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PIONIC DOUBLE CHARGE EXCHANGE* **

H. Clement[a]

representing the LEPS Collaboration

R. Bilger[a], A. Denig[b], K. Föhl[a†], J. Gräter[a], W. Kluge[b], R. Meier[a], J. Pätzold[a], M.G. Schepkin[c], and G.J. Wagner[a]

[a]Physikalisches Institut, Univ. Tübingen
Auf der Morgenstelle 14, 72076 Tübingen, Germany
[b]Institut für Exp. Kernphysik, Univ. Karlsruhe, Germany
[c]Institute for Theoretical and Experimental Physics
B. Cheremushinskaya ul., 25 Moscow, Russia

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The pionic double charge exchange reaction on nuclei is reviewed. The observed systematics in the data points to a large sensitivity to short-range nucleon-nucleon correlations in nuclei — as anticipated since long for this genuine two-nucleon process. This is particularly true for non-analog transitions, which do not contain the mean-field driven analog route. In non-analog transitions the resonant $\Delta\Delta$ process dominates at high energies, whereas at low energies another resonance-like narrow structure appears, which has led to the hypothesis of a very special correlation, the formation of a πNN resonance decoupled from the NN-channel, the so-called d' resonance.

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1. Introduction

The pionic Double Charge Exchange (DCX) reaction (π^+,π^-) or (π^-,π^+) changes the charge of a nucleus by two units while leaving the number of nucleons constant. Charge conservation ensures that this process involves at least two nucleons. Hence this reaction is already to lowest order a genuine

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† Present address: Department of Physics and Astronomy, University of Edinburgh.

two-nucleon process and therefore has been looked at since long as an ideal tool for studying nucleon-nucleon (NN) correlations. Moreover, since the DCX cross sections are tiny on the scale of hadronic reactions and since the probability to change the charge of a nucleon pair simultaneously may depend strongly on the distance between these nucleons, this reaction should be particularly sensitive to NN-correlations of short range.

Motivated by these unique features much effort has been undertaken in the last two decades at LAMPF, PSI and TRIUMF to systematically study this reaction over a wide range of incident pion energies and nuclei [1]. Since the cross sections turned out to be very small, in the nanobarn to microbarn range, such measurements using secondary beams are very time consuming and require good momentum resolution combined with a very effective background suppression. This is particularly true for low pion energies, where most of the pions decay before reaching the detector, thereby lowering the detection efficiency by simultaneously rising the background. Hence nearly all of the DCX measurements have been carried out with dedicated magnetic spectrometer setups.

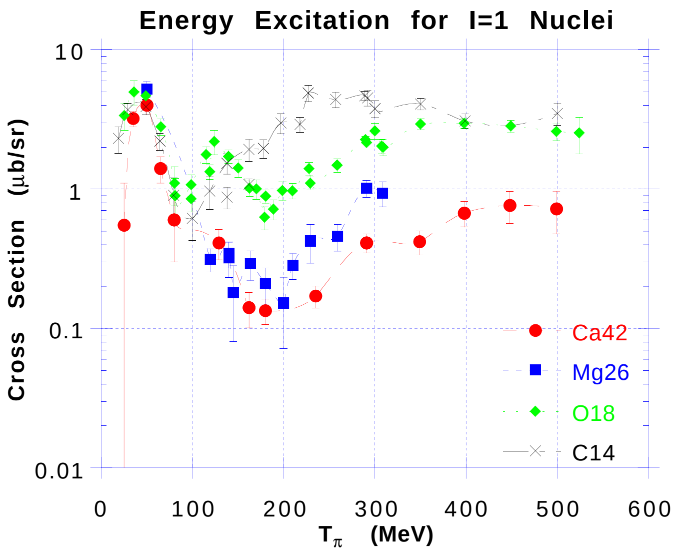

Fig. 1. Energy dependence of the forward-angle cross sections for the DIATs on isovector mirror nuclei (from Ref. [1]).

