Pionic Double Charge Exchange on $N = Z$ Doubly Closed Shell Nuclei

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The (π^+, π^-) reaction on the isoscalar, doubly magic nuclei ^{16}O and ^{40}Ca has been measured in the energy range $T_\pi = 45-90$ MeV. The forward angle cross sections of the ground state transitions (GST) show a very pronounced resonancelike energy dependence. The observed energy and angle dependences are well described by the recent hypothesis of the formation of a πNN resonance in the course of the double charge exchange process. The deduced spreading widths are in accordance with estimates of the d' collision damping in the nuclear medium. In the reaction on ^{16}O in addition to the GST the transition to a 0^+ state at $E_x = 2.1(2)$ MeV in ^{16}Ne has been observed, which is interpreted as the quadruple isobaric analog state (QIAS) of the 0_2^+ state in ^{16}C at $E_x = 3.03$ MeV. [S0031-9007(97)04511-0]

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The pionic double charge exchange (DCX) reaction on nuclei has received much attention in recent years, mainly because of two features. First, it has been shown that this genuine two-nucleon (N) process is particularly sensitive to correlations at small NN distances at energies below the Δ resonance [1,2], where distortion effects no longer play a major role. Second, the experimental observation of a peculiar but systematic resonancelike energy dependence has come as a big surprise and has not yet found a satisfactory conventional explanation. Even an elaborate coupled-channel treatment carried out on one particular example [3] has not been able to provide a quantitative description of both energy and angular dependences. Also such a coupled-channel mechanism, which crucially depends on details of the structure of individual nuclei, is not likely to explain a feature common to all nuclei investigated so far. We therefore have proposed recently [4] that this peculiar behavior of the DCX at low energies should be due to a particular NN short-range correlation, the formation of a NN-decoupled πNN resonance, called d'. With this hypothesis we have shown that all hitherto measured DCX transitions may be described reasonably well, both in their energy and in their angular dependence, by assuming for this resonance $I(J^P) = \text{even}\ (0^-)$, $\Gamma_{\pi NN} \approx 0.5$ MeV, $\Gamma_{\text{total}} = \Gamma_{\text{spread}} + \Gamma_{\pi NN} \approx 5$ MeV, and $m_{d'} \approx 2065$ MeV. We also demonstrated [4] that such an assumption is not at variance with data on any other reaction, where d' could have been observed. Further support for the d' hypothesis stems from recent measurements at CELSIUS, which exhibit a narrow peak near 2.06 GeV in the $pp\pi^-$ invariant mass spectrum of the reaction $pp \rightarrow pp\pi^-\pi^+$ [5].

In this Letter we report on measurements of the ground state transitions (GST) on doubly magic isoscalar nuclei. In such cases cross shell transitions dominate, which in conventional mechanisms are expected to be particularly weak. The measurements have been carried out with the Low Energy Pion Spectrometer (LEPS) setup [6] at the πE3 channel at the Paul Scherrer Institute. In case of $^{16}\text{O}(\pi^+, \pi^-)^{16}\text{Ne}$ we have used as target purified water with thicknesses of 4–15 mm, which has been contained in an aluminium frame between thin polyethylene foils. For the $^{40}\text{Ca}(\pi^+, \pi^-)^{40}\text{Ti}$ measurements we used natural metallic Ca (isotopic abundance of ^{40}Ca: 97%) of thickness 5 mm. Measurements have been performed in the energy range of $T_\pi = 45-90$ MeV with angle settings of $\Theta_{\text{lab}} = 30°$ and 45° for most cases. In addition measurements at $\Theta_{\text{lab}} = 17°$ and 65° have been carried out at a few energies.

