Isobar Production in the Reaction $\pi^- + n \rightarrow p + \pi^- + \pi^-$ at 2.26 GeV/c *

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A baryon resonance of mass 1667 ± 5 MeV/c^2 is produced in the reaction $\pi^- d \rightarrow pp\pi^-\pi^-$ at 2.26 GeV/c in a non-t-channel process. Its properties and production mechanism are discussed. The branching ratio for its decay was found to be $\Delta\pi/N\pi < 0.11$.

REPORTED here are the results of a study of isobar production in the reaction

$$\pi^- n(p_s) \rightarrow (p_s) p\pi^-\pi^- \quad (1)$$

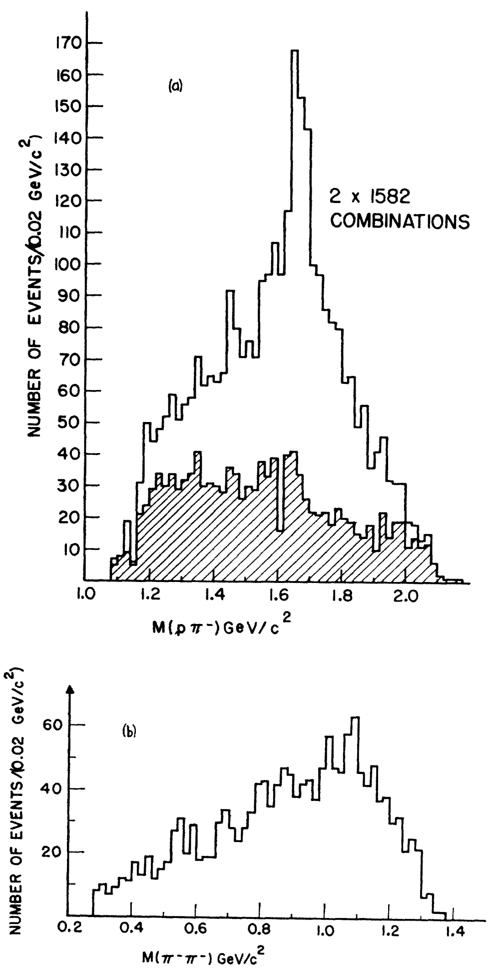

FIG. 1. (a) Effective mass of $\pi^- p$. Shaded region represents events with 4-momentum transfer from neutron to $p\pi^-$ system less than 0.6 (GeV/c)^2. (b) Effective mass of the $\pi^-\pi^-$ system.

produced by 2.26-GeV/c π^- mesons in the 72-in. LRL bubble chamber filled with deuterium; (p_s) denotes the spectator proton. In this analysis, only events for which the spectator proton was too small to produce a measurable track were used.[1] The LRL geometrical reconstruction and fitting program SIOUX (combined TVGP and SQUAW) was used. The distribution of the χ^2 probabilities for fits to reaction (1) showed an excess of events below 0.04. We therefore required a χ^2 probability greater than 0.04. A total of 1582 events was selected in this way.

The effective-mass distribution of the $p\pi^-$ system is shown in Fig. 1(a). The distribution is dominated by a

TABLE I. Characteristics of the 1670-MeV/c^2 peak produced in $\pi^- n$ and $\pi^+ p$ experiments.

Reaction	Beam momentum (GeV/c)	$E_{\text{c.m.}}$ (GeV)	Mass (GeV/c^2)	Width (GeV/c^2)	Cross section (μb)
(2)	1.59[a]	1.97	···	···	470 ± 50
(2)	2.0[b]	2.16	1668 ± 13	168 ± 35	775 ± 95
(1)	2.26 (this expt)	2.27	1667 ± 5	105 ± 16	930 ± 110
(2)	2.34[c]	2.30	1681 ± 14	109 ± 32	320 ± 100
(2)	2.75[d]	2.42			530[e]
(2)	···[f]				

[a] Reference 3.
[b] Reference 4.
[c] Reference 5.
[d] Reference 6.
[e] Calculated from data in Ref. 6.
[f] Indications of the peak were reported at 2.77 and 4 GeV/c but no details were given (Ref. 7).

peak in the region of 1670 MeV/c^2, which does not appear to be caused by any unusual structure in the $\pi^-\pi^-$ system [Fig. 1(b)]. (The $\pi^-\pi^-$ system will be the subject of a separate study.) We fitted this distribution with a Breit-Wigner resonance plus phase-space background and determined the following parameters for the peak: mass 1667 ± 5 MeV/c^2, width 105 ± 16 MeV/c^2 (after correcting for the measurement resolution of 25 MeV); it was found that $(40 \pm 4)\%$ of the events in the channel was contained in the peak. If we assume that the 1582 events used for this analysis

