Analysis of the $N^*(1500)$ and $N^*(1700)$ Baryon Resonances Produced via Diffraction Dissociation*

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(Received 23 November 1970)

We report on evidence in the $\pi\pi N$ mass spectrum for the production of two nucleon isobars, the $N^*(1500)$ and $N^*(1700)$. They appear to be produced very peripherally, and have the same production cross section at both 7.0 and 25.0 GeV/c, indicating that a nuclear diffraction-dissociation process is dominant. The $N^*(1500)$ seems to be $J^P=\frac{1}{2}^+$ and decays principally via $p\sigma$ and not $\Delta^{++}\pi^-$ as previously suggested. The $N^*(1700)$ could be the $N^*(1688)$ $\frac{5}{2}^+$ decaying partially into $\Delta^{++}\pi^-$, or it could be the $N^*(1700)$ $\frac{1}{2}^-$ decaying in a non-$\Delta^{++}\pi^-$ mode riding on a large $\Delta^{++}\pi^-$ $\frac{5}{2}^+$ nonresonant Deck-type background. Finally the ΛK decay of the $N^*(1700)$ is observed and evidence presented for it being a $J=\frac{1}{2}$ object. Production of this $\frac{1}{2}^-$ isobar should be forbidden by the Morrison $\Delta P=(-1)^{\Delta J}$ rule.

Studies of the nucleon-dipion system in the reactions $xp \rightarrow xp\pi^+\pi^-$, where $x=\pi$, K, or p, at momenta from 1.5 to 28.5 GeV/c, have revealed the presence of low-mass $p\pi^+\pi^-$ enhancements at 1.5 and 1.7 GeV/c^2.[1] In addition, counter experiments have revealed evidence for a 1.4-GeV/c^2 effect in both πp and pp collisions at momenta ranging from 5 to 30 GeV/c.[2] Fits to the $\pi\pi N$ data using nonresonant dissociation models have been rather unsuccessful for these purely kinematic effects; while reproducing the general characteristics of the data, they are unable to account for the sharper structures observed.[3] Only Gellert *et al.*[4] conclude that all of the 1.5-GeV/c^2 enhancement is a kinematic effect. The remaining groups generally conclude that the 1.5-GeV/c^2 enhancement is a bona fide resonant state, probably the nuclear isobar $P_{11}(1470)$, which rides on a large nonresonant Deck-type background.[5] Further evidence for these low-mass isobars has been seen in the ΛK final states appearing as a threshold enhancement in the ΛK system in the reaction $\pi N \rightarrow \pi\Lambda K$.[6]

The mechanism for producing these isobars seems to be independent of the nature of the incident particle, strongly suggesting a nucleon diffraction-dissociation process (NDD). Such processes have the following additional characteristics:

(1) Constant total cross section at high energies (> 5 GeV/c).

(2) $d\sigma/dt$ strongly peaked toward small momentum transfers.

(3) The larger the mass change in the dissociation process, the less the probability and the higher the energy required. The matrix elements show a general $P_{\rm lab}/(M^{*2}-M^2)$ dependence, where M^* is the dissociated object, and M the mass of the target.[7]

(4) There should be no change in isospin.

(5) Only orbital angular momentum may be transferred. With baryons no final states are disallowed; however, Morrison[8] has proposed the rule $P=(-1)^{\Delta J}$ requiring $\frac{1}{2}^+ \rightarrow \frac{1}{2}^+, \frac{3}{2}^-, \frac{5}{2}^+, \ldots$.

