A DIBARYON CANDIDATE FROM PIONIC DCX REACTIONS AT LOW ENERGIES†*

G.J. Wagner

Physikalisches Institut, Universität Tübingen
D-72076 Tübingen, Germany

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The resonance-like excitation function that is observed in (π^+, π^-)-reactions near 50 MeV in all investigated nuclei, has not been explained by conventional reaction mechanisms. We demonstrate that the world data base is reproduced with few parameters assuming a narrow resonance in the πNN-subsystem with mass 2065 MeV, $J^P = 0^-$ and isospin even.

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1. Introduction

The investigation of pionic double-charge-exchange (DCX) reactions within the LEPS collaboration (Univ. Karlsruhe, Univ. Tübingen, Paul Scherrer Institut) is part of a more general program to study nucleon-nucleon correlations in nuclei. Another major activity of the Tübingen group is the systematic investigation of kinematically complete (γ, pn)-reactions with tagged photons at the CW-accelerators at Lund and Mainz. Both types of reactions are potentially suited for that purpose because at least two nucleons are involved; their actual suitability naturally has to be demonstrated in each case.

For the DCX reaction near pion energies of 50 MeV the sensitivity to nucleon–nucleon correlations at short ranges has emerged from theoretical work of several groups; based on recent reviews [1, 2] I shall outline the current view of the prevailing reaction mechanism in Sect. 2. Before the LEPS

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program started most low-energy DCX measurements were performed at LAMPF, some at TRIUMF. The experimental difficulty is the low data rate resulting from μb/sr cross sections and typical pion fluxes of $10^7/s^{-1}$. In Sect. 3 I shall show that the LEPS spectrometer excells in a high background rejection capability which is crucial in such a situation. A few of our own DCX data obtained on ^{34}S and ^{56}Fe [3] will be presented. Conventional theories fail to describe the observed resonance-like excitation functions; this prompted us to consider seriously the suggestion of Martem'yanov and Schepkin [4] that a dibaryon resonance could be responsible for the unexplained excursion of the cross section. In Sect. 4 the success of adopting this hypothesis will be shown and the dibaryon parameters will be derived. In the final discussion (Sect. 5) it will be made plausible why this dibaryon was not seen before.

2. Conventional DCX mechanisms

In (π^+, π^-) reactions two neutrons are transformed into two protons. The dominant transition on $T_0 \geq 1$ nuclei (taken for simplicity) is to the double isobaric analog state (DIAS) with no change in the space-spin part of the wave function. The ground state (GS) and other $T_0 - 2$ states are generally more weakly excited. The reaction mechanisms in the delta resonance region are quite different from those prevailing in the low energy region. Fig. 1 shows the mass dependence of the forward angle cross sections. The steep fall-off at $T_\pi = 180$ MeV is the result of strong pion absorption; this prevents a study of nucleon-nucleon correlations in this energy region. Progress came with the advent of dedicated low-energy pion spectrometers, such as CLAMSHELL at LAMPF and LEPS at PSI. One systematic feature that emerged from these painstakingly slow measurements is the mass independence of the forward angle cross sections for $T_0 = 1$ nuclei shown in Fig. 1. This is already suggestive of a common origin — such as the dibaryon resonance.

The conventional mechanism at low energies is that of two successive single-charge exchange (SCX) processes. The long mean-free path of pions in nuclear matter in the region of the destructive s-p wave interference (7 - 9 fm) makes the PWIA a reasonable approximation. The forward peaking of DCX angular distributions (while SCX shows a backward rise) was shown [5] to arise from two sequential 90° SCX scatterings. The transition amplitude is essentially determined by the two-particle form factor [6]

$$F(q_1, q_2) = \int e^{iq_1 r_1 + iq_2 r_2} \rho^{(2)}(r_1, r_2) d^3 r_1 d^3 r_2 , \tag{1}$$