Figure 1 shows a sample π^- spectrum of the $^{16}\text{O}(\pi^+, \pi^-)$ reaction. In addition to the peak due to the GST a second peak is observed sitting upon a continuum from the DCX to the unbound systems $^{14}\text{O} + 2p$ and $^{15}\text{F} + p$. This second peak corresponds to an energy excitation of $E_x = 2.1(2)$ MeV in ^{16}Ne and shows an angular distribution identical to that of the GST within uncertainties (Fig. 2). Since the latter is characteristic for a monopole transition we identify the peak as being due to the transition to the 0_2^+ state in ^{16}Ne, the quadruple isobaric analog state (QIAS) of the 0_2^+ state at $E_x = 3.03$ MeV in ^{16}C [7]. This finding constitutes the

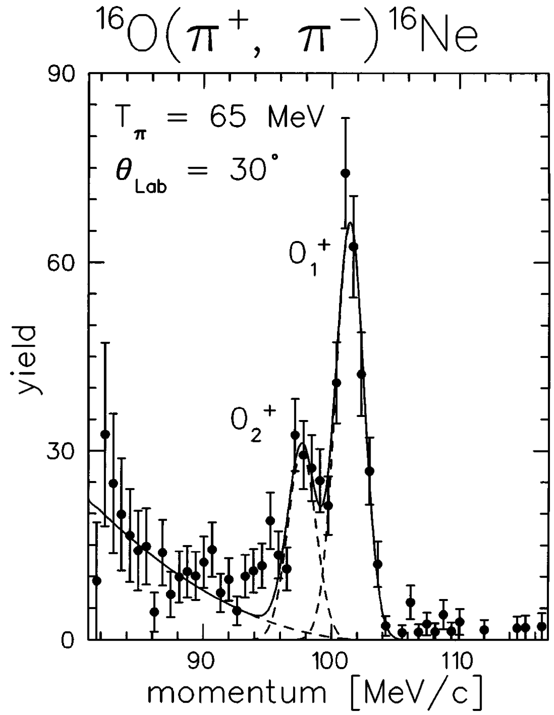

FIG. 1. Pion momentum spectrum of the DCX on ^{16}O, corrected for the acceptance of LEPS. The drawn lines show the fits to peaks at $E_x = 0$ and 2.1 MeV in ^{16}Ne, which sit upon a smooth background due to ^{16}Ne breakup.

first observation of an excited 0^+ QIAS in an isotensor quintuplet of nuclei. The observed energy difference of $E_x(^{16}C) - E_x(^{16}Ne) = 0.9(2)$ MeV for these 0_2^+ states is substantially higher than that known from the corresponding 2_1^+ states, which is only 0.1(1) MeV [7]. This very different behavior may be due to the Thomas-Ehrman shift [8], which occurs if levels in the isobar multiplet get proton unstable and which is particularly large for nucleons in $s_{1/2}$ shells. Both is the case for the 0_2^+ state in ^{16}Ne. Adding the energy displacement of the ^{16}Ne ground state as given in Ref. [9] results in a total displacement of $-1.5(2)$ MeV for the 0_2^+ state. This value, though very large, fits very well into the phenomenological systematics of Thomas-Ehrman shifts across the proton dripline (see Fig. 1 of Ref. [9]). Based on shell model calculations predicting this 0_2^+ state at 2.6 MeV Gilman *et al.* [10] calculate for this transition a cross section 6 times smaller than for the GST at pion energies in the Δ-resonance region. At energies below the Δ resonance we observe both transitions to have comparable energy dependences with a cross section ratio of roughly 1:3.

Sample angular distributions are shown in Fig. 2. At the energies shown, as well as at the other energies measured, the data are well described by the shape of angular distributions calculated within the d' hypothesis (solid lines in Fig. 2; see discussion below). Hence we have used these calculated shapes to deduce forward angle ($\Theta = 5°$) cross sections. This way we may compare our results with corresponding LAMPF data [10] at higher energies (Fig. 3). We note that as shown in Ref. [4] angular distributions calculated within the d' hypothesis are very close in shape to those obtained with standard DCX calculations. Hence this procedure should be largely model independent and clearly superior to previous purely phenomenological extrapolation methods [11].