The energy independence of the cross section is what one expects from "vacuon" exchange, since total cross sections of hadrons tend to become nearly energy-independent. The most general type of diagram for this process is shown in Fig. 1(a). It is an inelastic vacuon exchange (i.e., an exchange in which the quantum numbers exchanged are those of the vacuum). Another diagram which is expected to make a strong nonresonant contribution is the elastic vacuon exchange shown in Fig. 1(b). It is basically a "Deck" mechanism which, from purely kinematical effects, produces a broad, very peripheral, low-mass $N\pi\pi$ background. It is essential to understand the kinematic background when trying to determine the characteristics of genuine resonant states, since these kinematic-background amplitudes are large and can be expected to interfere strongly with the diffractively produced resonant amplitudes. Finally, in Fig. 1(c) is shown a Deck-type elastic scattering, followed by a final-state interaction which produces the N^* final state. Such a two-step process has been discussed in detail by Rushbrooke.[5]

In our studies, we have looked at the $\pi^-\pi^+p$ mass spectrum from the reaction $\pi^-p \rightarrow \pi^-\pi^-\pi^+p$ at both 7.0 and 25.0 GeV/c, and the $\pi^-\pi^0p$ spectrum from the reaction $\pi^+ d \to p_s p \pi^+ \pi^- \pi^0$ at 7.0 GeV/c.[9] Further, we have observed similar low-mass enhancements in the ΛK mass spectrum in the reactions $\pi N \to \pi \Lambda K$ at incident beam momenta between 6 and 7 GeV/c.[10]

In studying the $N\pi\pi$ mode we always choose the combination $\pi_2^- \pi^+ p$, where π_2^- is determined by demanding $t_{\pi\pi_1^-} < t_{\pi\pi_2^-}$, where $t_{\pi\pi_i^-}$ is the momentum transfer between the incident beam and the ith outgoing π^-. Figure 2 shows the $\pi^-\pi^+p$ mass spectra at 7.0 and 25.0 GeV/c, and the $\pi^-\pi^0 p$ mass spectrum at 7.0 GeV/c. The $\pi^-\pi^+p$ data show small, yet clear enhancements around 1.5 and 1.7 GeV/c^2, and these signals remain when a $\Delta^{++}[M(\pi^+p) = 1.24 \pm 0.1$ GeV/$c^2]$ is demanded. Evidence for similar structures in the $\pi^-\pi^0 p$ data is not so clear [Fig. 2(c)]. The data are not statistically convincing, and while there is no clear evidence of either a 1.5- or 1.7-GeV/c^2 enhancement, there are hints of signals at both 1.5 and 1.7 GeV/c^2. The data, however, are also consistent with what one expects for peripheral $p\pi\pi$ phase space.

These isobars are produced very peripherally, with characteristic forward peaking of $e^{-10|t_{\pi\pi}|}$ (see Table I). Although copious Δ^{++} production is observed in the $\pi^+\pi^-p$ channel, it is hard to estimate the percentage due to the strong enhancement of the low-mass $p\pi^+\pi^-$ spectrum. This feature is shown in Fig. 4 below.

In light of the small signal-to-noise ratio of these states, it is necessary to test their statistical significance, as well as estimate the nature and amount of background before central-mass values, widths, production cross sections, and spin-parity assignments can be made. To do this, we fit the 7.0- and 25.0-GeV/c $\pi^+\pi^-p$ data with two Breit-

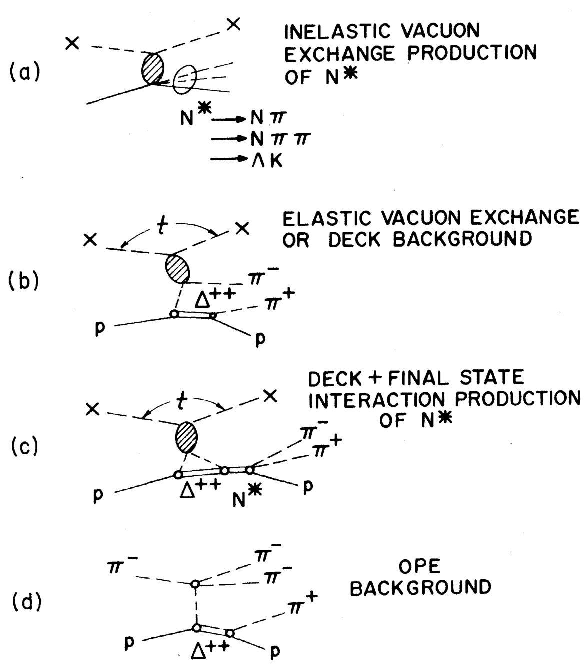

FIG. 1. Baryon diffraction-dissociation graphs: (a) inelastic-vacuon-exchange production of the N^* nucleon isobar; (b) elastic vacuon-pion scattering – the "Deck" mechanism; (c) same as (b), followed by a final-state interaction which produces the N^*; (d) OPE diagram.

