# Evidence for a Dibaryon Signal in the Measurement of Elastic $\pi^+$-$d_{pol}$ Scattering

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The vector analyzing power ($iT_{11}$) in elastic $\pi$-$d_{pol}$ scattering has been measured for several angles at $T_\pi$ = 142 and 256 MeV. The results are compared with calculations reported in the literature. At the lower energies, Faddeev calculations agree fairly well with the data. At the higher energies, the experimental results differ markedly from any conventional calculation, but agree surprisingly well with predictions in which effects of dibaryon resonances are explicitly included.

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The two-nucleon system—the possibility of resonances in this system in particular—has recently been the subject of intense investigation. The measurement of $p$-$p$ total cross sections with both polarized proton beams and targets was the first experiment which showed some hint of possible dibaryon resonances.[1] Several phase-shift analyses[2] and a dispersion-relation analysis[3] have been made of these data in which the possible existence of dibaryons was investigated but the conclusions have remained controversial.[4] An anomalous structure in the proton polarization from deuteron photodisintegration has also been reported[5] but the detailed assignment of dibaryon quantum numbers to explain these anomalies remains less than conclusive. A measurement of $\Delta\sigma_L(pd)$ recently gave evidence for structure in the isospin-0 channel.[6]

Since these suspected dibaryon resonances in the $p$-$p$ channel have large inelasticities, there must be a considerable coupling into the $\pi$-$d$ and $\pi$-$np$ channels. The $\pi$-$d$ channel is particularly useful since it is the only channel where at present the "background" amplitude can be calculated with sufficient confidence to study the effects of dibaryon resonance admixtures. The differential cross sections for the elastic $\pi^+$-$d$ scattering at intermediate energies have been measured very precisely by Gabathuler *et al.*[7] A remarkable feature of these cross-section data is the deep minimum in the angular distribution at 256 MeV incident pion energy, which so far has not been reproduced by even the most sophisticated Faddeev calculations[8-10] which include all $S$ and $P$ pion-nucleon partial waves, the effect of intermediate $\pi$ absorption, and a realistic deuteron wave function. Therefore, it is suspected that some essential ingredient in the $\pi$-$d$ reaction dynamics is still missing. A phase-shift analysis of the $\pi^+$-$d$ cross sections[11] showed counterclockwise Argand loops for $J_\pi = 2^+$ and $3^-$ amplitudes at energies corresponding to possible $^1D_2$ and $^3F_3$ dibaryons but in this analysis there exists no possibility to separate the effects of $\Delta$-$N$ interactions from real resonances. Kanai *et al.*[12] have proposed that the deficiencies in reproducing the large-angle cross-section data above the (3, 3) resonance can be removed if the effects of dibaryon resonances are included. In the differential cross section, however, the dibaryon signals are appreciable only in the backward hemisphere, where the use of the Glauber model with exponentially falling $\pi N$ amplitudes remains a doubtful prescription. Kubodera *et al.*[13] have investigated the interference of dibaryon resonances with Faddeev amplitudes for elastic $\pi^+$-$d$ scattering. While only relatively small effects were observed for the differential cross sections, strong dibaryon signals were predicted for the various polarization observables.

In this experiment the vector analyzing power defined as

$$iT_{11} = \frac{\sqrt{3}}{2}\,\frac{1}{P}\left(\frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}\right),$$

where the subscript $\uparrow$ indicates the direction of $\vec{k}\times\vec{k}'$, $\vec{k}$ is the incident-pion momentum, and $\vec{k}'$ is the scattered-pion momentum, was determined by measuring the differential cross sections $\sigma_\uparrow$ and $\sigma_\downarrow$ of elastic $\pi^+$-$d_{\rm pol}$ scattering for the two spin states of a vector polarized deuterium target of polarization $P$. In such an experiment the kinematics of elastic $\pi$-$d$ scattering must be accurately established in order to separate the background produced by pions interacting with the other nuclei in the target. For this reason the experiment was performed at the high-resolution pion beam and spectrometer facility at the Swiss Institute of Nuclear Research [Schweizerisches Institut für Nuklearforschung (SIN)]. The details of this facility are described by Albanese *et al.*[14] The incident pion beam was defined by scintillation counters which limited the target spot size to $10\times 10$ mm$^2$. These beam-defining counters were aligned to $\pm 0.2$ mm to ensure that only the central region of the polarized target cell was illuminated. The $p$, $\mu$, and $e$ contamination in the beam were removed by an electrostatic separator, pulse-height discrimination, and time-of-flight measurement. The effect of different beam intensities was studied by varying the opening of the beam-line slits; no change in the differential cross section was measured. The incident-beam normalization was also found to scale linearly to a monitor counter below the target. The influence of the target magnetic field of 2.5 T on the counters in the vicinity of the target was checked and suppressed by the use of long light pipes and magnetic shielding on the photomultipliers.