The energy excitation functions of the forward angle cross sections are shown in Fig. 3. They exhibit two pronounced bumps, a narrow one at low energies, and a broad one in the region of the Δ resonance. The latter one is well explained by the resonant ΔΔ—or DINT—mechanism [10] and exhibits a very systematic $A^{-4/3}$ dependence of the forward angle cross section, where A

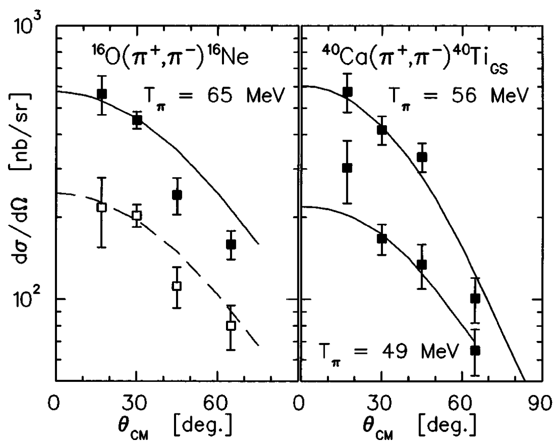

FIG. 2. Sample DCX angular distributions of the GSTs in ^{16}O and ^{40}Ca, preferably at energies where the forward angle cross sections peak. The open symbols give the results for the transition to 0_2^+ state in ^{16}Ne. The drawn curves show d' calculations. The angular distribution for $T_\pi = 49$ MeV on ^{40}Ca is scaled down by a factor of 2.

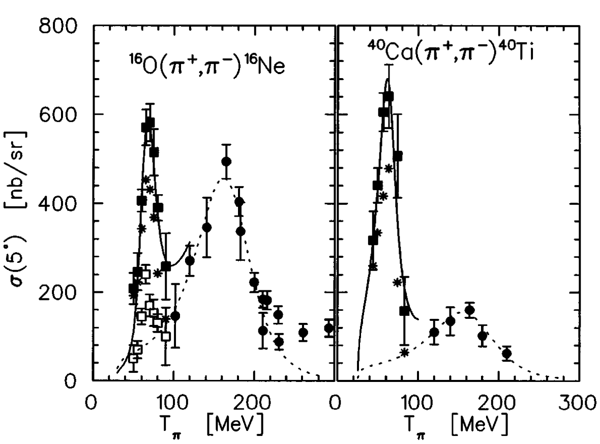

FIG. 3. Same as in Fig. 2, but for the energy dependence of the forward angle cross sections. The open symbols show our results for the 0_2^+ state in ^{16}Ne. Stars indicate the GST measurements at $\theta = 30°$. Data for $T_\pi \geq 100$ MeV are from LAMPF [10,14]. Dotted lines give the parametrization of the ΔΔ process, solid lines are d' calculations with $\Gamma = 10$ and 20 MeV for ^{16}O and ^{40}Ca, respectively.

denotes the target mass number. The narrow bump at low energies is very pronounced in both cases with a peak-to-valley ratio of 6:1. The energy location of the peak cross section turns out to be closely related to the reaction Q value. Figure 4 shows the A dependence of the peak energies of all GSTs and double isobaric analog transitions (DIATs) measured so far (with the exception of the DIAT in ^{48}Ca, which shows no bump for reasons discussed in Ref. [4]). In Fig. 4 we also have included our most recent results for the GST on ^{7}Li and ^{12}C, which will be published in a forthcoming paper [12].

Figure 4(left) shows the peak energies characterized by the kinetic energy of the incoming pions $T_{\text{in}} = T_{\pi^+}$. We would expect a smooth systematic behavior, if the origin of the bump were due to an initial state interaction (ISI) effect; vice versa, if we characterize the peak energies by the kinetic energy of the outgoing pions $T_{\text{out}} = T_{\pi^+} + Q$ [Fig. 4(right)], then we would expect a smooth behavior in case of a final state interaction (FSI) effect. In neither case such a systematics shows up. On the other hand if plotted as $T_{\text{mean}} = T_{\pi^+} + Q/2$ the peak energies of both GST and DIAT do indeed group into two smooth lines [Fig. 4(middle)]. Such a $Q/2$ dependence, which gives a symmetric situation with regard to entrance and exit channels, would appear to be characteristic for some intrinsic process, like, e.g., the formation of a πNN resonance.