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[1] The four-prong events in this film were analyzed earlier as part of a search for $T=2$ boson resonances: J. Vander Velde, V. G. Lind, E. Marquit, B. Roe, and M. L. Good, Bull. Am. Phys. Soc. **9**, 679 (1960).

correspond to a cross section of 2.38±0.14 mb found by Alff-Steinberger *et al.*[2] for the charge-conjugate reaction

$$\pi^+ p \rightarrow n\pi^+\pi^+ \qquad (2)$$

at 2.35 GeV/c, we find a production cross section of 930±110 μb. This result must be considered approximate, insofar as it does not reflect differences arising from the use of the deuteron as a source of target neutrons.

Although this enhancement has been observed by other workers[3–7] (see Table I), little attention has been paid to establishing the identity of the isobar (or isobars) responsible for it. Partial-wave analyses[8] have yielded the following resonances in this mass region: $S_{31}(1630)$, $D_{33}(1670)$, $P_{33}(1690)$, $D_{15}(1675)$, $F_{15}(1690)$, and $S_{11}(1715)$. The question of identification is of particular importance because the peak is not associated with a t-channel process[5,6] and yet is produced

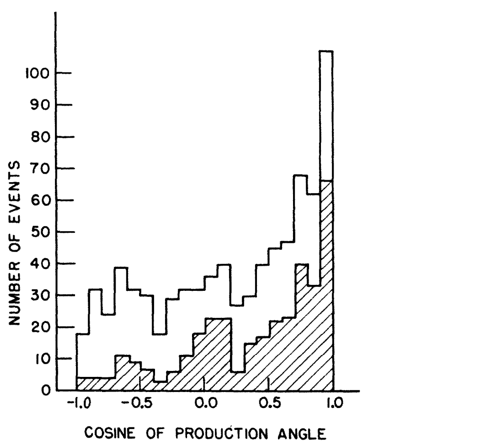

FIG. 2. Cosine distribution for angle between $p\pi^-$ system and incoming π^- in $p\pi^-\pi^-$ c.m. for $1620<M(p\pi^-)<1740$ MeV/c^2. Shaded region represents distribution with estimated background subtracted.

with a very large cross section. The non-t-channel nature of the production process is demonstrated by the fact that the enhancement in the effective-mass distribution primarily involves events for which the four-momentum transfer from the target neutron to the

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[6] SACLAY-ORSAY-BARI-BOLOGNA Collaboration, Nuovo Cimento **37**, 361 (1965).

[7] S. S. Yamamoto and D. C. Rahm, Phys. Rev. **173**, 1303 (1968); British-German Collaboration, *ibid.* **138**, 897 (1965).

[8] A. Donnachie, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN, Geneva, 1968), p. 143.

