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# EVIDENCE FOR THE $I=\frac{1}{2}$ $N^*(1400)$ RESONANCE PRODUCTION IN $\pi^{\pm}p$ INTERACTIONS AT 6 GeV/c*

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Results from a number of high-energy missing-mass spectrometer experiments have indicated the presence of a peak in the strangeness-zero and baryon-number–one system at a mass of about 1.4 GeV.[1] Because its production is peripheral and the width is large (approximately 200 MeV), kinematic interpretations of this peak are possible.[2] However, an extensive pion-nucleon phase-shift analysis suggests that an amplitude, with the same quantum numbers as the nucleon ($I=\frac{1}{2}$ and $J^P=\frac{1}{2}^+$), exhibits resonant properties near this mass region with a large width and inelasticity ($\sigma_{\text{inel}}/\sigma_{\text{total}}\approx\frac{1}{3}$).[3] In order to associate this $N_{1/2}^*(1400)$ deduced from the pion-nucleon phase-shift analysis with the peak observed from production experiments, it is essential to determine its quantum numbers from its decay products. To date, the only relevant bubble-chamber data with adequate statistics have come from a study of the reaction $pp\to pp\pi^+\pi^-$ at 6.6 GeV/c,[4] where a kinematic interpretation of this enhancement is favored. In this Letter, we report our observation of well-defined $\pi^+n$ and $\pi^-p$ enhancements centered at 1.42 GeV with a width of the order of 100 MeV, from the reactions $\pi^+p\to\pi^+\pi^+n$ and $\pi^-p\to\pi^0\pi^-p$ at 6 GeV/c. The resonance interpretation of this enhancement is clearly favored in our data. We have determined its isospin to be $\frac{1}{2}$, and we associate it with the $N_{1/2}^*(1400)$ suggested by the phase-shift analysis.

The samples of events for this study come from a 6-GeV/c $\pi^{\pm}p$ experiment in the Brookhaven National Laboratory (BNL) 80-in. liquid-hydrogen bubble chamber. About 30 000 two-prong events in the $\pi^+p$ exposure and 60 000 two-prong events in the $\pi^-p$ exposure were analyzed. About one-half of the events were measured by conventional measuring machines and the other half by the BNL flying-spot digitizer. The size of the event samples and cross-section equivalents of the four reactions studied[5] are shown below:

| Reaction | Number of events | Events/Cross section equivalent (events/μb) |
|---|---|---|
| (1) $\pi^+p\to\pi^+\pi^+n$ | 1195 | 1.5 |
| (2) $\pi^+p\to\pi^0\pi^+p$ | 265 | 0.3 |
| (3) $\pi^-p\to\pi^+\pi^-n$ | 5334 | 4.8 |
| (4) $\pi^-p\to\pi^0\pi^-p$ | 3376 | 4.8 |

In these four reactions, there are two major sources contributing to the background observed in the low $(\pi N)_{I_z=\pm\frac{1}{2}}$ mass region. They are (a) the reflection of strong $\pi\pi$ resonances,[6] which contribute to reactions (2), (3), and (4) but not to (1), and (b) proton dissociation into $(\pi N)_{I_z=+\frac{1}{2}}$ at the nucleon vertex without $N_{1/2}^*$ formation, which contributes to all $(\pi N)_{I_z=+\frac{1}{2}}$ combinations but not to $(\pi^-p)$ in reaction (4). It should be emphasized that the $(\pi^+n)$ and $(\pi^-p)$ mass spectra from reactions (1) and (4), respectively, are the only ones that have just one of these two sources of background present; and it is data from these two reactions, presented in Fig. 1, which show strong evidence for the $\pi N$ enhancement at 1.42 GeV. Similar $(\pi N)_{I_z=\pm\frac{1}{2}}$ mass plots from reactions (2), (3), and the $\pi^0 p$ combination from reaction (4) have been examined (not shown); however, the large background in the low-mass region makes the separation of any peak difficult.