with the two-nucleon density

$$\rho^{(2)}(r_1, r_2) = \rho(r_1) \cdot \rho(r_2) + C(r_1, r_2) . \tag{2}$$

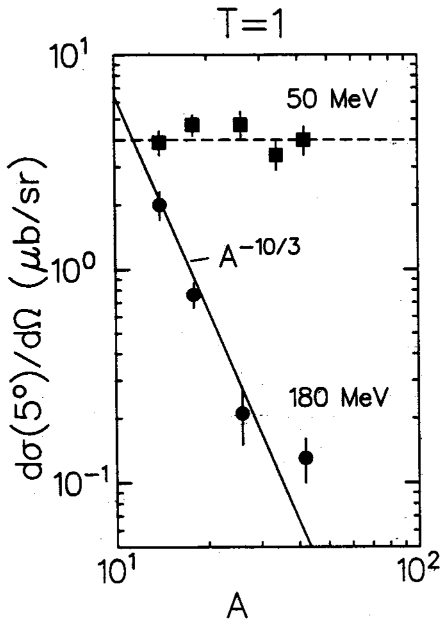

Fig. 1. Mass dependence of DIAS cross sections on $T_0 = 1$ target nuclei at two energies [2].

The first term contributes to analog transitions only and is sensitive to long NN distances. The correlation function $C(r_1, r_2)$ is the only ingredient for non-analog transitions and was shown to be sensitive to short-range correlations (SRCs).

With this reaction theory many observed features were explained, e.g. the comparable size of the DIAS transitions on ^{42}Ca and ^{48}Ca and the more forward peaked cross section for ^{42}Ca relative to ^{48}Ca. Also the steeper fall-off of GS angular distributions is understood as a manifestation of SRCs. But in contrast to the shapes of the angular distributions their magnitude in the 50 MeV region was severely underestimated. This failure could not be cured by accounting for pion absorption; the "nuclear translucence"[7] at that energy increased(!) the amplitudes between 35 and 55 MeV by some 20% only [5], by far not enough to describe the measured resonance excursion.

3. LEPS measurements

Following the upgrade of the primary proton beam at PSI (currently 600μA) the new πE3 channel provides a π^+ flux of 10^7/s. To maintain the necessary background rejection ratio of $1 \div 10^8$ at these rates we have

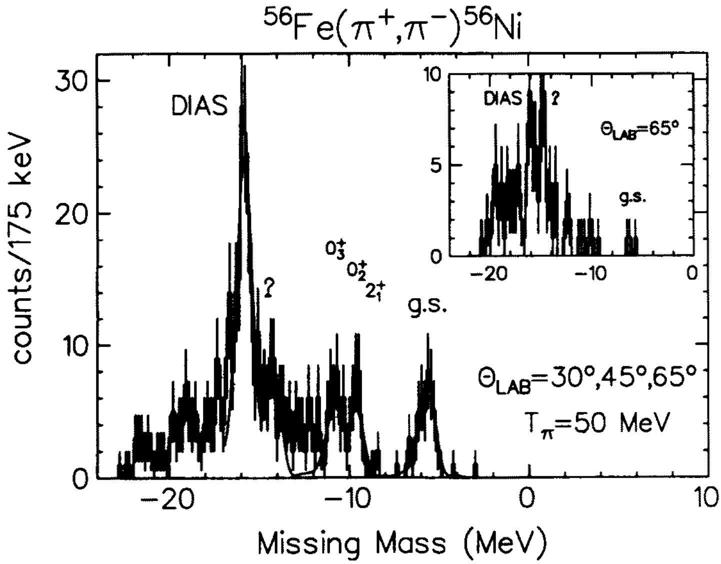

Fig. 2. DCX spectrum on ^{56}Fe [3].

recently added a TOF start scintillation counter at the LEPS entrance. Otherwise the set-up is as described earlier [8].

A spectrum, rather a sum of three DCX spectra obtained on ^{56}Fe is displayed in Fig. 2. The dominant groups are the DIAS and GS transitions. Interestingly three non-analog groups are visible at energies where 0^+ states are known. The group at $Q = -14.1$ MeV remains still unexplained; it has the only known backward rising DCX angular distribution (see insert in Fig. 2). All other angular distributions on ^{34}S and ^{56}Fe measured by us fit into the general patterns mentioned above. More importantly: the 50 MeV resonance that is consistently observed for $T = 1$ nuclei appears also for $T = 2$ nuclei, ^{44}Ca [9] and ^{56}Fe, both for GS and DIAS transitions. As this is not predicted by available reaction calculations we are reminded of H. Baer's 1991 conclusion that "the energy dependence of DCX reactions is not well understood" [1].

