POSSIBLE NUCLEON RESONANCE ADMIXTURE IN THE DEUTERON

P. BENZ and P. SÖDING
Deutsches Elektronen-Synchrotron DESY, Germany
and *II. Institut für Experimentalphysik der Universität Hamburg, Germany*

Received 15 July 1974

Low-energy, apparently resonant $p\pi^+$ systems are found to emerge when deuterons are struck by high energy photons. These could be $\Delta(1236)$ "spectators" set free from a hypothetical virtual $\Delta\Delta$ state of the deuteron occurring with ~3% probability. The possibility of other interpretations of this observation is also explored.

Although in most situations nuclei are adequately described as being composed of ordinary nucleons, transient existence of nucleon resonances in the nuclei may be expected, due to the strength of the interaction at small internucleon distances. Such virtual nuclear states could manifest themselves at high momentum transfer, and it has been conjectured that they may contribute in detectable amounts to nuclear scattering cross sections as well as to magnetic moments and decay matrix elements [1–8]. We report here on an observation that may be direct evidence of such a resonance admixture in the simplest nuclear state, the deuteron.

Among the lightest possible resonance configurations of the deuteron one expects a state consisting of two $\Delta(1236)$ resonances (since the $\Delta(1236)$ plus nucleon state is forbidden by isospin conservation). We searched for this configuration by splitting the deuteron with high energy photons, looking for the reaction

$$\gamma d \to \Delta^{++}(1236) + \text{anything} \qquad (1)$$

with the $\Delta^{++}(1236)$ going *backward* in the laboratory ($\theta_{\Delta^{++}} > 90^\circ$ with respect to the photon direction). A Δ^{++} produced by absorption of the photon on one of the *nucleons* in the deuteron (fig. 1a) cannot move backward in the laboratory, unless the absorbing nucleon had an instantaneous backward-directed Fermi momentum of

$$P_N > \frac{m_N^2 - (m_d - m_\Delta)^2}{2(m_d - m_\Delta)} \approx 350\ \text{MeV}/c \qquad (2)$$

which is highly unlikely. If, however, the photon was

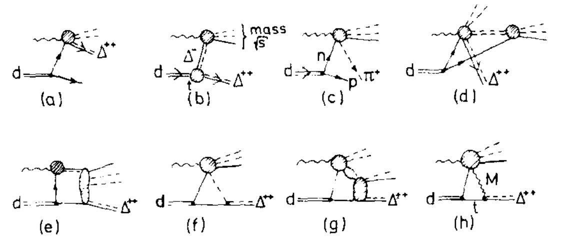

Fig. 1. (a) Δ^{++} production by interaction with a single nucleon. (b) Production of a Δ^{++} as a spectator from a virtual $\Delta\Delta$ state of the deuteron. (c) Proton spectator process, giving principal background to (b) (d)–(h) Second order processes.

absorbed by the Δ^- in an instant when the deuteron was in a virtual $\Delta^-\Delta^{++}$ state (fig. 1b), a significant fraction of the Δ^{++} which are "spectators" in the reaction, is expected to move backward in the laboratory system. Thus, the requirement of backward motion will considerably reduce the background from Δ^{++} production on nucleons, and a rather direct observation of Δ spectators appears to be possible [9].

In an experiment with the 85 cm cryogenic bubble chamber at DESY we have measured about 10^5 photon-deuteron interactions produced by a bremsstrahlung beam of 5500 MeV maximum energy. We found 736 events of the reaction

$$\gamma d \to p\pi^+ + \text{anything} \qquad (3)$$

with $E_\gamma > 1000$ MeV and with a backward moving $p\pi^+$ system. The effective masses of these $p\pi^+$ systems were concentrated near the $p\pi^+$ threshold. The decay angular distribution of the $p\pi^+$ systems (in their rest frame) showed strong forward-backward asym-

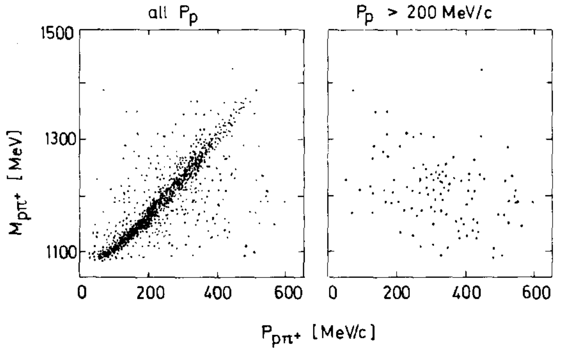

Fig. 2. Correlation of momentum with mass of the backward moving $p\pi^+$ systems from reaction (3).