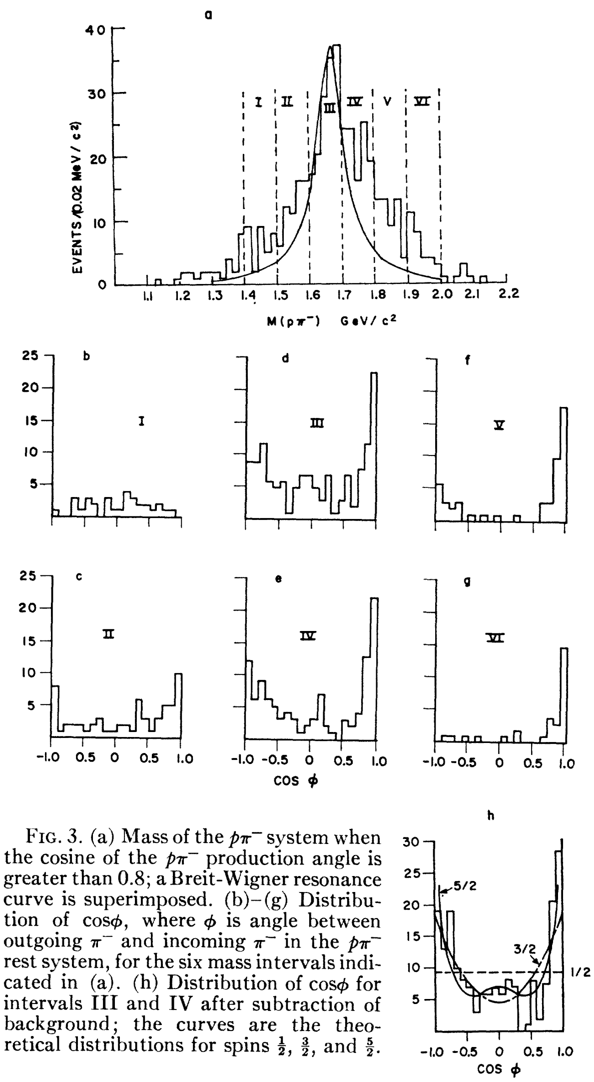

FIG. 3. (a) Mass of the $p\pi^-$ system when the cosine of the $p\pi^-$ production angle is greater than 0.8; a Breit-Wigner resonance curve is superimposed. (b)–(g) Distribution of $\cos\phi$, where ϕ is angle between outgoing π^- and incoming π^- in the $p\pi^-$ rest system, for the six mass intervals indicated in (a). (h) Distribution of $\cos\phi$ for intervals III and IV after subtraction of background; the curves are the theoretical distributions for spins $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$.

$p\pi^-$ system is greater than 0.6 (GeV/c)^2 [see Fig. 1(a)]. From Fig. 2 we see that the $p\pi^-$ system in the region of the peak is emitted preferentially forward at small c.m. angles relative to the beam direction, which allows us to obtain information on the spin from an Adair analysis.

To obtain information on the spin from the distribution of the decay angle ϕ, we will have to take into account the contribution of background; here ϕ is the angle made by the π^- from the decay relative to the incident π^- in the $p\pi^-$ rest system. Figure 3(a) shows the $p\pi^-$ mass distribution for production angles with $\cos\theta>0.8$. The decay-angle distributions for six mass intervals, 100 MeV/c^2 wide, are shown in Figs. 3(b)–3(g).

A rough estimate of nonresonant background can be obtained by comparing the mass distribution of Fig. 3(a) with a Breit-Wigner curve for a resonance of mass and width 1667 and 105 MeV/c^2; the height was chosen to match the peak of the histogram. From Figs. 3(b)–3(g) it appears that on the low-mass side of the resonance, the background is essentially flat and contributes approximately 1.5 events per $\cos\phi$ bin of 0.1. On the high-mass side, the background appears flat over the interval $-1.0<\cos\phi<0.7$ with about 0.5 event per bin; there is a forward peaking with about 15 events in the most forward bin.

Under the assumption of an incoherent background and a smooth (linear) transition of the background from mass region I to mass region VI, we obtain the corrected decay-angle distribution for mass regions III and IV shown in Fig. 3(h).

Applying the Kolmogorov-Smirnov test[9] to check the compatibility of the corrected decay-angle distribution with the expected distributions for spins $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$, we obtain confidence levels of 0.01, 8, and 56%, respectively. In order to avoid the large correction for the region $\cos\phi>0.7$ (where the background estimate is less certain, especially in view of the assumption of an incoherent background), we applied the same test to the region $-1.0<\cos\phi<0.7$. We then obtained confidence levels of 0.0001, 0.7, and 14%, respectively, for spins $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$.

Our results appear to rule out spin $\frac{1}{2}$, and favor spin $\frac{5}{2}$ over spin $\frac{3}{2}$. We thus conclude that while the $D_{15}(1675)$ and $F_{15}(1690)$ appear to be favored, we cannot rule out $D_{33}(1670)$ and $P_{33}(1690)$. However, having eliminated spin $\frac{1}{2}$, we can find other arguments against the D_{33} and P_{33}.

If an $I=\frac{3}{2}$ resonance were involved, it would follow from charge independence that the reaction $\pi^+p\to p\pi^+\pi^0$ should show 1670-MeV/c^2 peaks in the $p\pi^0$ and $p\pi^+$ systems with cross sections 2 and $\frac{9}{2}$ times as great, respectively, as in the case of reaction (1) (for $I=\frac{1}{2}$, the corresponding factors are $\frac{1}{2}$ and 0). No peaks of such magnitude have been observed in studies of these reactions at c.m. energies close to ours.[2–6] Thus the D_{33} and P_{33} isobars could not be the primary contributors to the observed peak.

Our value for the mass favors the D_{15}. (It is of interest to note that the mass and width are in good agreement with the average Glasgow values 1668 and 115 MeV/c^2 cited in Ref. 8.) However, because of the uncertainty in the masses determined from phase-shift analyses and the possibility of interference effects, we cannot rule out the presence of the $F_{15}(1690)$. In what follows, we will denote the possible combination of the D_{15} and F_{15} isobars we are observing by the collective designation $N(1670)$.