Figures 1(a) and 1(c) are sections of Chew-Low plots for $M(\pi^+n)$ versus the square of the four-momentum transfer, $t_{p\to\pi^+n}$, and for $M(\pi^-p)$ vs $t_{p\to\pi^-p}$ for reactions (1) and (4), respectively. Figures 1(b) and 1(d) are the $\pi^+n$ and $\pi^-p$ effective mass projections for $t_{p\to\pi N} \leq 0.5$ GeV$^2$ in the same final states. The marked enhancement at 1.42 GeV, as well as the $N_{1/2}^*(1688)$, are clearly seen in both projections.[7,8] It is interesting to note that the $N_{3/2}^*(1240)$ is seen clearly only in the $\pi^-p$ effective mass spectrum and we will discuss this point later. The solid curve in Fig. 1(b) shows a fit with Breit-Wigner resonances having masses $1223\pm20$, $1405\pm30$, and $1640\pm30$ MeV and widths 100, 100, and 100 MeV, respectively, plus an estimated background,[9] to the $\pi^+n$ mass spectrum. Figure 1(d) shows a similar fit yielding masses of $1225\pm10$, $1436\pm20$, and $1680\pm30$ MeV and widths of 130, 50, and 160 MeV, respectively, to the $\pi^-p$ spectrum. The masses and widths of these enhancements obtained from the $\pi^+n$ and $\pi^-p$ mass spectra are consistent within statistics; however, the values of the widths are strongly dependent on the shapes assumed for the estimated background. There is also disagreement with the width obtained from the phase-shift analysis (approximately 200 MeV), but that analysis may be affected by the strong inelasticity of this resonance as well as the difficulty in determining the background contribution from other partial waves.

Kinematic interpretations of this $\pi N$ enhancement are extremely unlikely since the enhancement is produced with similar mass and width in two independent reactions in which the background distributions differ. In the $\pi^+n$ mass spectrum, the 1.42-GeV enhancement starts at 1320 MeV (about 240 MeV above the threshold). A simple smooth curve cannot describe the $\pi^+n$ mass distribution from the threshold to 1.56 MeV because of the shoulder extending from 1.2 to 1.32 GeV. In the $\pi^-p$ mass

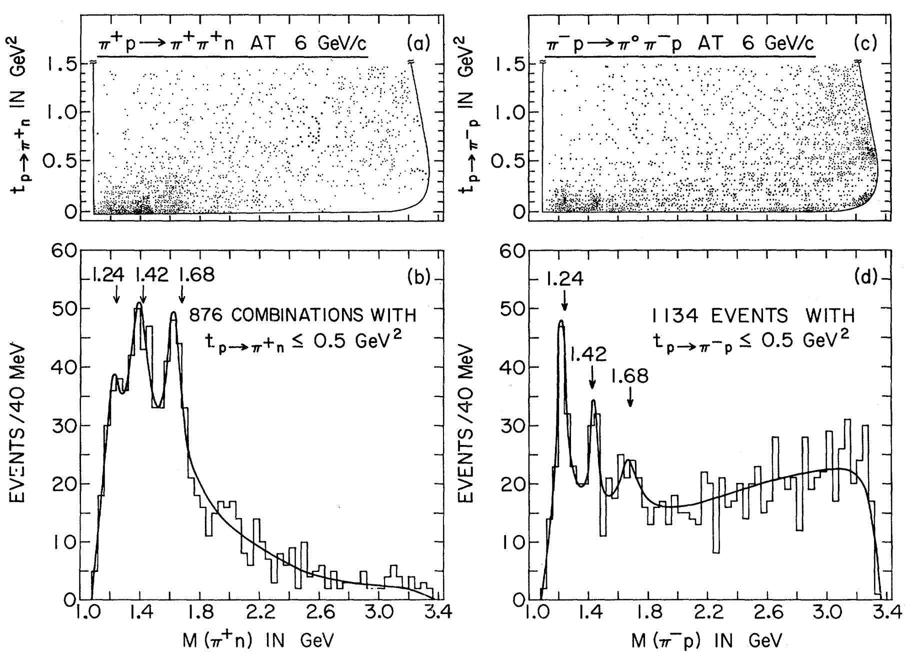


FIG. 1. (a), (c) Sections of the Chew-Low plot for $M(\pi^+n)$ vs $t_{p\to\pi^+n}$ in reaction (1), and for $M(\pi^-p)$ vs $t_{p\to\pi^-p}$ in reaction (4). (b), (d) Mass projections for $M(\pi^+n)$ and $M(\pi^-p)$ with low $t_{p\to\pi N}$ as indicated. There are two $\pi^+n$ combinations for each event in reaction (1). In (b) there are 826 events in the histogram and no event has both combinations in the $N_{1/2}^*(1400)$ region.

spectrum, the background is influenced in general by the peripheral nature of the interaction. A beam like $\pi^-$ and a target like $p$ tend to have a high $\pi^-p$ effective mass, and it is difficult to explain the low-mass enhancement with any known kinematic effect. In particular this enhancement is observed between the well-known $N_{3/2}^*(1240)$ and $N_{1/2}^*(1688)$. We have also studied the reflection of strong $\pi^-\pi^0$ resonances (such as $\rho^-$ and $g_1^-$ mesons) on the low $\pi^-p$ mass spectrum; the 1.42-GeV enhancement, as well as the $N_{3/2}^*(1240)$ and $N_{1/2}^*(1688)$, are not associated with these effects. We conclude that the enhancement at 1.42 GeV is indeed a resonance.