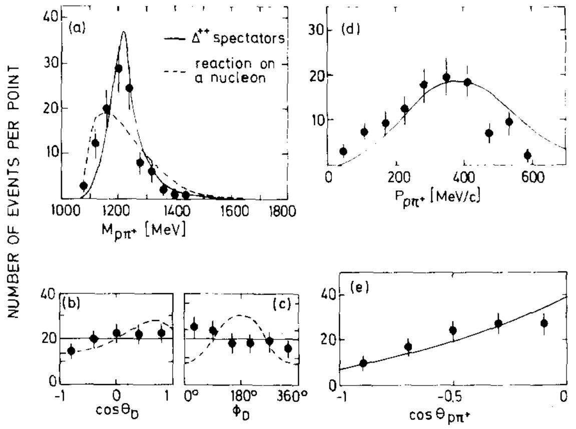

Fig. 3. (a) Effective mass distribution, (b) and (c) polar and azimuthal distributions of the π^+ in the $p\pi^+$ rest frame with respect to the incident photon direction in the laboratory system, (d) laboratory momentum distribution, and (e) laboratory production angular distribution with respect to the photon direction, for the backward moving $p\pi^+$ system of reaction (3) after spectator protons have been removed. The solid curves are the predictions for Δ spectators (fig. 1b), the dashed curves for the proton spectator process (fig. 1c), normalized to the experimental numbers.

metry; thus, these $p\pi^+$ systems were *not pure* Δ^{++} *states*. Indeed if the photon was absorbed by the neutron producing a slow π^+ in the laboratory, this can result, together with the spectator proton, in a low-mass backward moving $p\pi^+$ system (fig. 1c). This manifests itself clearly in a "ridge" in the correlation plot of momentum $P_{p\pi^+}$ versus mass $M_{p\pi^+}$, which arises because the spectator protons have relatively small laboratory momenta (fig. 2). A correlation of this kind must be absent for Δ^{++}.

To remove the proton spectator events (fig. 1c) we made a selection $P_p > 200$ MeV/c on the proton momenta. This cut, while only slightly reducing the phase space for genuine Δ^{++} decays, eliminates most of the spectator protons and indeed causes the ridge in fig. 2 to disappear. We have also refined this selection in the following way. We calculate the momentum distribution of the proton spectators from the deuteron wave function [10]; from the excess of the observed P_p distribution above 100 MeV/c over the calculated distribution, we then know for each P_p value the probability for the proton *not* to be a spectator, and can weigh the events with this probability. We thus obtain a sample of backward moving $p\pi^+$ systems with the spectator protons statistically removed, provided the spectators are distributed according to the deuteron wave function. We have checked that none of our results depends on the precise way in which we make this spectator cutoff. The sample of 100 events separated in this way was carefully checked for correct identification of the proton and pion, and for possible biases in scanning or measuring.

We show next that these $p\pi^+$ systems have properties characteristic of *decay products of the* $\Delta^{++}(1236)$. First of all, the distribution of their effective mass $M_{p\pi^+}$ has resonant shape, somewhat distorted towards lower mass (fig. 3a). Such a shape is predicted by the $d \to \Delta\Delta$ transition matrix element (fig. 1b), the distortion arising both from phase space effects and from the pole in the Δ^- propagator $(m_\Delta^2 - \mathrm{i}m_\Delta\Gamma_\Delta - t)^{-1}$ where $\sqrt{t}$ is the mass of the exchanged Δ^- (solid curve in fig. 3a). Another crucial test for the resonance interpretation makes use of the symmetry and complexity limitations of the decay angular distribution of the $p\pi^+$ system with $J^P = \frac{3}{2}^+$. As shown in figs. 3b and 3c, the angular distributions are in fact consistent with isotropy, i.e. with unpolarized Δ^{++} (solid lines). As a further test, we looked whether the effective mass $M_{p\pi^+}$ depended on the incident photon energy, or on the production or decay angles of the $p\pi^+$ system. All of the six correlations tested were below the 95% confidence level.

We now ask whether these supposedly resonant $p\pi^+$ systems can be Δ^{++} "*spectators*" as they would be expected to emerge after a $\gamma\Delta^-$ interaction with a virtual $\Delta^{++}\Delta^-$ state of the deuteron (fig. 1b). We make four checks.