4. Role of a possible dibaryon

QCD-string models [10, 11] predict a non-strange isoscalar triplet of 6q-states with $J^P = 0^-, 1^-, 2^-$ and masses of about 2100 MeV, all other NN-decoupled 6q-states being substantially heavier. Their structure is basically a diquark with angular momentum $l = 1$ relative to a four-quark cluster with spin 1. Following the suggestion of Ref. [4], Bilger, Clement, Schepkin

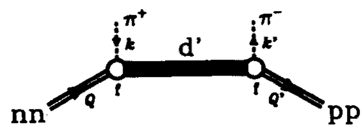

Fig. 3. Formation of the d' in DCX reactions.

et al. [12–14] investigated the role of such a dibaryon, called d' in the following, on DCX cross sections. The basic diagram is shown in Fig. 3.

A free d' with $J = 0$ or 2 is expected to have a small decay width since it will not couple to the NN channel and because the available energy in the πNN channel is small. If, however, the two nucleons of Fig. 3 are embedded in the nuclear medium, their Fermi momenta Q and Q' at the two vertices have to be taken into account properly. The transition amplitude will go like [13]

$$\int \frac{\sqrt{\Gamma_+\Gamma_-}}{T_\pi - E_R + \frac{\vec{Q}\cdot\vec{k}}{2m_N} + i\Gamma/2} P_J(\cos\gamma)\Psi_i(\vec{Q})\Psi_f(\vec{Q})d^3Q\,. \tag{3}$$

It is here where details of the shell structure of initial and final states enter: the Fermi smearing depends on the two particle wave functions Ψ_i and Ψ_f in q-space and the value of the vertices is determined by two-particle coefficients of fractional parentage.

The probability of d'-formation is parametrized by a range parameter for which 1 fm is assumed; fortunately the DCX transition amplitude is very weakly depending on this quantity. However, as Eq. 3 shows, it scales directly with $\sqrt{\Gamma_+\Gamma_-}$, which are the partial widths for π^+nn or π^-pp decay, respectively. The best fit parameters which underlay all results shown in the following are $m = 2065$ MeV, $\Gamma_+ = \Gamma_- = 0.17$ MeV and a total width $\Gamma \simeq 5$ MeV, which is larger than $3 \cdot \Gamma_+$ because of an additional spreading width of the d' in the nuclear medium. The gamma decay width of the d' on the other hand is expected to be tiny. One realizes that the experimentally observed widths of about 20 MeV result from Fermi smearing. The resonance amplitude fixed in this way has to be added to the published [7] amplitudes for the conventional, sequential mechanism. The relative phase between sequential and resonance amplitudes far from resonance was taken as $\phi = 60°$ based on PIESDEX [15] calculations.

With these few parameters the world data base of low energy DCX cross sections may be well described. Examples are given in Figs 4 and 5. The angular distributions are well reproduced if we assume that d' is the $J = 0$ member of the mentioned dibaryon triplet. The similarity of sequential and resonance amplitude for $J = 0$ explains the previous success

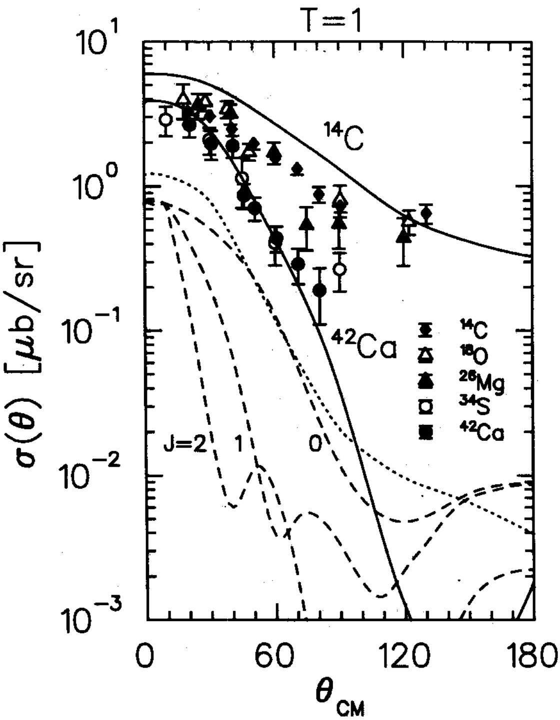

Fig. 4. Angular distributions on $T = 1$ target nuclei. Dashed(dotted) curves represent the resonant (sequential) mechanism for ^{42}Ca. Solid curves are the results for the full calculations on ^{14}C and ^{42}Ca.

of the conventional calculations in reproducing the shapes of the angular distributions.

