Signature of a πNN Resonance in Pionic Double Charge Exchange at Low Energies

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(Received 6 July 1992)

All currently available data on the pionic double charge exchange reaction (π^+,π^-) on nuclei exhibit a very peculiar energy dependence near $T_\pi=50$ MeV, while the angular distributions behave quite regularly. We demonstrate that these features find their natural explanation by a narrow resonance in the πNN subsystem with $J^P=0^-$ and a mass of 2.065 GeV.

PACS numbers: 25.80.Gn, 14.20.Pt, 24.30.Gd

By charge conservation pionic double charge exchange (DCX) on nuclei has to take place on at least two nucleons within the nucleus. Hence, one of the original hopes was that this reaction represents a unique tool for studying correlations between two nucleons, preferably at small spatial distances. However, experimental data taken at energies in the region of the delta resonance and above soon showed that the bulk features of DCX at these pion energies arise from simple A dependences due to strong absorption. And it was only recently discovered [1,2] that the original hope seems to be fulfilled indeed at pion energies considerably below the delta resonance, where absorption processes are largely reduced. In various theoretical investigations [1–7] it has been demonstrated that the DCX cross sections at low energy exhibit a high sensitivity to nucleon-nucleon (NN) correlations concerning internuclear distances of 1–2 fm and below. This discovery prompted quite a number of experiments at low energies, though low beam intensities, high background from π decay, and small DCX cross sections render measurements in this energy region very difficult. As a result of the common efforts undertaken at LAMPF, TRIUMF, and PSI there now exists a substantial base of low-energy DCX data on light and medium nuclei, which all exhibit a very regular and smooth angular dependence—as predicted by the various theoretical models—however, also a very peculiar and totally unexpected energy behavior (Figs. 1 and 2) near $T_\pi \approx 50$ MeV. Whereas the structure in the energy dependence is reminiscent of some resonance, we see from the angular distributions that this cannot be a pion-*nucleus* resonance, since then the angular distributions would be characterized by $P_J^2(\cos\theta)$, where J is the spin of such a resonance and θ the scattering angle.

In this Letter we demonstrate that this puzzling energy behavior, which as of yet has not been understood within current models, finds its natural explanation by a resonance in the πNN subsystem, having $J^P=0^-$, $T=0$, and a mass of 2.065 GeV. Preceding short notes of this idea are found in Refs. [8,9]. Such a low-mass dibaryon resonance actually has been predicted by QCD-inspired models [10,11] for several years. Because of its quantum numbers this resonance, henceforth called d', does not couple to the NN channel, where most of the dedicated yet unsuccessful dibaryon searches have been undertaken, but nearly exclusively to the πNN channel. Hence to look for dibaryon resonances in this channel the DCX at low pion energies appears as an ideally suited reaction. Its features, very small cross sections due to its two-step character and high sensitivity to small NN distances, render this reaction particularly sensitive to exotic, i.e., non-nucleonic processes, as already speculated some time ago in the six-quark concept of Miller [12].

In the context of correlations the d' resonance arises from a particular NN correlation, which leads near $T_\pi \approx 50$ MeV to a resonant enhancement of correlations between nucleons in a relative s state. In fact, such an enhancement had already implicitly been demanded in Ref. [13] for the explanation of the DCX data on ^{14}C.

Figures 1 and 2 comprise the bulk of existing DCX data [13–20] which extend down to low energies; for ^{12}C and ^{56}Fe see Ref. [9]. The measured transitions are to the double isobaric analog state (DIAT), in general heavily favored due to maximum overlap of initial and final state wave functions, and in the case of $T>1$ target nuclei also to the ground state (GST) in the final nucleus, these latter transitions being then of nonanalog type. All measured forward angle cross sections exhibit a steep rise towards $T_\pi \approx 50$ MeV, with the exception of the DIAT on ^{48}Ca. The special role of the latter has successfully been explained by Auerbach *et al.* (AGGK) [1] within the seniority concept. Though the AGGK model is in agreement with the DIAT data on ^{48}Ca, it cannot explain the steep resonancelike energy dependence for all the other transitions (dotted lines in Figs. 1 and 2). This failure is common to other current theoretical investigations.

