Search for Evidence of a $\Delta(1236)$-$\Delta(1236)$ Component of the Deuteron*

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Evidence for a bound $\Delta_{33}(1236)$-$\Delta_{33}(1236)$ component of the deuteron is sought by using π^+, π^-, and K^+ mesons as probes of nuclear structure. Events are observed which might contain $\Delta(1236)$ "spectators" in the breakup of a deuteron in a $\Delta\Delta$ state. However, other mechanisms may contribute to the signal, and we cannot unambiguously ascribe our events to a $\Delta\Delta$ contribution in the deuteron. With certain assumptions we obtain an upper limit of $\sim 0.7\%$ for the $\Delta\Delta$ component of the deuteron.

It has been known for some time that the conventional nuclear theory which assumes nuclei to be composed of weakly bound protons and neutrons has some small but persistent discrepancies with experiments. It has been suggested[1] that these inconsistencies may be explained by the presence of nucleon isobar components in the nuclear wave function. Kerman and Kisslinger[2] have proposed such a model to explain the large backward "pick-up" peak in pd scattering.

We have searched[3] for direct evidence of a $\Delta\Delta$ component of the deuteron wave function (note: an $N\Delta$ component is forbidden by isospin) by looking for the process diagrammed in Fig. 1(a). In this model, a beam meson (m) scatters "elastically" on a virtual Δ^- from a deuteron in a $\Delta^{++}\Delta^-$ bound state. If the impulse approximation is qualitatively valid, this yields a "spectator" $\Delta^{++}(\Delta_s^{++})$ on breakup. For a discussion of this point see

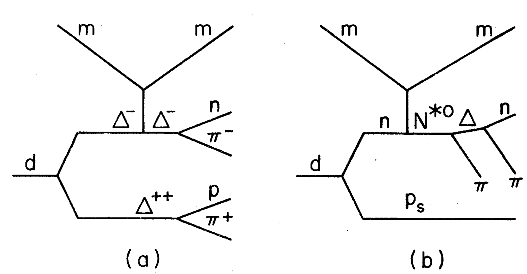

FIG. 1. Diagrams for (a) $\Delta\Delta$ model, and (b) N^* model.

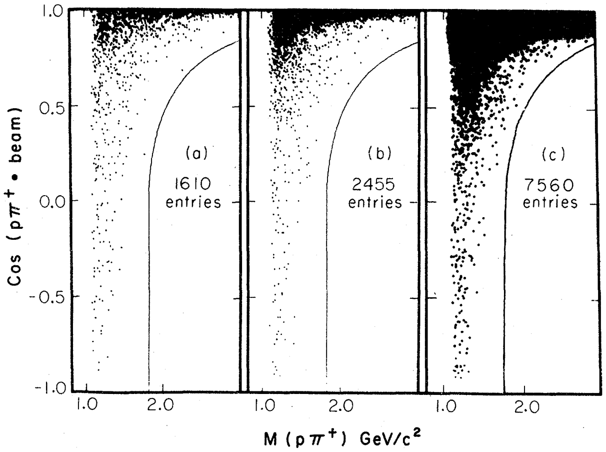

FIG. 2. $M(p\pi^+)$ versus $\cos(p\pi^+, \text{beam})$ in the lab for $md \to m\pi^+\pi^- pn$, where m is (a) π^+, (b) π^-, (c) K^+. Curves show kinematic boundaries.

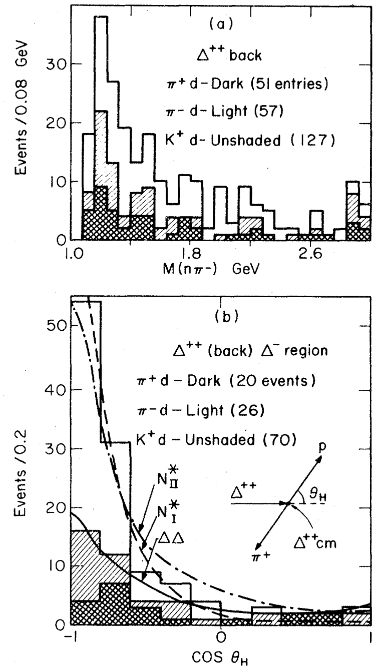

FIG. 3. Sum of the data from the $m\pi^+\pi^- pn$ channel of all three experiments: (a) $M(\pi^- n)$ for events with $p\pi^+$ in backward Δ^{++} region. (b) $\cos\theta_H(p\pi^+) = \hat{p}\cdot\hat{v}$, where $\hat{p}$ is the proton direction in the $p\pi^+$ rest frame and $\hat{v}$ is the direction of the $p\pi^+$ combination in the lab frame, for events in the Δ^{++}(back)Δ^- region. The N^* model curves (broken) are normalized to $\cos\theta_H < 0$; N_I^* uses the pure Hulthén spectrum, N_{II}^* uses the modified spectator proton spectrum. The $\Delta\Delta$ model curve (solid) is normalized to $\cos\theta_H > 0$.