The main success of the model is a fair reproduction (Fig. 5) of the resonance excursions which may be quite different in size for the various nuclei. Naturally in individual cases improvements by parameter adjustments or choice of shell-model wave functions are easily conceivable.

5. Discussion and conclusions

One has seen many dibaryons come and go over the years; so a critical attitude is in place.

1 Why would the d' — if it exists — show up in DCX reactions? After all, in contrast to most previous dibaryon candidates the signal is unambiguous this time. (It is its interpretation which is disputed). But note that the cross section of about 1μb/sr is nevertheless quite weak! So the difficulty of measuring DCX reactions may finally turn out as a blessing which enabled us to see the d'-signal. Already in SCX re-

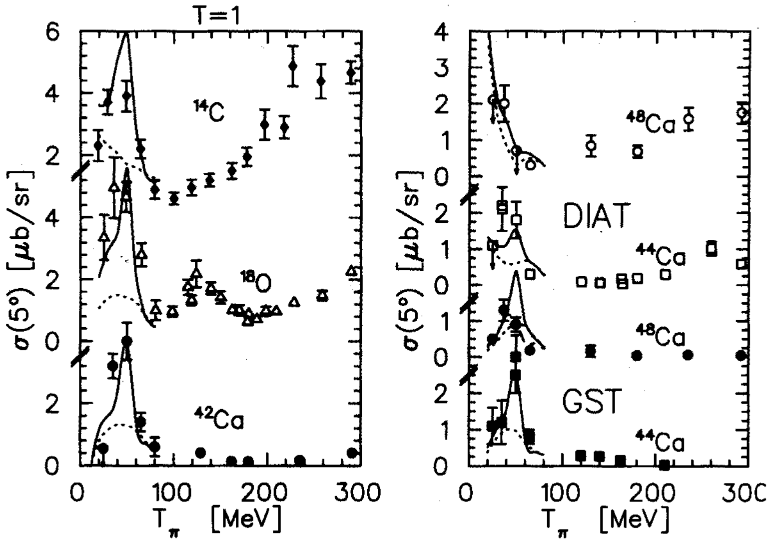

Fig. 5. Examples of excitation functions for DIAS and GS transitions. Conventional calculations are represented by dashed lines.

actions, where the d' will also contribute, the "background" amplitude from the conventional mechanism is 10 to 100 μb/sr. Even worse is the situation for photoexcitation $\gamma d \to d' \to pp\pi^-$, for which we estimated nb-cross sections at a background level known to be several 100 μb. Finally, in sect.2 we have reviewed the current wisdom that the DCX mechanism near 50 MeV, where pion absorption is weak, is sensitive to SRCs. This may well be a prerequisite for the observation of a small object.

2 Why was the d' — if it exists at all and outside the nuclear medium — not discovered before? This state, even though about 190 MeV heavier than the deuteron, has a width of half a MeV only, mainly because a $I; J^P = 0; 0^-$ state will not couple to the NN channel; but for the very same reason it could not be found in the well studied NN channel. Rather we propose to study the $pp \to d'\pi^+ \to (pp\pi^-)\pi^+$ reaction and determine the invariant mass of the $pp\pi^-$ subsystem, preferentially for small relative pp-momenta.

3 Does the surprisingly narrow width make sense? The three particle decay of the free $d' \to NN\pi$ with $p_{max} = 130$ MeV/c may be compared to the dominant $\eta' \to \pi\pi\eta$ decay with $p_{max} = 230$ MeV/c. There $\Gamma(\eta') = 0.2$ MeV, which compares well with our $\Gamma(d') = 3\Gamma_+ \simeq 0.5$ MeV.

In conclusion, we have seen that DCX reactions are sensitive to short-range effects. They show a clear resonance signal on the μb/sr level, which is typical for DCX cross sections. To date a conventional explanation has not been given. With the dibaryon hypothesis a few parameters suffice to explain all known DCX angular distributions and excitation functions fairly well. The d' parameters are consistent with QCD predictions and, where available, experimental evidence. Nevertheless, a direct proof of the existence of the d' in or outside the nuclear medium is called for.

The work presented is from the LEPS collaboration (Univ. Karlsruhe – Univ. Tübingen – PSI) and I like to thank all present and former members for the pleasant and fruitful collaboration. Above all I like to thank Ralph Bilger, Heinz Clement and Misha Schepkin, who performed the d' calculations and with whom I enjoyed many discussions about this exciting subject.

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