(i) Momentum distribution: Neglecting spin effects, diagram 1b leads to a laboratory differential cross section‡ for reaction (1)

$$\frac{d^3\sigma}{dP^3_{\Delta^{++}}} = \sigma_{\gamma\Delta^-}(s)\left[1+\frac{P_{\Delta^{++}}\cos\theta_{\Delta^{++}}}{m_d-(P^2_{\Delta^{++}}+m^2_\Delta)^{1/2}}\right]$$

$$\times \tfrac{1}{2}\sum_{L,S} |\psi^{LS}_{\Delta\Delta}(P_{\Delta^{++}})|^2 \qquad (4)$$

Here, $\sigma_{\gamma\Delta^-}(s)$ is the total photon $\Delta^-(1236)$ cross section as a function of the square of the $\gamma\Delta^-$ cms energy $s=(p_\gamma+p_d-p_{\Delta^{++}})^2$. Our assumptions on $\sigma_{\gamma\Delta^-}(s)$ will be explained later; they do not critically influence the $P_{\Delta^{++}}$ distribution of eq. (4). The factor $\frac{1}{2}$ is the square of an isospin Clebsch-Gordan coefficient ($d\to\Delta^{++}\Delta^-$ and $d\to\Delta^+\Delta^0$ occur with equal probability). For the four $\Delta\Delta$ wave functions $\psi^{LS}_{\Delta\Delta}(P_\Delta)$ (^3S, ^3D, ^7D and ^7G) of the deuteron we use one-pion exchange wave functions [12] which probably are rather crude approximations. Nevertheless, we find reasonable qualitative agreement with the observed Δ^{++} momentum distribution (see solid curve in fig. 3d).

(ii) Production angular distribution: This is also predicted by eq. (4). Again, reasonable agreement is found with the data (see solid curve in fig. 3e).

(iii) Shape of the Δ^{++} mass spectrum (fig. 3a): This is quite close to the expectation for Δ^{++} spectators (solid curve) as already discussed.

(iv) Absence of correlations: No correlations are observed between the Δ^{++} momentum and production angle on the one hand, and the mass or decay angles of the Δ^{++} on the other, consistent with the spectator picture.

We thus have observed a sample of $p\pi^+$ systems moving backward in the laboratory system, with properties apparently consistent, within the rather large statistical uncertainties, with those expected for Δ^{++} "spectators" (i.e. the process of fig. 1b). If one takes the spectator picture seriously, one can determine from our data the probability

$$W_{\Delta\Delta} = \int \sum_{L,S} |\psi^{LS}_{\Delta\Delta}(P_\Delta)|^2 \, dP^3_\Delta \qquad (5)$$

for the deuteron to be in a $\Delta\Delta$ state. Our observed production cross section for backward moving Δ^{++}, averaged over the photon energy range from 1000 to 5300 MeV, is (0.5 ± 0.1) μb. For $\sigma_{\gamma\Delta^-}(s)$ in eq. (4) we use the quark model; for "high" energies ($\gtrsim$ 2 GeV) it predicts $\sigma_{\gamma\Delta^-}=\sigma_{\gamma n}=\sigma_{\gamma p}$ and since the second of these equalities is fulfilled within ~5% we have assumed the first one to be reasonably valid also. For small energies the quark model predicts M1 matrix element for $\gamma p\to\Delta^+$. Between the Δ region and 2 GeV, we use a smooth extrapolation of the high energy behaviour. One then obtains from eqs. (4) and (5) the result $W_{\Delta\Delta}=0.031$. Crude theoretical estimates for this probability, based on one-pion exchange forces and on the discrepancy of the deuteron magnetic moment with what is calculated on the basis of the pn wave function alone, range between about 0.01 and 0.05 [5].

Some caution, however, is necessary at this point. First of all, the momentum spectrum of the Δ^{++} extends up to 600 MeV/c, where the mass $\sqrt{t}$ of the off-shell Δ^- has dropped to zero and the spectator picture may not apply. This may be a cause for the discrepancy with the spectator model calculation at large $P_{p\pi^+}$, seen in fig. 3d. Even more seriously, could it be that our attempts to eliminate the background were insufficient, such that the observed spectator-like properties of the $p\pi^+$ systems were "faked" by some other process?

Consider first the possibility of production of the Δ^{++} on a nucleon in the deuteron (fig. 1a). This was rendered improbable by the selection of backward moving $p\pi^+$ systems for which eq. (2) applies. We have in fact computed, for each of the actually selected events, the minimum Fermi momentum that the absorbing nucleon must have had if the production mechanism was that of fig. 1a. This came out to be larger than 700 MeV/c for half of the events, and would require the occurrence of Fermi momenta above 700 MeV/c with > 5% probability. This seems to be very unlikely.