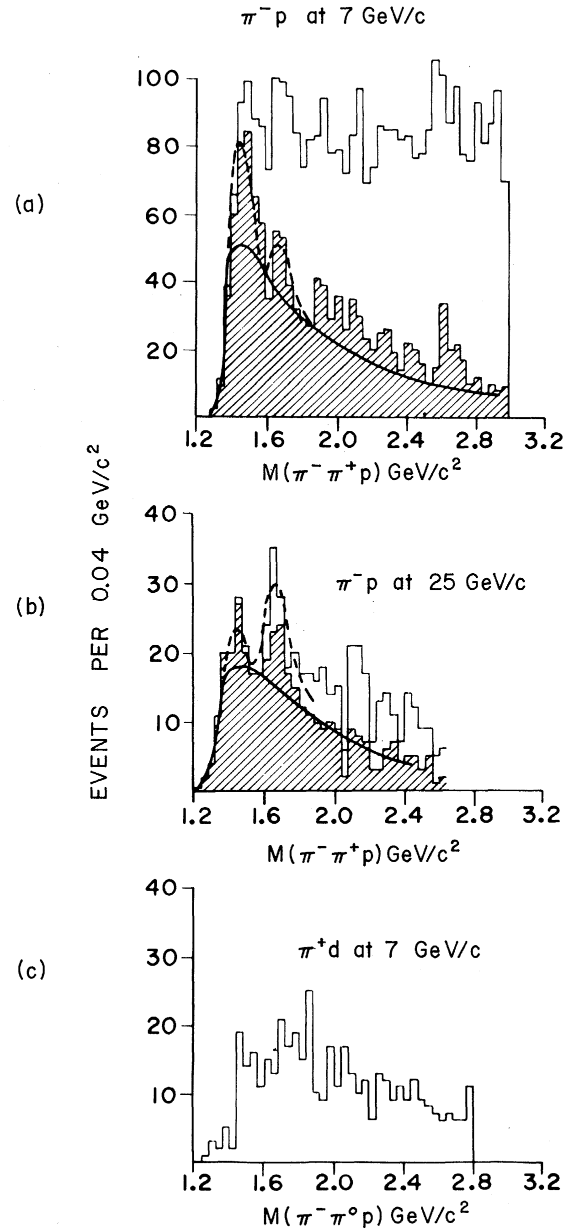

FIG. 2. $N\pi\pi$ mass spectra: (a) $\pi^-\pi^+p$ mass spectrum for the reaction $\pi^-p \to \pi^-\pi^-\pi^+p$ at 7.0 GeV/c; (b) same as (a) but at 25.0 GeV/c; (c) $\pi^-\pi^0 p$ mass spectrum for the reaction $\pi^+d \to p_s p \pi^+\pi^-\pi^0$ at 7.0 GeV/c. Δ^{++} events are shaded. The curve in (a) is a fit to the $\Delta^{++}\pi^-$ data using a matrix element proposed by Stodolsky.

TABLE I. Characteristics of the $N^*(1500)$ and $N^*(1700)$.