We next examine its quantum numbers and production mechanism.

Isospin.—Observation of the $\pi N$ decay mode requires $I=\frac{1}{2}$ or $\frac{3}{2}$. For reactions (1) and (2), the relative intensities for $\pi^+n$ and $\pi^+p$ would be 2 and 9 if the isospin assignment for this resonance were $\frac{3}{2}$. Figure 2 is the $\pi^+p$ mass distribution for the final state $\pi^0\pi^+p$, and we expect $36\pm 12$ events in the 1.4-GeV region for the $I=\frac{3}{2}$ assignment. We see none above the background and conclude that this is an $I=\frac{1}{2}$ pion-nucleon state.

$J^P$.—We have studied the moments $A_L^M = \sum_i Y_L^M(\theta_i, \varphi_i) \pm [\sum (Y_L^M)^2]^{\frac{1}{2}}$ of the decay angular distributions of the $(\pi^+n)$ and $(\pi^-p)$ systems from reactions (1) and (4), where $\theta_i$ and $\varphi_i$ are the polar and aximuthal angles defining the direction of the $\pi$ in the $\pi N$ rest frame of the $i$th event.[10] The moments from both $(\pi^-p)$ and $(\pi^+n)$ states show structure at 1.4-GeV mass region. However, limited statistics together with large backgrounds under the resonance preclude any conclusive answer from the spin-parity analysis.

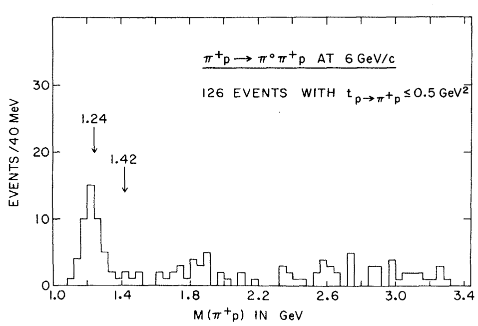


FIG. 2. $M(\pi^+p)$ mass projection from reaction (2) with low $t_{p\rightarrow\pi^+p}$ as indicated.

Production mechanism.—Results from counter experiments suggest that the production of this $N_{1/2}^*(1400)$ has much sharper $t$ dependence than that of elastic scattering. Figures 3(a) and 3(b) are the $t$ distribution for events in the $N_{1/2}^*(1400)$ region with $t \leq 0.5$ GeV$^2$, from reactions (1) and (4). The solid curves are maximum-likelihood fits of the form $\exp(-\gamma t_{p\rightarrow\pi N})$ to the data, giving $\gamma = 6.1\pm 0.7$ and $5.7\pm 1.0$ GeV$^{-2}$ for reactions (1) and (4), respectively. These values are to be compared with a value of $\gamma = 7.5\pm 0.3$ for our $\pi^-p$ elastic events in the same $t$ region. Our results are significantly different from those deduced from previous $\pi^+p$ counter experiments[11] for the $N_{1/2}^*(1400)$ ($\gamma \approx 12$ to 16).

Peripheral production of the $N_{1/2}^*(1400)$ suggests the single-particle-exchange production mechanism shown in Fig. 3; the production mechanism can be described in terms of $I=0$, $I=1$ isospin-exchange amplitudes for reaction (1), and $I=1$ isospin-exchange amplitude for reaction (4). Both exchanges must involve

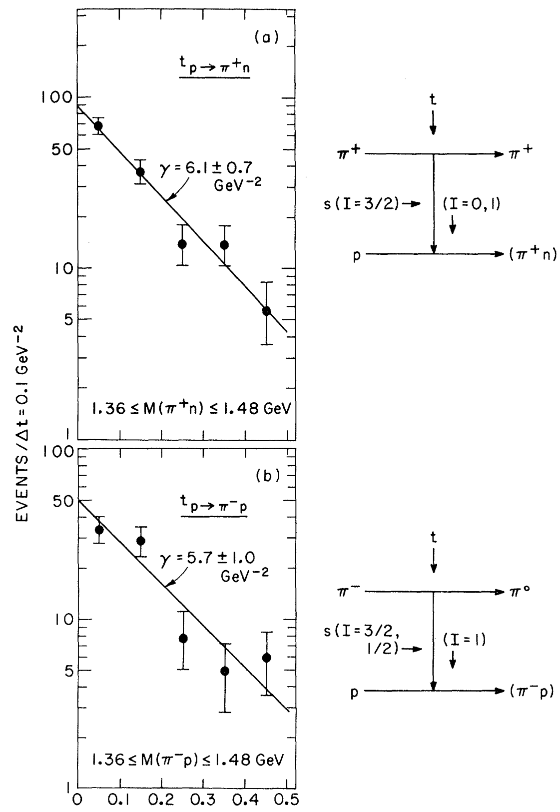


FIG. 3. (a), (b) The $t_{p\rightarrow\pi N}$ distributions for events in the $N_{1/2}^*(1400)$ region from reactions (1) and (4). Single-particle-exchange diagrams for these production processes are also shown.