The DCX reaction is highly selective, in general only monopole transitions give sizeable cross sections. Transitions involving a finite angular momentum transfer are heavily suppressed due to angular momentum mismatch. Most favored are usually transitions to the double analog state (DIAT) in the final nucleus, since there the nuclear wavefunction of final and initial states are identical in their space and spin parts (except for Coulomb effects) and hence provide maximum overlap in the transition matrix element. The simplest situation, both experimentally and theoretically, is given in case of isovector ($I = 1$) mirror nuclei, where the DIAS is identical with the ground state in the final nucleus. Fig. 1 shows the observed energy excitation function of the forward angle cross sections for DIATs in $I = 1$ mirror nuclei. The cross sections are largest at $T_\pi \approx 50$ MeV, where all $I = 1$ nuclei appear to have comparable cross sections. Towards higher energies the cross sections decrease until a minimum is reached in the region of the Δ-resonance. Thereafter the cross sections rise again until they saturate at about $T_\pi \approx 300$ MeV.

2. High-energy region

In the whole energy region past the low-energy peak the data exhibit a strong A-dependence. Together with the results on $I > 1$ nuclei all observed DIATs can be parametrized [2] for $T_\pi \gtrsim 100$ MeV remarkably well by

$$\sigma_{\mathrm{DIAT}}(0^\circ) \sim \binom{N-Z}{2} A^{-10/3}\,,$$

where the permutational factor gives the number of possible combinations of valence neutron pairs available in the target nucleus (N, Z) to undergo the DIAT. This simple behavior may be understood [3,4] as being due to

(i) the small mean free path of pions in the Δ-resonance region and above with the consequence that the DCX process takes place only on the circumference of the nucleus, *i.e.* the scattering amplitude f will be proportional to the nuclear radius $f \sim R \sim A^{1/3}$,

(ii) the reaction mechanism, which at these energies proceeds mainly via the analog state in the intermediate nucleus (analog route) by sequential single charge exchange. It means that the mean-field part of the DCX amplitude dominates, which contains the uncorrelated part of the 2N-density. Hence $f \sim \rho_1 \cdot \rho_2 \sim \frac{1}{V} \cdot \frac{1}{V} \sim A^{-2}$ where ρ_i denote the single particle densities and V the nuclear volume.

In contrast, transitions which do not proceed to the DIAS show a much different A-dependence in the Δ-resonance region. The non-analog ground state transitions (GST) are well described by [2]

$$\sigma_{\mathrm{GST}}(0^\circ) \sim A^{-4/3}\,.$$

Again this feature may be understood as being due to the black disc behavior as above (i), but now the reaction mechanism obviously picks out the short-range part of the DCX amplitude which is sensitive to nucleon pairs highly correlated at very short NN distances, such that $f \sim \rho_1 \rho_2 \delta_{12} \sim \frac{1}{V} \sim A^{-1}$. The nature of this process gets apparent from the energy dependence of the GSTs which resembles very much the excitation of the Δ-resonance. Indeed, for $T_\pi > 100$ MeV the GSTs can be well explained by the successive $\Delta\Delta$ or DINT process [5], which is of short range.

We note by passing that measurements at $T_\pi \approx 300$ MeV show evidence for a $A^{-7/3}$ dependence of DIATs in $I = 1$ nuclei, *i.e.* a situation in-between the two cases discussed above, which means that at energies far above the Δ-resonance region some sensitivity to NN correlations is present also in these particular transitions.

3. Low-energy region

Having understood some main features of the DCX in the high energy region, we now turn to the discussion of the DCX at energies below the Δ resonance. The first observation noticed already in section 1 is that all DIATs in $I = 1$ mirror nuclei peak at $T_\pi \approx 50$ MeV with practically identical forward angle cross sections. This drastic change from a $A^{-10/3}$ to a A^0