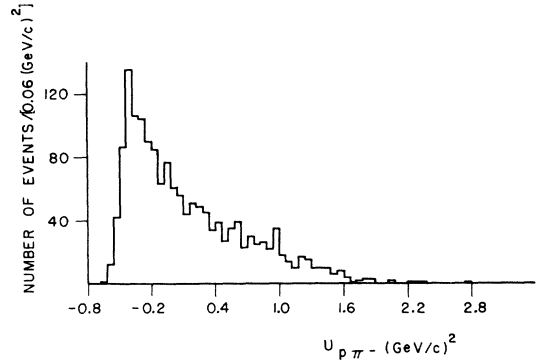

FIG. 4. Distribution of 4-momentum transfer from incoming pion to the outgoing π^-p system for events in the $N(1670)$ region [$1620<M(p\pi^-)<1740$ MeV/c^2].

Angelov *et al.*,[5] who studied reaction (2) at 2.34 GeV/c in a heavy-liquid bubble chamber, suggested that a baryon-exchange process is involved. They showed that the u distribution is characteristically peaked at low values of u (as is the case with our data—Fig. 4). To investigate this further, we looked at the Treiman-Yang angle[10] for the u channel (Fig. 5). It turns out to be consistent with the exchange of a spin-$\frac{1}{2}$ baryon, i.e., consistent with isotropy. On the other hand, one cannot but note that the cross section associated with the forward production of the $N(1670)$

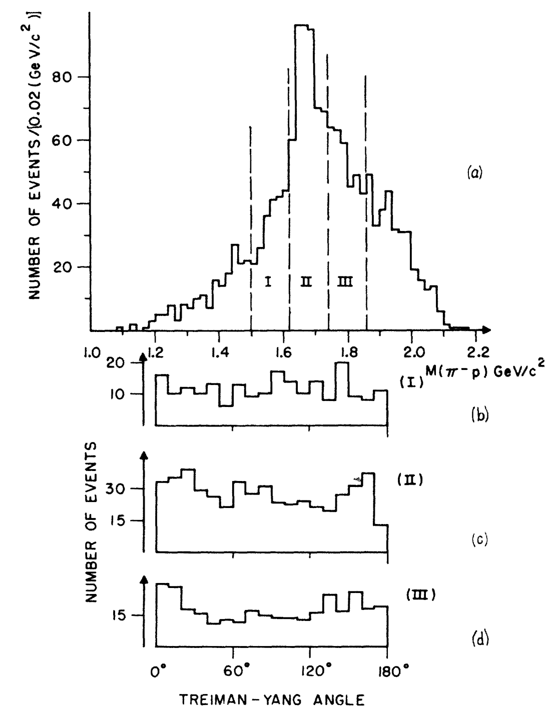

FIG. 5. (a) Effective-mass distribution of the π^-p system for events with $u(p\pi^-)<0.4$ (GeV/c)^2. (b)–(d) Treiman-Yang angle distribution for events in regions I, II, III of *a*.

[9] B. V. Gnedenko, *The Theory of Probability* (Chelsea Publishing Co., 1963), p. 389; F. Massey, Am. Statistical J. **46**, 68 (1951). We have used the Kolmogorov-Smirnov test rather than the χ^2 test, since in the case of the former it is unnecessary to combine bins (or fold distributions) to increase the population of bins. If we apply the χ^2 test to the corrected data, which give a minimum expected bin population of 5 events, we obtain χ^2 confidence levels of 10^{-6}, 1.8, 3.6% for spins $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ with the decay-angle range restricted to $-1.0<\cos\phi<0.7$.

[10] J. D. Jackson, Nuovo Cimento **34**, 1645 (1964).

appears to be at least an order of magnitude higher than that which one would expect for a baryon-exchange process.

We have also considered the possibility that we are dealing with a direct-channel process. Since the initial state is a pure $I=\frac{3}{2}$ state, it is possible that the observed peak is due to the decay of the $\Delta(1920)$ and $\Delta(2420)$ into $N(1670)\pi$. Making use of Galloway's estimates,[11] we find that at our c.m. energy of 2.27 GeV the contribution of the decays of the $\Delta(1920)$ and $\Delta(2420)$ to reaction (1) are 135 and 235 μb, respectively. As Galloway noted, these results should be viewed only as crude estimates because of lack of information on the energy dependence of the partial widths and possible interference effects. Then if the $\Delta(1920)$ and $\Delta(2420)$ contributed to reaction (1) primarily via the cascade decay process

$$\Delta \rightarrow N(1670)\pi \rightarrow N\pi\pi,$$

we could account for the large cross sections of Table I. We do note, however, that the assumption of this direct-channel mechanism involves a rather strong reliance on interference effects to explain the asymmetry in the $N(1670)$ production angle.