The polarized deuteron target was modified from the standard polarized proton target at SIN. A detailed description of these proton targets is given by Amsler.[15] The target was $18\times 18$ mm$^2$ in cross section and was 5 mm thick. The positioning of the scattering cell within the cryostat was checked by taking x-ray pictures. The target material was 95% perdeuterated $n$-butanol (98% atomic purity) and 5% deuterium oxide, doped with about 1% porphyrexide by weight. The deuterons were polarized dynamically in a magnetic field of 2.5 T at a temperature of ~ 0.5 K. The rf power was provided by two solid-state oscillators (one for positive and one for negative polarization) which were coupled by a rf switch to the single waveguide which fed the target cell. The deuteron polarization was measured by NMR methods with use of a fast-sweep $Q$ meter and a signal averager. The polarization value has been determined by calibration with respect to the thermal-equilibrium signal at $T = 0.46$ K and checked against the asymmetry of the enhanced polarized-deuteron resonance signal. This normalization was the most significant contribution to the uncertainty of the polarization measurement, which was measured with a relative accuracy of $\pm 10\%$. In a separate experiment the homogeneity of the target polarization over the target volume has been confirmed. The NMR signal was recorded every 5 min during the experiment and was written onto tape along with the pion-event data. By this frequent monitoring of the polarization signal it was possible to confirm that the liquid $^3$He had not evaporated as a result of too much microwave power. All important target parameters were recorded repeatedly. The vector polarization of the target was typically $16\% \pm 1.6\%$. The "contamination" of the vector polarization with tensor components amounted to less than 1.6%, which results in an insignificant correction to the measurement of $iT_{11}$.

The scattered pions were detected by the pion spectrometer within an acceptance angle of 9°, which could be divided into smaller angular bins. As described by Albanese *et al.*,[14] the data are collected as energy-loss spectra. As is shown in the upper part of Fig. 1, at forward angles a prominent elastic $\pi^+$-$d$ peak is observed in the spectra on top of a background from inelastic processes from the other target nuclei. At larger scattering angles the recoil deuteron was detected in coincidence with the pion by using a thin scintillator followed by an absorber (adjusted for the deuteron range) and veto counter. This recoil detector greatly reduced the background un-

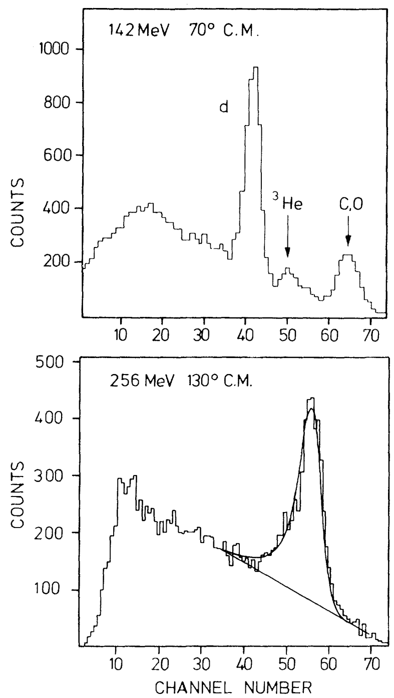


FIG. 1. Upper part, energy-loss spectra at forward angles without detection of the recoil deuteron; lower part, with the recoil deuteron in coincidence.

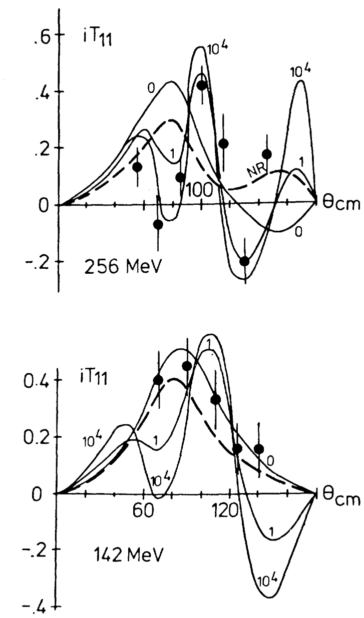


FIG. 2. Vector analyzing power in elastic $\pi^+$-$d_{\rm pol}$ scattering at $T_\pi = 142$ and 256 MeV. The theoretical curves are described in the text.

der the $\pi^+$-$d$ peak (lower part of Fig. 1). The consistency of the measurements with and without the recoil detector was demonstrated by turning off the recoil requirement in the software.