Ref. 2. We use the presence of $n\pi^-$ and $p\pi^+$ combinations simultaneously in the Δ mass region [defined here as $M(N\pi) < 1360$ MeV], with the $p\pi^+$ combination backward in the laboratory frame, as the signature of this process. We estimate background from competing processes to be less serious for this case than for other $\Delta\Delta$ states available to this experiment.

The channel $md \to m\pi^+\pi^- pn$ (with visible proton), where m is the beam meson, has been studied in three independent experiments performed with the Stanford Linear Accelerator Center 82-in. deuterium-filled bubble chamber: 15-GeV/c π^+ (350 000 photos analyzed by Florida State University-University of Pennsylvania), 15-GeV/c π^- (500 000 photos, University of California, Berkeley-University of Washington, Seattle), and 12-GeV/c K^+ (500 000 photos, Lawrence Berkeley Laboratory–California Institute of Technology). Channel ambiguities are reduced by cuts on missing mass, confidence level, fits to alternative channels, and ionization-density measurements of positive tracks, as appropriate for each experiment. Proton-π^+ identification ambiguities are small for backward-going $\pi^+ p$ combinations.

Evidence for $\Delta\Delta$ *events.*—Figure 2 shows the cosine of the laboratory angle between the momentum vectors of the $\pi^+ p$ combination and the beam (with no restriction on masses) versus the $\pi^+ p$ mass. We observe events in the backward hemisphere ($\cos\theta < 0$) in the Δ mass region.

The combined $\pi^- n$ mass distribution for events with a backward Δ^{++} candidate is shown in Fig. 3(a). A peak in the Δ^- mass region suggests that the $n\pi^-$ combination is a Δ resonance a substantial fraction of the time. Table I lists the numbers of events found.

Backgrounds.—Nucleon dissociation into $\Delta\pi$ states (here referred to as N^*'s, even though not necessarily resonant), well known in hydrogen and deuterium data,[4] is probably the major background for the Δ^{++}(back)Δ^- signal. We have cal-

TABLE I. Results for the reaction $md \to m\pi^+\pi^- pn$; $m = \pi^+, \pi^-, K^+$.

	$\pi^+ d$	$\pi^- d$	$K^+ d$
Total events	1809	3474	12693
Δ^{++}(back)	56	48	132
Δ^{++}(back)Δ^-	20	26	73
$\sigma(\Delta\Delta_s)$ (mb)	0.04[a]	0.03[a]	0.06[a]
R (%)	0.6[b]	0.5[b]	1.3[b]

[a]Upper limit, statistical error $\lesssim 0.01$ mb.
[b]Upper limit, statistical error $\lesssim \pm 0.15$ (see Ref. 10).

culated[5] the expected shape using the model of Fig. 1(b) assuming the same mass, width, and momentum-transfer distributions found in hydrogen data at similar energies.[4] Two different "spectator" proton momentum spectra are used in the impulse approximation. One is based entirely on the Hulthén wave function; the other modifies this spectrum above 200 MeV/c to resemble the backward proton spectrum from the $K^+d \to K^0pp$ ($K^0 \to \pi^+\pi^-$) reaction of the K^+ experiment, in attempt to include contributions in the high-momentum region from double scattering and possible inadequacies of the Hulthén wave function. In the K^0pp channel contamination from other reactions is quite small, and isobar terms in the deuteron wave function are not expected to contribute significantly to the spectator spectrum.

This model gives a backward $p\pi^+$ mass distribution in good agreement with the data. Further evidence for an N^*-model contribution is the asymmetry of the decay angular distribution of the backward Δ^{++} candidate, Fig. 3(b). The forward component of this angular distribution is in poor agreement with the N^* model using the pure Hulthén spectrum (curve labelled $N_{\rm I}^*$) but consistent with the model using the modified spectrum ($N_{\rm II}^*$).

In the $\Delta\Delta$ model (solid curve) this distribution is expected to show forward-backward symmetry if the Δ^{++} does not decay until leaving the interaction region. The spectator Δ^{++}, generated by using the $d(\Delta\Delta)$ wave functions according to Kisslinger[7] (neglecting double scattering), was given a $1+3\cos^2\theta_H$ decay angular distribution. The result is insensitive to the details of $m\Delta$ elastic scattering. Events with nonstopping protons are lost in the π^+d and K^+d data; simulation of this loss (done for all models) results in the asymmetry of this curve. This effect alone is not adequate to explain the observed asymmetry and N^* contribution is needed.

Within the approximations, we cannot distinguish the contributions of the $\Delta\Delta$ model and the N^* model with the modified Hulthén spectrum. Basing this calculation on the K^0pp data, while probably an improvement over a pure Hulthén spectrum, neglects final-state interactions (other than those in the K^0pp channel) and possible significant variation with channel of double-scattering contributions. In addition, the impulse approximation may not be adequate in the region of large ($\gtrsim 300$ MeV/c) spectator momenta, where the greatest sensitivity to differences between the models may lie.