In the AGGK model [2] based on seniority and on the conventional DCX mechanism of two successive charge-exchange processes, the GSTs on isoscalar nuclei are predicted to have vanishing cross sections. Though it would be inappropriate to simply transfer this prediction to our cases of cross shell transitions, we may, however, expect that calculations of the conventional DCX process in these nuclei lead to very small cross sections—aside from the problem of describing the observed narrow structure in the energy dependence. We hence investigate in the following, whether the recently proposed d' hypothesis is

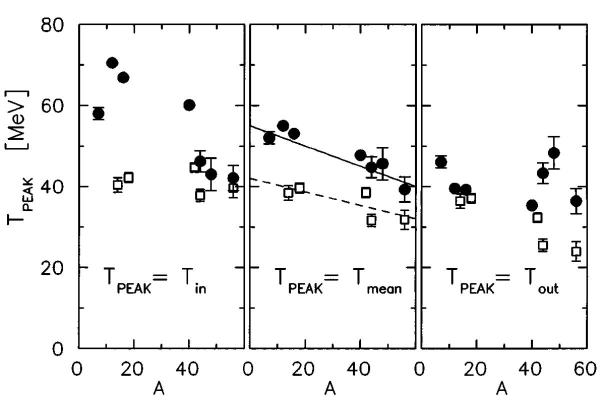

FIG. 4. Energy position T_{peak} of the peak forward angle cross sections for GSTs (full circles) and DIATs (open squares), plotted versus the target mass number and in dependence of the ingoing and outgoing pion energies $T_{\text{in}} = T_{\pi^+}$ and $T_{\text{out}} = T_{\text{in}} + Q$, respectively, as well as of $T_{\text{mean}} = T_{\text{in}} + Q/2$.

able to provide a reasonable description. Since the Q values of the reaction on ^{16}O and ^{40}Ca are huge (-27.7 and -24.8 MeV, respectively), we have to account for them properly also in the Breit-Wigner denominator of the d' transition amplitude by substituting there [Eq. (1) of Ref. [4]] E_R by $E_R - Q/2$. The amplitude due to the d' formation will interfere with the one of the $\Delta\Delta$ process, which is indicated by the dotted lines in Fig. 3. Because of the large width of the Δ resonance the extension of this process to low energies is significant. In particular in case of light nuclei like ^{16}O, where this process is quite strong, the interference of d' and $\Delta\Delta$ amplitudes is considerable and moves the peak energy towards higher pion energies.

The calculations based on the d' hypothesis are shown in Figs. 2 and 3 by the solid curves. For the GST on ^{16}O we have assumed a pure $(\nu 1p_{1/2})^2 \rightarrow (\pi 1d_{5/2})^2$ transition. If we assume for the DCX process to the 0_2^+ state in ^{16}Ne the transition $(\nu 1p_{1/2})^2 \rightarrow (\pi 2s_{1/2})^2$, then we obtain from these calculations a cross section ratio of 1:3, which is compatible to the observed one. For ^{40}Ca we have assumed that the shell closure is complete only to 90%, the rest being due to configuration mixing as suggested by transfer reaction analyses and microscopic calculations [10,13,14].

The d' resonance parameters have been taken from Ref. [4] except for the total width in the nuclear medium, which has been adjusted to the data resulting in $\Gamma = 9(4)$ and 19(5) MeV for ^{16}O and ^{40}Ca, respectively. For the description of the $\Delta\Delta$ process (dotted lines in Fig. 3) we have used the phenomenological Breit-Wigner ansatz of Ref. [15] including the parameters given there and with a phase running over 360° in this double-resonance process. The latter assures that this amplitude is real at resonance as requested for the $\Delta\Delta$ mechanism. The relative phase $\Delta\varphi$ between the d' and $\Delta\Delta$ processes is not known *a priori*; hence it is treated as a free parameter. For the calculations shown in Fig. 2 (solid lines) we have used $\Delta\varphi = 0°$ for ^{40}Ca and $\Delta\varphi = -90°$ for ^{16}O. Since this phase has quite some influence on the peak position if the $\Delta\Delta$ process is large as is the case in ^{16}O, we obtain an equally good description for the ^{16}O data, if we take $\Delta\varphi = 0°$ but readjust the effective d' mass to $m_{d'} = 2.071$ GeV. We note that the calculations of the d' amplitude according to Eq. (1) of Ref. [4] do not include pion distortions in entrance and exit channels. Estimates of their effect in the energy range of interest range from 10% [1] up to a factor of 2 [2,3] of increase in DCX cross sections. Hence, inclusion of distorsions in the d' amplitude could significantly change the calculated energy dependences and thus reduce the value for the partial widths $\Gamma_{\pm} = \Gamma_{\pi NN}/3$ derived in Ref. [4].