In the following we demonstrate that the low-energy DCX data suggest the existence of a $J^P=0^-$ resonance in the πNN subsystem within the nucleus. Since a resonance in the πNN subsystem is smeared out by the corresponding center-of-mass (c.m.) motion of the particular NN pair within the nucleus, the DCX transition for such

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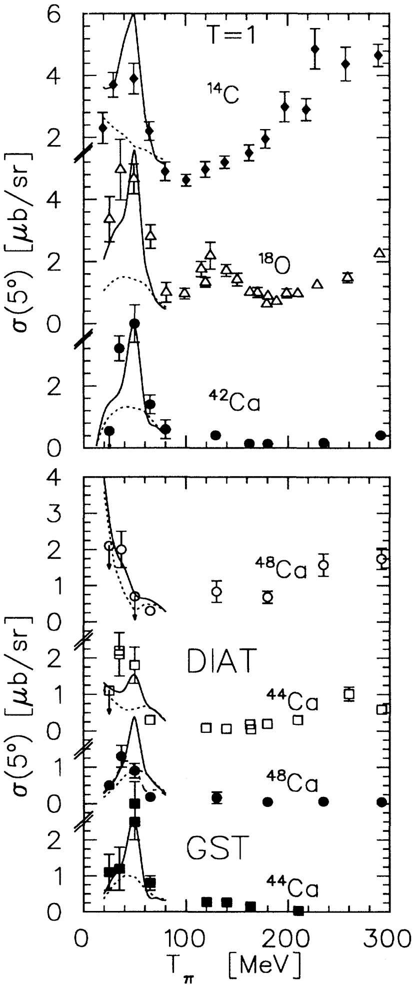

FIG. 1. Excitation functions of (π^+,π^-) forward angle cross sections for the DIAT in $T=1$ nuclei (top) as well as for GST and DIAT in $T>1$ Ca isotopes (bottom). The full calculations are shown by solid, and the nonresonant part by dotted lines. The dash-dotted curve for ^{48}Ca GST is for $\phi_0=+30°$.

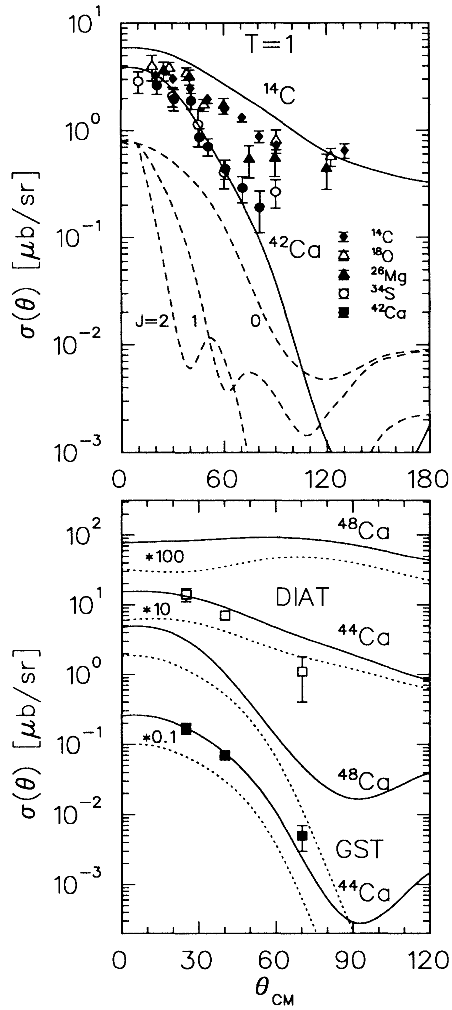

FIG. 2. Same as Fig. 1 except for the angular distributions at $T_\pi=50$ MeV. For the $T=1$ nuclei (top) calculations are shown only for ^{14}C and ^{42}Ca. For the latter the resonant part is displayed for spin $J=0$, 1, and 2 by the dashed lines.

a process is given by the primary resonance amplitude evaluated from the graph shown in Fig. 3, and folded with the NN c.m. wave functions for valence nucleons in initial and final nuclear states:

$$f_{\rm res}=\left(\frac{2^7}{m_N^3 m_\pi}\right)^{1/2}\frac{\alpha^6}{\pi^2(E_R-m_\pi)^2}\frac{k_R}{k}\left(\frac{k'}{k}\right)^{1/2}\sqrt{\Gamma_+\Gamma_-}\sum_{\substack{NN'nn'L\\ j_1j_2j_1'j_2'}}\left(\int\psi_{n0}(\mathbf{r})e^{-\alpha^2r^2}d^3r\right)\left(\int\psi_{n'0}(\mathbf{r}')e^{-\alpha^2r'^2}d^3r'\right)$$
$$\times c_L(j_1j_2)d_{L'}(j_1'j_2')b_{LNn}(j_1j_2)b_{L'N'n'}(j_1'j_2')$$
$$\times\int\frac{R_{NL}(Q)R_{N'L'}(Q')P_L(\cos\beta)P_J(\cos\gamma)}{E-E_R-k_R^2/4m-\mathbf{Q}\cdot\mathbf{k}/2m+i\Gamma/2}d^3Q\,. \quad (1)$$