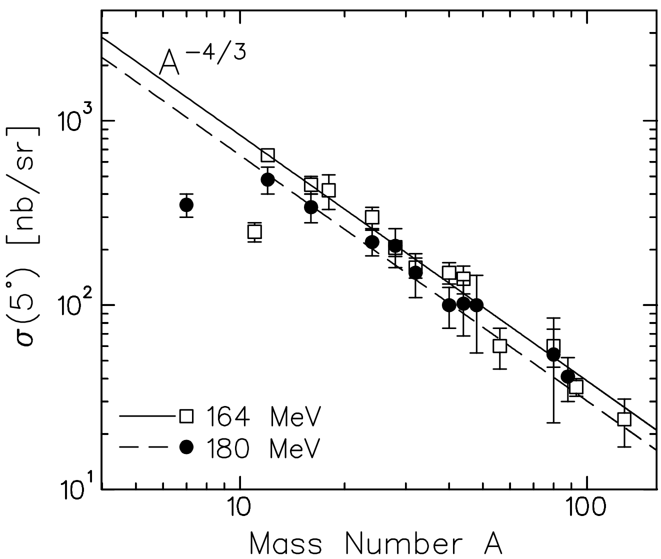

Fig. 2. Systematics of the nonanalog GSTs in the Δ-resonance region. Solid (open) symbols represent the data at $T_\pi = 164(180)$ MeV. The solid and dashed lines give the $A^{-4/3}$ dependence fitted to these data (from Ref. [11]).

dependence is demonstrated in Fig. 3. In terms of the discussion above this A independence can only be understood

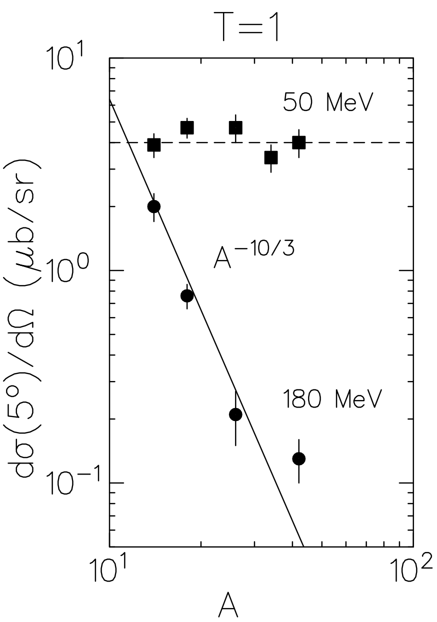

Fig. 3. A-dependence for forward angle cross sections for DIATs on $I = 1$ nuclei at $T_\pi = 50$ and 180 MeV (from Ref. [1]).

(i) if the reaction is sensitive to the full nuclear volume, which is reasonable due to the large mean free path of pions at low energies, *i.e.* $f \sim V \sim A$, and

(ii) if the reaction is sensitive dominantly to NN-correlations at short NN distances, *i.e.* $f \sim A^{-1}$.

Indeed, this has also been the outcome of previous theoretical work [6,7]. The expected (N, Z)-dependence for DIATs can be generalized to $I \geq 1$ nuclei. According to Ref. [4] the DIATs should show a dependence proportional to $\binom{N-Z}{2}$, in case the long-range part of the DCX amplitude dominates — as in the Δ-resonance region. However, if the short-range part dominates they should exhibit a $(N - Z - 1)/(N - Z)$ dependence. The latter agrees very favorably with the systematics of DIAT data around $T_\pi \approx 50$ MeV [8,9] emphasizing that the low-energy DCX is indeed sensitive to short NN distances — as hoped initially.

The real surprise, however, has been the energy dependence at low energies. Not only the DIATs exhibit a pronounced peak structure as shown in Fig. 1 for the $I = 1$ nuclei, but also the GSTs, where such a narrow structure shows up even more spectacular exhibiting a clear resonance-like shape. Examples are shown in Fig. 4. The position of this peak varies between 40 and 80 MeV depending systematically on the reaction Q-value [10]. The width of this structure is in the order of 20 MeV with a tendency to decrease with increasing A. The peak cross sections for cross-shell transitions are almost constant, only slowly decreasing between ^{16}O and ^{93}Nb. The intra-shell transitions in the Ca isotopes are a factor two to three larger, which is easy to understand from the increased overlap of initial and final states in these cases. A big though well understood exception is the GST on ^{7}Li, which is much weaker than expected from systematics, both at low energies and in the Δ-resonance region, see Figs. 2 and 4. This suppression can be traced back to the extraordinarily large radius of ^{7}Li and the even larger one of ^{7}B [11].