only even $G$ parity (for example $f^0$ and $\rho$). Moreover, the $I=0$ isospin exchange seems to be dominant in reaction (1) since the $I=\frac{1}{2}$ nucleon isobars are produced copiously, but the $I=\frac{3}{2}$ isobar state $N_{3/2}{}^*(1240)$ is suppressed. In reaction (4) only the $I=1$ isospin-exchange amplitude is allowed, and both $I=\frac{1}{2}$ and $\frac{3}{2}$ isobars are produced. It is interesting to note in this respect that the cross section at 6 GeV/$c$ for

$$\pi^+ p \to N_{1/2}{}^*(1400)\pi^+ \quad (\llcorner \pi N)$$

is approximately 34 $\mu$b, whereas for

$$\pi^- p \to N_{1/2}{}^*(1400)\pi^0 \quad (\llcorner \pi N)$$

it is approximately 8 $\mu$b. We have not obtained a value of the inelasticity of the $N_{1/2}{}^*(1400)$ at the present time since the many-prong (>2) events are not analyzed.

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[2]See, for example, Marc Ross and Y. Y. Yam, Phys. Rev. Letters 19, 546 (1967). Earlier references can also be found there.

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[4]E. Gellert et al., Phys. Rev. Letters 17, 884 (1966).

[5]The criteria used to obtain the sample of events for reactions (1) and (3) were (a) 790 MeV < missing mass < 1090 MeV and (b) consistency of observed or measured bubble density with that required by the kinematic fit. For reactions (2) and (4), the criteria were (a) −300 MeV < missing mass < 450, (b) consistency of observed or measured bubble density with that required by the kinematic fit, (c) error in the missing mass < 500 MeV, and (d) $\chi^2$ probability 5%. In all the $\pi^-p$ film and in 20% of the $\pi^+p$ film, no preselection was used to reduce the number of elastic events that were measured. However, in the remaining 80% of $\pi^+p$ film, two-pronged events found in scanning which had an identifiable proton were not measured. Since this preselection to remove elastic events also removed events of reaction (2), the event sample and equivalent cross section for reaction (2) presented here are based on the 20% of $\pi^+p$ film in which no preselection was used.

[6]No $I=2$ $\pi^+\pi^+$ resonance is observed in reaction (1). This gives an upper limit of 15 $\mu$b for production of any $\pi^+\pi^+$ resonance, assuming a width of approximately 100 MeV and a mass less than 2.2 GeV, with 99% confidence level.

[7]The $N_{1/2}{}^*(1525)$ is not clearly resolved from the broad $N_{1/2}{}^*(1688)$ in our data.

[8]The cluster of events in the higher $\pi^-p$ mass region of Fig. 1(c) is due to reflections of $\pi^-\pi^0$ resonant states ($\rho^-$ and $g_1{}^-$).

[9]A number of fits have been made to each distribution of which one is shown in the figures. In each fit the assumed background shape is fixed, the various fits differing in the amount of peaking in the low-mass region of the background. The mass values obtained are insensitive to the background changes, while their widths and intensities vary widely.

[10]See, for instance, J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[11]K. J. Foley et al., Phys. Rev. Letters 19, 397 (1967). Our results of $\gamma$ for events in the $N_{1/2}{}^*(1400)$ region with $t \leq 0.2$ GeV$^2$ are $6.0 \pm 1.7$ and $6.3 \pm 1.5$ GeV$^{-2}$ for reactions (1) and (4), respectively.

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## MAGNETIC MOMENTS, FORM FACTORS, AND MASS SPECTRUM OF BARYONS*

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We have been able to derive and correlate the following baryon properties: (a) absolute values of the magnetic moments, (b) form factors $G_M(t)$ and $G_E(t)$, (c) mass spectrum, and (d) decay rates, in a relativistic theory based on the unitary representations of the dynamical group O(4, 2) ~ SU(2, 2). We are then able to make a number of new predictions.

The starting point of the theory is a conserved four-vector current operator $j_\mu$ constructed from the generators of the dynamical group and from the momentum operators $P_\mu = (p'+p)_\mu$ and $q_\mu = (p'-p)_\mu$, where $p_\mu{}'$ and $p_\mu$ are the baryon momenta in a vertex. In a recent paper[1] where the general theory is described we have considered a simple current operator that gives positive magnetic moments and "physical" mass spectra.[2] No attempt was made there to fit the experimental properties of the hadrons with the theory. In this paper we shall