions,[7] given by

$$R_{nl}(r) = \left[\frac{2n!}{\Gamma(n + l + 3/2)}\right]^{3/2} (m_N\omega)^{3/4} \rho^l e^{-\rho^2/2} L_n^{l+1/2}(\rho^2), \quad (5)$$

$\rho = r/(m_N\omega)^{1/2}$, $\omega = 11.3$ MeV, and $m_N$ is the mass of the nucleon.

We denote by $P_{nl}$ the probability for the formation of a $6q$ state with $T = 1$ by two nucleons with the corresponding values of $n$ and $l$. As we have already mentioned, the states with $l = 0$ dominate the situation (such states correspond to $6q$ with $J^P = 0^+$), so we have $n = 0$ or 1. If we use the model of constituent quark bags,[8] and if we allow for the nonorthogonal nature of $NN$ and $6q$ (Ref. 9) with identical quantum numbers, we find $P_{00} = 0.5\%$ and $P_{10} = 1.2\%$ (Ref. 10). This model incorporates the dynamics of the $NN \to 6q$ transition; its parameters are determined from $NN$ scattering. A simpler ("geometric") estimate can be found by assuming $P_{n0}$ to be simply the probability for an overlap of the wave functions of the two nucleons: $P_{n0} = (2\sqrt{2})^{-1} \int_0^{r_0} |R_{n0}(r/\sqrt{2})|^2 r^2 dr$, where $r_0 \sim 1$ fm. We then find $P_{00} \sim P_{10} \sim 3$–$4\%$. This estimate can be justified on the basis that a sufficient condition for the formation of $d'$ is that the two nucleons approach each other to within a small distance; i.e., it is sufficient that a three-particle ($NN\pi$) collision become possible. To decide just which of the estimates is more appropriate for a given process would hardly be possible without knowledge of the particular features of the mechanism by which $d'$ forms and decays.

The expression for $P_{6q}$ in terms of $P_{n0}$ [see (1)] is determined by the nuclear wave function. For various versions of the $^{14}C$ wave function given in Ref. 2 we find $P_{6q} = (0.62$–$1)(1/2)(P_{10} + P_{00})$. The corresponding quantity for the transition $^{12}C \to ^{12}O$ (under the condition that the $p$ shell is filled in $^{12}C$) is $(P_{10} + P_{00})/3\sqrt{2}$.

To compare the results with experiments, we need to allow for the "blurring" of the peak as the result of the Fermi motion of the nucleons in the nucleus; we also need to consider nonresonant contributions to the cross section. If the resonance is sufficiently narrow (the estimate $\Gamma = 2$–$3$ MeV was given in Ref. 3), the shape observed for the peak would be determined essentially unambiguously by the motion of the center of mass of the two nucleons and would be described by the expression

$$f(E_\pi) \sim \frac{1}{k} \exp\left[-\left(\frac{k^2 - k_0^2}{q_0 m_\pi k} m_N\right)^2\right], \quad k^2 \approx 2 m_\pi T_\pi,$$

which is found from the known radial wave function $R_{NL}(R\sqrt{2})$ with $q_0 = 146$ MeV. The width of this distribution is $\Delta E = 15$–$20$ MeV. This result appears to be consistent with experimental data if we assume that the resonant contribution amounts to half the cross section at the maximum,[2] i.e., that $d\sigma(\vartheta = 0^\circ)/d\Omega \approx 2\ \mu b/sr$ at $T_\pi = T_0$ (Fig. 2). At $\Gamma = 2$–$3$ MeV the probability for an admixture of $6q$ states should then be $P_{6q} \approx 1\%$; this figure does not contradict the estimates above.

One might attempt to find a limitation on $\Gamma$ from data on the $NN \to NN\pi\pi$ cross section,[11] to which $d'$ production would contribute: $NN \to (d' \to NN\pi)\pi$ (this contribution and also the $d'$ decay are described by "half" of the diagram in Fig. 1). If we assume that the matrix element is a constant, we can write

$$\sigma(pp \to d'\pi^+) = \frac{8\pi}{3\sqrt{2}} \frac{|\vec{p}_\pi|}{|\vec{p}_p|} \frac{1}{E_{pp}^2} \frac{m_{d'}}{(m_{d'} - 2m_N - m_\pi)^2} \sqrt{\frac{m_N}{m_\pi}}\, \Gamma,$$

where $p_\pi$, $p_p$, and $E_{pp}$ are the momenta and energy in the c.m. frame. We thus find a fairly strong limitation on the width of the resonance: $\Gamma \leqslant 0.2$ MeV. However, such an estimate can hardly be considered reliable, since the matrix element may have an extremely strong energy dependence. If we nevertheless use this estimate, we find that $P_{6q} \approx 4\%$ would be required for this explanation of the effect; such a value is apparently not ruled out.

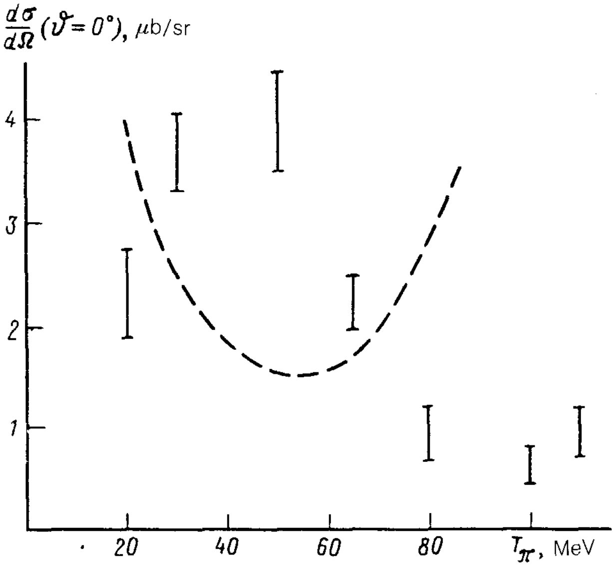


FIG. 2. Cross section for the double charge exchange $^{14}C(\pi^+,\pi^-)^{14}O$ at zero angle.[1] The dashed line represents the standard model.[2]

The peak in the cross section for the inclusive production of $\pi^-$ and $\pi^+$ (backward) in the reaction $\pi^+ + A(C,Xe) \to \pi^\pm + kp$ $(k = 0,1,2...) + A'$ at the same $T_\pi$ (within 5 MeV) was seen previously.[12] The relationship between the effects which we have been discussing here on the basis of the hypothesis of a $d'$ dibaryon is obvious, but estimates of the cross sections are ambiguous. Clearly, $\sigma$ would be proportional to the first power of $P_{6q}$ for an inelastic reaction. The cross section for the inclusive production of $\pi^\pm$ should therefore be one or two orders of magnitude larger than the cross section for elastic double charge exchange, and this is what is found experimentally.[12]

We wish to thank P. É. Volkovitskiĭ, I. I. Vorob'ev, L. S. Vorob'ev, I. Yu. Kobzarev, L. A. Kondratyuk, M. V. Kosov, A. E. Kudryavtsev, G. A. Leksin, and I. S. Tsukerman for useful discussions.

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Translated by D. Parsons