4. The hypothesis of a πNN resonance

The observed approximate A-independence of GSTs and DIATs at low energies demonstrates that distortions obviously do not play a major role there, and that the observed systematics is in accordance with a high sensitivity of the low-energy DCX to short-range phenomena. Moreover the measured energy excitation functions exhibit a Breit–Wigner shaped structure in close resemblance to that of a resonance, whereas the angular distributions behave smoothly as expected from a perturbative treatment of the DCX process. Putting all these features together led to the hypothesis that a narrow πNN resonance might be the reason for this peculiar resonance-like behavior of the DCX at low energies, in particular since conventional calculations have not been able so far to account for the systematic appearance of this structure. Assuming for this so-called d' resonance quantum numbers $I(J^P)$ = even (0^-), a mass of $m \approx 2.06$ GeV and a vacuum width of $\Gamma_{\pi NN} \approx 0.5$ MeV the low-energy structure can be well explained in all cases [10-13], see solid lines for the examples in Fig. 4. In order to understand the very narrow width, this resonance has to be NN-decoupled. Hence the isospin has to be even. The assigned spin has been derived from the observed angular distributions [12]. In the nuclear medium the width of such a resonance is broadened very much by "Fermi smearing" due to the motion of the nucleon pair active in the DCX process as well as by collision damping due to $d'N \rightarrow 3N$, so that the resulting width in the nuclear medium gets in the order of 20 to 30 MeV. The question whether this picture is correct or whether a subtle, as of yet not understood medium effect is the origin of this resonance-like structure, is not easy to settle within the DCX, since the medium-free process on a dinucleon is not observable. However, one could expect to minimize the influence of such contingent medium effects by studying the DCX process on the lightest nuclei possible. ^{7}Li is the light-

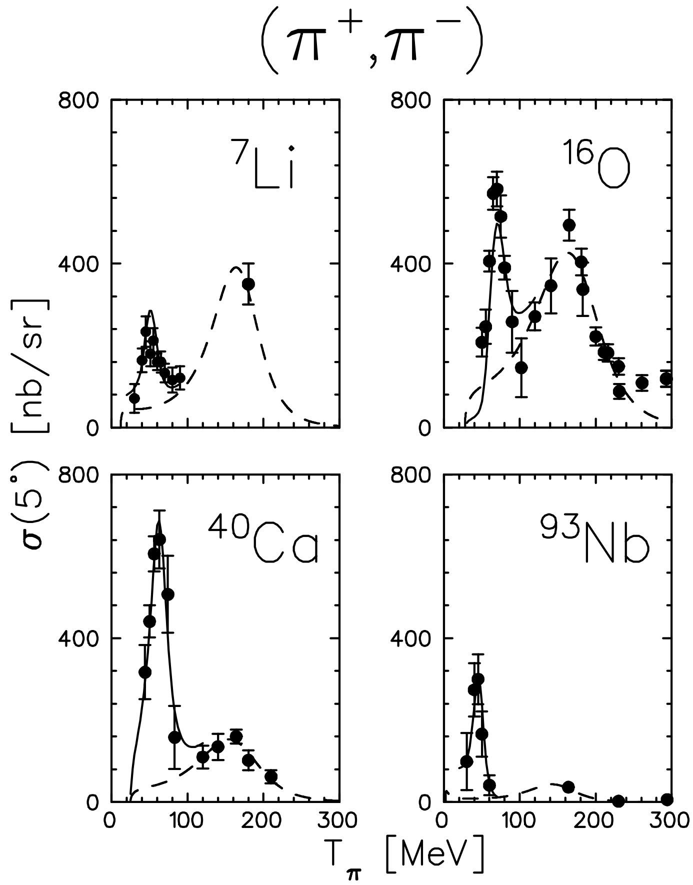

Fig. 4. Energy dependence of the forward angle cross sections for nonanalog GSTs. As examples the transitions on ^{7}Li [11], ^{16}O, ^{40}Ca [10] and ^{93}Nb [13] are shown. The data for $T_\pi \geq 100$ MeV are from LAMPF, the others are from PSI. The dashed lines indicate a phenomenological representation of the $\Delta\Delta$ process, whereas the solid lines show the result, if the d' formation amplitude is added.