It is, of course, not unlikely that we are dealing with a combination of the u-channel and direct-channel processes. To resolve this question it would be useful to have more detailed data on reactions (1) and (2) over the range 2.0–3.5 GeV/c, especially above 3 GeV/c where the c.m. energy is sufficiently removed from the $\Delta(2420)$ resonant energy to test the direct-channel hypothesis.

Information on the branching ratio $N(1670)\rightarrow \Delta(1236)\pi/N\pi$ can be obtained from 2447 events fitting the reaction

$$\pi^- n(p_s) \rightarrow (p_s) n\pi^-\pi^-\pi^+ \qquad (3)$$

from our original sample of three-prong events.[12] If the $N(1670)$ were to decay into $\Delta\pi$, the most favorable place to look in reaction (3) would be the $\Delta^-\pi^+$ state. Predictions based on $I=\frac{1}{2}$ for the $N(1670)$ give 9:1 for the ratio $\Delta^-\pi^+/\Delta^+\pi^-$ in reaction (3). Figure 6 shows the effective mass of the $\Delta^-\pi^+$ system for the entire sample and for the region $|t|>0.6$ (GeV/c)^2, the latter corresponding to the region in which most of the $N(1670)$ is observed in reaction (1). We see no significant peaking at 1670 MeV/c^2. If we take as an upper limit the number of events required for a three-standard-deviation effect in the mass range $1620<M(\Delta^-\pi^+)<1720$ MeV/c^2 for the over-all distribution of Fig. 6, we obtain 51 events, which corresponds to a cross section of 75 μb. To obtain an upper limit on the branching ratio $[N(1670)\rightarrow\Delta\pi]/N(1670)$ from the experimentally observed upper limit on the ratio $[N(1670)^0\rightarrow\Delta^-\pi^+]/[N(1670)^0\rightarrow p\pi^-]$ under the assumption of charge independence, we apply the factor 4/3 to the latter ratio. In this way we obtain the upper limit:

$$\frac{N(1670)\rightarrow\Delta\pi}{N(1670)\rightarrow N\pi}<0.11.$$

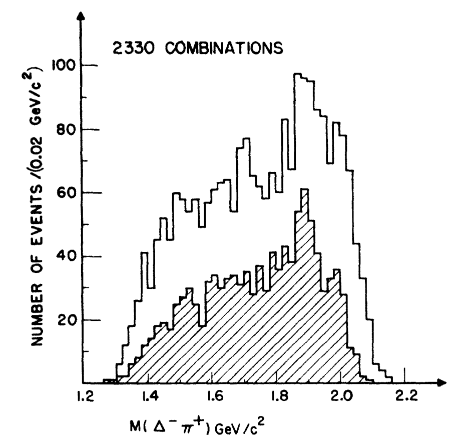

FIG. 6. Effective mass of $\Delta^-\pi^+$ sample for reaction (3) where Δ^- is defined by $1120<M(n\pi^-)<1300$ MeV/c^2. Events with $|t|<0.6$ are shaded.

It is of interest to compare these results with those obtained by other workers. Lee *et al.*[13] obtained a ratio of $\Delta\pi/N\pi>1.3$ for the $N(1688)$ decay (at that time it was not known that several isobars existed in this mass region). Brody *et al.*[14] reported the ratios $\Delta\pi/(\text{all})\sim0.15$ for the $D_{15}(1675)$ and $\Delta\pi/(\text{all})\sim0.2$ for the $F_{15}(1690)$. Taking the values[15] 0.45 and 0.60 for the $N\pi/(\text{all})$ ratio of the D_{15} and F_{15}, we find that the results of Brody *et al.* lead to $\Delta\pi/N\pi$ ratios of 0.34 and 0.33, respectively. The differences between our results and those of Lee *et al.* and Brody *et al.* could, in part, be due to the fact that the limited phase space available for the decay of the $N(1670)$ into a nucleon and two pions leads to difficulties in determining if the decay proceeds via $\Delta\pi$ rather than directly into $N\pi\pi$. Also, one cannot rule out the presence of an appreciable amount of the $I=\frac{3}{2}$ isobars in the reactions on which the authors of Refs. 12 and 13 base their results.

We thank Dr. D. Geffen, Dr. H. Suura, and Dr. J. Uretsky for helpful discussions. We are also grateful to the Lawrence Radiation Laboratory for the loan of the film.

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[14] A. D. Brody, A. Kermán, D. W. G. S. Leith, B. S. Levy, A. Minten, B. C. Shen, P. Berge, D. Herndon, R. Longacre, L. Price, A. H. Rosenfeld, and P. Söding, in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968* (CERN, Geneva, 1968), p. 151.
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