Here Γ, Γ_+, Γ_-, $E_R=M_R-2m_N$ denote total and partial widths as well as the resonance energy of d' in the nuclear medium, and k_R is the pion momentum at resonance. R_{NL} and $R_{N'L'}$ ($\mathbf{Q}$ and $\mathbf{Q}'$) are the radial wave functions (momenta) of the c.m. motion of the NN pair in initial and final nuclear states, whereas $\psi_{n0}(\mathbf{r})$ and $\psi_{n'0}(\mathbf{r}')$ describe the relative motion of the two nucleons with $l=0$ and $S=0$ at distance $\mathbf{r}$ and $\mathbf{r}'$, respectively. N, N', n, n', L, and L' are the quantum numbers for nodes and c.m. angular momentum resulting from the Talmi-Moshinsky transformation [coefficients b_{LNn} (j_1j_2) in-

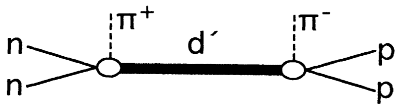

FIG. 3. Graph of the d' resonance process in DCX.

cluding $jj \to LS$ coupling] of the single particle wave functions with j_1 and j_2, and c_L (d_L) denote the two-nucleon coefficients of fractional parentage for initial (final) nuclear states. The angles β and γ appearing in the Legendre polynomials $P_L(\cos\beta)$ and $P_J(\cos\gamma)$ are functions of the momenta Q, Q', k, and k', where k and k' denote initial and final pion momenta, respectively, and J stands for the spin of d'. Since $S=0$, $l=0$, we have $L'=L$. For the formation of d' we simply assumed a Gaussian interaction of range α^{-1}. From quark models a range in the order of 1 fm seems to be realistic. In the calculations shown in this paper as well as in Ref. [9] we have used $\alpha^{-1}=1$ fm. The final result does not crucially depend on this choice. If we use $\alpha^{-1}=0.5$ fm (0) instead, then $f_{\rm res}$ increases by a factor 1.2 (1.7), lowering correspondingly our results on the partial widths.

The measured structures in the DCX energy dependence have roughly a width of 20 MeV. Using Eq. (1) we see that the c.m. motion of the NN pair alone, already contributes a width of 13–17 MeV. Thus the width Γ of d' within the nuclear medium has to be small, in the order of a few MeV. For a detailed analysis we need to account for the nonresonant "background" (f_b) due to the conventional DCX process, which interferes with the resonance amplitude,

$$f_{\rm tot}(\Theta)=f_b(\Theta)+e^{i\phi_0}f_{\rm res}(\Theta)\,, \qquad (2)$$

with ϕ_0 being a relative phase between background and resonance amplitude. For the background we adopt the AGGK concept [1], which has been most widely used for the description of low-energy data. For the calculation of Eqs. (1) and (2) we have used the wave functions of Refs. [1,2] for Ca and Ti isotopes, and those of Refs. [21–23] for ^{14}C, ^{18}O, and ^{34}S, respectively. The background cross section is shown in Figs. 1 and 2 by dotted lines. From inspection of the angular distributions we see that the conventional mechanism, which also takes into account the c.m. motion of the correlated NN pair in its form factor, does already give quite a reasonable description of the shape of the measured angular distributions near $T_\pi=50$ MeV, though not of its absolute magnitudes. From this we may infer already that the spin of d' is likely to be zero, since then $P_J(\cos\gamma)=1$ and Eq. (1) leads to a comparable angular dependence. Indeed calculations of Eq. (1) assuming $J=1$ or 2 predict angular distributions which decline faster than the data by 1 and 2 orders of magnitude, respectively, between 0° and 70° (dashed lines in Fig. 1, for ^{42}Ca). Only the $J=0$ calculations are in agreement with the required angular dependence. The solid curves in Figs. 1 and 2 give the result if, according to Eqs. (1) and (2), a πNN resonance is included having $J^P=0^-$, $M_R=2.065$ GeV, $\Gamma=5$ MeV, $\Gamma_+=\Gamma_-=0.17$ MeV, and $\phi_0=-60°$. The inclusion of the resonance provides, for the first time, a quantitative description for all measured transitions (for ^{12}C and ^{56}Fe, see Ref. [9]), and only a few data points are severely missed, most notably those for ^{14}C DIAT and ^{48}Ca GST at $T_\pi=50$ MeV. In the latter case a good description could be retained if we would change the phase ϕ_0 in Eq. (2) from $-60°$ to $+30°$ for this particular transition (dash-dotted curve in Fig. 1). Unfortunately there is as yet no measurement of its angular distribution. With regard to ^{14}C DIAT the configuration mixing in the realistic wave function for the ^{14}C ground state increases the resonant cross section by as much as a factor of 3 compared to the case of a pure configuration. This extraordinary sensitivity to configuration mixing is observed in particular for DIATs, since there $d_L=c_L$ causing the same NN wave function to enter the cross section with the fourth power.