In order to reliably extract the number of counts in the elastic $\pi^+$-$d$ peaks from the background in the spectra the peaks were systematically fitted by skewed Gaussian line shapes; the smooth background was simultaneously fitted by a polynomial. The fitting procedure was compared to a variety of other methods and the results were consistent. The background under and next to the elastic $\pi^+$-$d$ peak was investigated by replacing the deuterated butanol by normal butanol and also by comparing background runs with and without liquid $^3$He in the target cell. These studies indicated there was no structure in the background under the elastic $\pi^+$-$d$ peak. The final uncertainties in the data include the statistical errors of the $\pi^+$-$d$ peaks, the statistical uncertainties of the background subtractions, the uncertainties resulting from the least-square fits and the errors in measuring the target polarizations.

Numerous consistency checks and various diagnostic measurements were performed. These checks were necessary in order to assure ourselves of the reproducibility of the data. In the course of the experiment, consistency has been obtained between runs with different target cells (copper versus Teflon) and different butanol targets. The reproducibility was also established by taking data for a specific angle with positive and negative polarizations in an alternating sequence. The average of the spin-up and spin-down cross sections was determined and it was found to agree with the cross sections from Ref. 7 within the uncertainty of knowing the target density in the polarized target.

The results obtained for $\theta_{\rm c.m.} = 70°$, 90°, 110°, 125°, and 140° at $T_\pi = 142$ MeV and for $\theta_{\rm c.m.} = 55°$, 70°, 85°, 100°, 115°, 130°, and 145° at $T_\pi = 256$ MeV are shown in Fig. 2. The curves shown in this figure are the predictions of Kubodera *et al.*[13] The dashed curves are the result of Faddeev calculations in which no dibaryon resonances are included. The solid curves are produced by including the $^1D_2(2140)$ resonance at $T_\pi = 155$ MeV, the $^3F_3(2220)$ at $T_\pi = 245$ MeV, and the $^1G_4$ or $^1S_0(2430)$ at $T_\pi = 415$ MeV. The dibaryon of a given $J$ couples to two pion angular-momentum states in the $\pi$-$d$ channel: $l_\pi = J \pm 1$. The various solid curves are labeled by the mixing parameter $\epsilon$ (the value $\epsilon = 10^4$ corresponds to a pure $l_\pi = J+1$ coupling and $\epsilon = 0$ corresponds to $l_\pi = J-1$). For a given resonance, the $\epsilon$ parameter is a characteristic constant. At the lower energy the results are compatible with the Faddeev calculation, but also with a mixing parameter $\epsilon = 0$. However, at the higher energy, none of the conventional theories[8,9,16] agrees even qualitatively with the structure of the data. The oscillatory behavior is surprisingly well reproduced by the predictions of Ref. 13 in which effects of dibaryon resonances are explicitly included (the experiment favors $l_\pi = 4$). We consider this as a strong indication for the presence of at least one dibaryon resonance in the $\pi$-$d$ channel with a strength compatible with the parameters of Ref. 13. Independent of the details of the model the very observation of strong oscillations is a direct indication of a strong contribution from a higher partial wave interfering with the background.

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# Correction to $Z_P/Z_T$ Expansions for Electron Capture

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For highly asymmetric electron-capture collisions, the ratio of the small charge $Z_P$, here taken to be that of the projectile, to the large charge of the target $Z_T$ forms the natural expansion parameter. Previous treatments with use of $Z_P/Z_T$ expansions obtain the impulse approximation which is shown to err by unknowingly neglecting terms of order $(Z_T/v)^2$; a simple correction factor in the limit of small $Z_P/v$ is derived.

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Electron capture in ion-atom collisions over a broad range of energies has proven to be difficult to treat theoretically. Fragmentary results, mainly at low velocities in nearly symmetric collisions where a molecular representation provides an adequate framework[1] and at asymptotically high velocities where the Thomas double-collision mechanism dominates,[2] exist but no comprehensive picture has emerged. Much recent research[3,4] attempts to define closely the importance of second Born terms, which describe the Thomas mechanism but may have broader significance. For highly asymmetric collisions, such as charge transfer from inner shells of atoms of

 