Probability of $d(\Delta\Delta)$.—If we assume that the cross section for off-mass-shell $m\Delta$ elastic scattering leading to deuteron breakup is equal to the mN elastic cross section[8] (leading to breakup), then the ratio $R = \sigma(md \to \Delta\Delta_s)/\sigma(md \to mpn)$ is a rough estimate of the $\Delta\Delta$ fraction of the deuteron.

The cross sections $\sigma(md \to mpn)$ are not measured but may be estimated by using Glauber theory.[9] We find for $\sigma(\pi^\pm d \to \pi^\pm pn)$ at 15 GeV/c and $\sigma(K^+d \to K^+pn)$ at 12 GeV/c the estimates 6.8 ± 0.6 mb and 4.8 ± 0.5 mb, respectively. We obtain an *upper limit* to $\sigma(md \to m\Delta\Delta_s)$ by counting *all* the Δ^{++}(back)Δ^- candidate events. Correcting this number by factors of (i) 2 for the probability that Δ^- is the spectator, (ii) 3 for the approximate probability that the spectator travels forward,[2] (iii) 2 for the equal probability of $d(\Delta^+\Delta^0)$ and $d(\Delta^{++}\Delta^-)$, and (iv) 1.2 for nonstopping proton events lost in π^+d and K^+d—loss of protons too short to be seen is neglected (based on the $\Delta\Delta$ model)—we obtain the upper limits shown in Table I. A statistically weighted average gives $R < (0.7 \pm 0.1)\%$.[10]

Neglecting final-state interactions and interference between the N^* and $\Delta\Delta$ models, we obtain a more restrictive upper limit to R by integrating under the (properly symmetrized) $\Delta\Delta$ curve of Fig. 3(b) (which was normalized to $\cos\theta_H > 0$). This more model-dependent limit is ~60% of the above limit for R, with the difference possibly due to the N^* contribution. It is probable that the N^* background relative to $\Delta\Delta$ production varies with the bombarding particle. Our results are compatible with theory.[7] The "spectator" method, with further refinements, may prove valuable in other situations where possible isobar effects may be more easily distinguished.

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[10]Uncertainties in microbarn equivalents and in $\sigma(md \rightarrow mpn)$ give systematic errors of ~±0.2.

Nuclear-Coulomb Interference in Inelastic Scattering of α Particles from ^{168}Er, ^{184}W, and ^{186}W†

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Excitation functions for the 0^+, 2^+, and 4^+ states of ^{168}Er, ^{184}W, and ^{186}W were measured at 140° and 173.5° with incident α-particle energies between 12.5 and 19 MeV. Strong destructive nuclear-Coulomb interference effects were observed. A coupled-channels code was developed and the deformation parameters β_2^N and β_4^N of the optical potential were determined and are compared with those of the charge distribution, β_2^c and β_4^c.

In recent years systematic experimental information has been accumulated concerning quadrupole and hexadecapole deformations in the rare-earth region using two different methods, i.e., Coulomb excitation by means of α particles[1-4] and inelastic scattering of α particles well above the Coulomb barrier.[5,6] From Coulomb excitation experiments it is possible, after making some reasonable model assumptions, to extract deformation parameters β_2^c and β_4^c for the *charge* distribution. Experiments far above the barrier, on the other hand, yield the deformation parameters of the optical potential. Early comparisons between the two types of experiments seemed to indicate that the deformation parameters obtained from high-energy (α, α') scattering were substantially smaller than those obtained by electromagnetic methods. This difference may, in principle, be attributed to one or both of two reasons:

(1) There is no *a priori* reason why the electric charge distribution and the optical potential need to have *exactly* the same deformation parameters, though one would certainly expect them not to be too different.

(2) It is well known that the quantities determined by inelastic scattering are not the β_λ's rather something like a deformation length $\beta_\lambda R$,[7] where R is the nuclear radius. The extraction of β_λ's from electromagnetic moments, on the other hand, depends critically (approximately like $R^{-\lambda}$) on the radius parameter chosen for the charge distribution. Thus some care must be exercised in comparing β_λ's obtained by these two different classes of experiments.

The question of the connection between the deformation of the charge distribution and that of the optical potential is an intriguing one. We expected experiments in the interference region between Coulomb and nuclear excitation to be most sensitive to possible differences or equalities in the two types of deformation parameters. Experiments were carried out at laboratory scattering angles of 140° and 173.5° in the energy range from 12 to 19 MeV on the isotopes ^{168}Er, ^{184}W, and ^{186}W. The experimental setup was similar to that used in earlier work of our group.[2] Its salient features are an annular surface-barrier detector at 173.5°, two surface-barrier detectors at ±140°, and another pair of detectors at ±30° which served as monitors. All detectors were cooled to