The d' spreading width $\Gamma_{\text{spread}} \approx \Gamma_{\text{total}}$ in the nuclear medium has recently been calculated by Valcarce *et al.* [16] assuming the isospin of the d' being $I = 2$ and exploiting the ΔN interaction in medium. Their result of a width increasing with the target mass is in qualitative agreement with our findings.

If the isospin of the d' is zero then the ΔN-interaction ansatz of Ref. [16] is inadequate. In such a case the spreading width due to collision damping by the $d'N \to 3N$ process may be estimated from virtual pion and sigma exchange of the d' with a nucleon in the surrounding medium. Starting with the Lorentz invariant amplitude of the d' decay in vacuum [17] $\mathcal{A}_{d' \to NN\pi} = \frac{f}{2m}\overline{u}_1 C\gamma_5(i\tau_2\vec{\tau})\overline{u}_2\vec{\pi}$, where $u_{1,2}$ are bispinors, $C = \gamma_2\gamma_0, m$ denotes the nucleon mass, and $f^2 \approx \frac{2^7\sqrt{2}}{3}\pi^2\sqrt{\frac{m}{\mu}}\frac{m_{d'}}{(m_{d'}-2m-\mu)^2\eta}\Gamma_{\pi NN}$ with η being the enhancement factor due to the NN FSI [17], then the invariant matrix element for the process $d'N \to 3N$ can be written as $M^{(0)} = \frac{fg}{4m}\sum_{ijk}\varepsilon_{ijk}\frac{\overline{u}_i C\gamma_5(\tau_2\vec{\tau})\overline{u}_j}{(P-p_k)^2-\mu^2} \cdot \overline{u}_k\gamma_5\vec{\tau}u$. There ε_{ijk} is the antisymmetrical tensor, $i, j, k = 1, 2, 3$ numerate outgoing nucleons with 4-momenta p_k, P, and u being the 4-momentum and bispinor, respectively, of the incoming nucleon, μ the pion mass, and $g^2/4\pi = 14.3$ the πNN coupling constant.

Following further the formalism given in Ref. [17] for the FSI we arrive at a value of $\Gamma_{\text{spread}} \approx 7$ MeV from pion exchange, if the surrounding medium has nuclear matter density. Assuming σ and π coupling constants are equal on the quark level, we obtain a spreading contribution from σ exchange comparable to that from π exchange. We note that a value of order $\Gamma \approx 15$ MeV appears to be quite reasonable in view of the resulting free mean path $\lambda_{d'}$ of the d' in nuclear matter. Since in DCX the d' picks up the momentum of the incident pion, i.e., $\sim$100 MeV$/c$, the d' velocity $v_{d'}$ relative to the medium is of the order $\sim c/20$; hence $\lambda_{d'} \approx v_{d'}/\Gamma_s \approx$ 0.7 fm which is comparable to the internuclear distance in nuclear matter.

In conclusion, the energy excitation function of the forward angle cross sections of GSTs on closed shell nuclei exhibits two pronounced resonancelike structures, a narrow one at low energies and a broad one in the region of the Δ resonance. While the latter one is well established to arise from the $\Delta\Delta$ process, the origin of the first one has become of increasing interest in recent years. We have demonstrated that this narrow structure exhibits quite well a $Q/2$ dependence. Such a dependence is in disagreement with ISI or FSI effects as origin of the narrow structure, however, in favor of the d' hypothesis, which is able to account also for the new data. The deduced collision damping of the d' in the nuclear medium is in qualitative agreement with estimates based on meson exchange mechanisms. We note, however, that inclusion of distortions could lead to significant changes in the resonance parameters, in particular in $\Gamma_{\pi NN}$. Finally, the (π^+, π^-) reaction on ^{16}O has revealed a hitherto unknown excited 0^+ state at $E_x = 2.1$ MeV in ^{16}Ne, which we identify as the QIAS of the 0_2^+ state in ^{16}C exhibiting a large Thomas-Ehrman shift.

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