Could this kinematic criterium be bypassed through some more complicated double-scattering process, involving *both* nucleons of a nucleon-nucleon

‡ Taking the Δ^- to its mass shell this formula approaches the usual pole expression of relativistic perturbation theory while its off-shell behaviour is determined by the relativistic spectator picture. See ref. [11].

state of the deuteron? To answer this question we note that there are two classes of such double scattering processes, according to whether the observed Δ^{++} came from the first or from the second interaction. In the first case we have the general class of diagrams of fig. 1d; this is nothing else than the process 1a with a final state interaction between reaction products other than the Δ^{++}, and therefore is subject to the same kinematic conditions on the Fermi momentum. In the second case we have diagrams like 1e, f and g which belong to the general class of diagrams 1h where M is a mesonic system. Since the t channel has Δ^- quantum numbers, it will for the t range of our experiment be dominated by the $\Delta^-(1236)$ and thus the leading term of diagram 1h will be subsumed under diagram 1b. In other words, one would double-count did one regard diagrams 1e-h as distinct from the $d \to \Delta\Delta$ transition diagram 1b. In particular, diagram 1f which is the resonant final-state interaction correction to 1c, is in its leading t-channel contribution dual to the one-pion exchange term from the $d \to \Delta\Delta$ vertex function.

This leaves the possibility, already discussed above, of a π^+ photoproduced on the neutron combining with a spectator proton into a *non*-resonant $p\pi^+$ system that fakes a backward going Δ^{++} (fig. 1c)[‡]. If the high momentum tail of the spectator momentum distribution is considerably larger than predicted from conventional deuteron wave functions [10], our selection procedure as described above may have been insufficient to eliminate such background. In order to study the properties of this possible background, we have used our measured events of the reaction $\gamma p \to \pi^- +$ anything from a previous experiment [13], transforming the π^- momenta into coordinate systems where the target protons have Fermi momenta distributed as given by a deuteron wave function with an exaggerated high momentum tail; we then added the corresponding spectator neutrons, thus constructing fake events of the process $\gamma d \to n_{spec}\pi^- +$ anything which is charge-symmetric to the process of fig. 1c. The faked "Δ" mass and decay angular distributions are shown as dashed curves in figs. 3a, b and c for the same event selection criteria as applied to the real events. The measured $p\pi^+$ distributions do not agree well with these faked background distributions; thus for the decay angular distributions the χ^2 is 29.7 for 9 degrees of freedom, which corresponds to a confidence level of 5×10^{-4}. This is connected with the fact that, as one expects, the background process is strongly at variance with the symmetry properties of resonance decay. Our data therefore do not support the explanation that what seem to be Δ^{++} spectators are in reality non-resonant $p\pi^+$ systems involving spectator protons (diagram 1c); nevertheless we cannot strictly exclude this possibility, since in the determination of this background possible off-shell effects of the target neutron as well as isoscalar-isovector interference effects are neglected. Neither can we base a rigorous argument on the observed large proportion of proton momenta above 300 MeV/c, because the spectator proton momentum distribution from diagram 1c could have been distorted by a secondary interaction of the proton.

In summary, our observations are consistent with, and most easily explained by, the interpretation of the recoiling $p\pi^+$ systems as $\Delta^{++}(1236)$ spectator particles preexisting in the deuteron (diagram 1b). The alternative possibility, that the observed $p\pi^+$ systems are non-resonant and produced from the ordinary nucleon-nucleon configuration of the deuteron (diagram 1c), cannot be rigorously excluded but is shown to be less likely. We suggest that accumulation of further similar evidence could establish the resonant nature of the $p\pi^+$ systems beyond doubt and thus resolve the issue. If the existence of Δ's in nuclei is thus confirmed, this may have important consequences in many aspects of nuclear physics.

[‡] If final-state interactions lead to a *resonant* $p\pi^+$ system, we obtain diagram 1f which has just been discussed.

We thank the authors of ref. [11] for their collaboration in the measurements, and acknowledge a useful discussion with E. Rössle.

References

[1] A. Kerman and L. Kisslinger, Phys. Rev. 180 (1969) 1483.
[2] L. Kisslinger, Phys. Lett. 29B (1969) 211.
[3] H. Primakoff and S.P. Rosen, Phys. Rev. 184 (1969) 1925.
[4] H. Arenhövel and M. Danos, Phys. Lett. 28B (1968) 299.
[5] H. Arenhövel, M. Danos and H.T. Williams, Nucl. Phys. A162 (1971) 12; Phys. Lett. 31B (1970) 109.
[6] J. Blomquist, Phys. Lett. 32B (1970) 1.

[7] D.O. Riska and G.E. Brown, Phys. Lett. 32B (1970) 662.
[8] H.T. Williams, H. Arenhövel and H.G. Miller, Phys. Lett. 36B (1971) 278.
[9] M. Goldhaber, Proc. Intern. Conf. on Nuclear physics eds. De Boer and Mang, Munich 1973, Vol. 2 p. 14.
[10] C. Michel and C. Wilkin, Nucl. Phys. B11 (1969) 99.
[11] P. Benz et al., Aachen-Bonn-Hamburg-Heidelberg-München Collaboration, Nucl. Phys. B65 (1973) 158.
[12] N.R. Nath and H.J. Weber, Phys. Rev. D6 (1972) 1975.
[13] Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Phys. Rev. 175 (1968) 1669.