est nucleus where this reaction may still proceed to a discrete final nuclear state, though the ^{7}B ground state is already 3.65 MeV above the proton emission threshold. Fig. 4 shows that again this peak structure appears in the measurements on ^{7}Li, though much less pronounced than in other cases. As mentioned already above the reason for this as well as for the low cross section in the Δ resonance region are the exceptionally large radii of ^{7}Li and in particular of ^{7}B. The latter is easily understandable from its particle unstable nature, the former is due to the loosely bound cluster structure $\alpha + t$. Due to these largely increased nuclear sizes the probability to find the active nucleons close together is strongly diminished, hence also the probability to form such a πNN resonance is strongly reduced by a factor of four [11].

The DCX reaction on still lighter nuclei leads to nuclear continuum states only. Measurements on ^{3}He and ^{4}He have recently been carried out at TRIUMF. First results are partly in support of the d' hypothesis [14]. Reactions which look for the d' production in elementary processes are $\gamma d \to np\pi^0$ and $pp \to pp\pi^-\pi^+$. In a first measurement of the latter at CELSIUS a signal consistent with the one expected from d' has been reported [15]. A detailed survey on the status of the d' search will be given by G.J. Wagner in the Workshop "The Structure of Mesons, Baryons and Nuclei" preceding this one.

5. Conclusions

Summarizing the pionic DCX as a genuine 2N-process has the appeal of being highly sensitive to NN-correlations. Though this reaction is very rare on the scale of hadronic cross sections, its stimulating features have led to a systematic study of this process over a wide range of energies and nuclei. Whereas the DIATs at high energies are dominated by the analog route, *i.e.* a long-range phenomenon of the mean field, the nonanalog GSTs, where this route is absent, show unique features of highly correlated nucleons at small distances. In the GSTs at high energies the resonant $\Delta\Delta$ process predominates, the tiny GST cross sections above the Δ-resonance region indicate that other processes obviously are very weak. At low energies, however, another resonance-like structure appears. Together with the observed sensitivity of this reaction to highly correlated NN-pairs this led to the hypothesis of a very special correlation, the formation of a πNN resonance. This hypothesis is currently pursued further in reactions suitable for the production of this resonance in vacuum.

REFERENCES

[1] For a survey see, *e.g.* M.B. Johnson and C.L. Morris, *Ann. Rev. Nucl. Part. Sci.* **43**, 165 (1993); H. Clement, *Prog. Part. Nucl. Phys.* **29**, 175 (1992) and in *Correlations and Clustering Phenomena in Subatomic Physics*, eds. M.N. Harakeh *et al.*, Plenum Press **B359**, 79 (1997) and references therein.

[2] R. Gilman *et al.*, *Phys. Rev.* **C35**, 1334 (1987).

[3] M.B. Johnson, *Phys. Rev.* **C22**, 192 (1980).

[4] N. Auerbach, D.C. Zheng, *Phys. Rev.* **C45**, 1108 (1992).

[5] R. Gilman *et al.* ., *Phys. Rev.* **C32**, 349 (1988) and **C34**, 1895 (1986).

[6] E. Bleszynski, M. Bleszynski, R. Glauber, *Phys. Rev. Lett.* **60**, 1483 (1988).
[7] N. Auerbach *et al.*, *Phys. Rev.* **C38**, 1277 (1988).
[8] H. Ward *et al.*, *Phys. Rev.* **C47**, 687 (1993).
[9] K. Föhl *et al.*, *Phys. Rev.* **C53**, R2033 (1996).
[10] K. Föhl *et al.*, *Phys. Rev. Lett.* **73**, 3849 (1997).
[11] J. Pätzold *et al.*, submitted to *Phys. Rev.*
[12] R. Bilger, H.A. Clement, M.G. Schepkin, *Phys. Rev. Lett.* **71**, 42 (1993) and **72**, 2972 (1994).
[13] J. Pätzold *et al.*, *Phys. Lett.* **B428**, 18 (1998).
[14] J. Gräter *et al.*, *Phys. Lett.* **B420**, 37 (1998).
[15] W. Brodowski *et al.*, *Z. Phys.* **A355**, 5 (1996).