It is not the intention of this paper to present best fits for each individual transition by adjusting resonance parameters individually or arguing about details of wave functions. We rather want to emphasize that with the use of reasonable wave functions and a single set of resonance parameters the understanding of the low-energy DCX data is improving drastically. Actually, an increase of the width to $\Gamma=10$ MeV would further improve the description of the transitions on the light nuclei; other improvements would be gained by an individual adjustment of ϕ_0 or E_R. Also the background description is not unambiguous, differing appreciably among different authors [1–7].

The resonance parameters as given above reflect the d' resonance embedded in nuclei. Hence both the total resonance energy M_R and the total width Γ may be affected by medium effects giving rise to the binding energy and spreading width of d'. Since Γ is in the order of a few MeV, d' must have even isospin, otherwise decay into NN would be allowed, causing a much larger width for d'. If it exists in vacuum d' can decay therefore only into $nn\pi^+$, $np\pi^0$, and $pp\pi^-$—and with a tiny probability also by γ emission. Thus we have $\Gamma_{d'}=3\Gamma_+$ and most of the observed width Γ for d' within the nuclear medium has to be attributed to spreading. Such a decay mechanism in the medium would be, e.g., $Nd' \to 3N$. Another medium effect would be a mixing phase hidden in the phase ϕ_0, which we introduced in Eq. (2) as a relative phase between resonance and background, primarily for practical reasons, since in the AGGK calculations only the moduli of their amplitudes A and B have been given. In calculations with the code PIESDEX [24] we find on the other hand that a phase of about $-60°$ is very plausible for the nonresonant background amplitude. Thus our fit value for ϕ_0 does not necessarily imply the need for a large mixing phase.

A low-mass dibaryon state with $J^P=0^-$ would, in fact, be in agreement with predictions based on QCD string models, if we assume that d' has an isospin of $T=0$. These models predict a triplet of states 0^-, 1^-, and 2^- in this very energy range, all other NN decoupled $6q$ states being substantially heavier [10,11]. In these models d' constitutes basically a singlet diquark with angular momentum $l=1$ relative to a four-quark cluster with $S=1$, $T=0$. Since the mass of d' is close to the πNN threshold, the tiny width $\Gamma_{d'}$ also appears to be very reasonable.

If d' really exists the question arises of why this resonance has not been observed in other reactions. From its quantum numbers the NN channel is excluded as already discussed above. Hence the natural channel to look for its existence is πNN, which means scattering as well as single and double charge exchange of pions on nuclei. From the tiny resonance cross section ($|f_{\text{res}}|^2 \approx 0.1-1$ μb/sr) it is clear, however, that only a dedicated reaction like DCX, where competing processes are heavily suppressed, is able to reveal its existence. So not many possibilities seem to be left to check independently the existence of d'. One possibility would be, in principal, $d+\gamma \rightarrow d' \rightarrow pp\pi^-$. However, as already mentioned above, the γ branch is tiny and we estimate this cross section to be in the order of nb/sr, which has to be compared with a nonresonant background of the order of 100 μb/sr. Alternatively we suggest searching for d' in the reaction $pp \rightarrow d'\pi^+ \rightarrow pp\pi^-\pi^+$, which gives experimentally the favorable situation of four charged particles in the exit channel. First estimates for the resonance contribution near threshold to this reaction give cross sections in the order of nb-μb, which seem to render measurements feasible. Experiments on this reaction are currently being planned.

In conclusion, we have presented evidence for the existence of a πNN resonance with $J^P=0^-$ by inspection of the pionic double charge exchange on nuclei. The assumption of such a resonance provides a natural explanation of the "peculiar" features of the low-energy DCX and gives for the first time a quantitative description of all presently available low-energy DCX data. Such a dibaryon resonance which constitutes an exotic, i.e., nonnucleonic 0^- state in the deuteron at $E_x \approx 190$ MeV with an extremely narrow width of about half a MeV would be in good agreement with predictions based on QCD string models, if d' is isoscalar.

We are grateful to L. B. Okun and G. J. Wagner for stimulating and fruitful discussions. One of us (M.S.) would like to acknowledge the hospitality of the Physikalisches Institut at the University of Tübingen. This work has been supported by the German Federal Minister for Research and Technology (BMFT) under Contract No. 06 TÜ 656 and by the DFG (Mu 705/3, Graduiertenkolleg).

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