Final state	Mass (MeV)	Γ (MeV)	σ (μb)	β $(\text{GeV}/c)^{-2}$	Reaction (energy in GeV)
			$N^*(1500)$		
π^+n	1490 ± 10	80 ± 15	8 ± 3	12.4	7.0 π^-p [a]
$\pi^+\pi^-p$	1510 ± 10	110 ± 30	25 ± 7	8.0	7.0 π^-p [a]
$\pi^-\pi^0p$	1460 ± 10	120 ± 30	8 ± 5	···	7.0 π^+d [a]
$\pi^+\pi^-p$	1510 ± 20	100 ± 30	22 ± 8	14.0	25.0 π^-p [a]
$\pi^+\pi^-p$	1427 ± 23	116 ± 43	15	9.6 ± 1.5	24.8 pp [b]
$\pi^+\pi^-p$	1443 ± 15	100 ± 15	155 ± 30	18.0 ± 2.3	22 pp [c]
			$N^*(1700)$		
π^+n	1670 ± 10	100 ± 20	28.8 ± 4	4.7	7.0 π^-p [a]
$\pi^+\pi^-p$	1690 ± 10	110 ± 20	24 ± 7	6	7.0 π^-p [a]
$\pi^-\pi^0p$	1730 ± 30	120 ± 30	10 ± 5	···	7.0 π^+d [a]
$\pi^+\pi^-p$	1700 ± 10	70 ± 20	25 ± 6	8	25.0 π^-p [a]
$\pi^+\pi^-p$	1707 ± 8	65 ± 20	17	···	7.3 K^-p [d]
$\pi^+\pi^-p$	1698 ± 11	100 ± 32	73	6.6 ± 0.9	24.8 pp [b]
$\pi^+\pi^-p$	1693 ± 15	235 ± 50	···	···	22 pp [c]
ΛK	1700	···	1.9 ± 0.9	···	7.3 K^-p [d]
ΛK	1700 ± 25	···	2.6 ± 0.5	5.9 ± 2.0	6.0 π^-p [e]

[a] Reference 9.
[b] Reference 14.
[c] Reference 15.
[d] Reference 13.
[e] Reference 6.

Wigner resonances and a Deck background (the details of the Deck calculation are given in the next section). While the 7.0-GeV/c $\Delta^{++}\pi^-$ data can be fitted quite well with a single resonant term, they are fitted better with two resonances, and the uncut data clearly require the two-resonance fit in this region [Fig. 2(a)]. The 25.0-GeV/c $\pi^+\pi^-p$ data again require a two-resonance fit. We thus conclude that the 1500- and 1700-MeV enhancements are statistically significant in that only the two-resonance terms plus Deck background give a reasonable fit to the data. We summarize these results in Table I.

PRODUCTION MECHANISM

Figure 3(a) shows the momentum-transfer distribution $|t_{\pi\pi}|$ for the $N^*(1500)$ and $N^*(1700)$ at both 7.0 and 25.0 GeV/c. The curves are least-squares fits to the functional form

$$\frac{d\sigma}{dt_{\pi\pi}} = Ae^{-\beta(M^*)|t_{\pi\pi}|}$$

to determine β's dependence on M^*. The extreme peripheral nature of this process is especially evident in the $N^*(1500)$ case where $\beta \simeq 8$ at 7.0 GeV/c and increases to $\beta \simeq 14$ at 25.0 GeV/c.

The dependence of β on M^* is shown in Fig. 3(b) for both the 7.0- and 25.0-GeV/c data. It is a monotonically decreasing function of M^*, falling from $\beta = 9.5$ $(\text{GeV}/c)^{-2}$ at 1.4 GeV/c^2 to about 4.6 $(\text{GeV}/c)^{-2}$ at 1.8 GeV/c^2. This should be compared with the much steeper $(d\beta/dM^*)$ at 25 GeV/c. This peripheral nature and the rapid rise in the $\pi^-\pi^+p$ mass spectrum is extremely suggestive of the NDD process. Here the dissociation process $p \to \Delta^{++}\pi^-$ [see Fig. 1(b)] would account for the large "Deck" background observed in the $\Delta^{++}\pi^-$ mass spectrum [shaded events in Figs. 2(a) and 2(b)].

In the spirit of Stodolsky,[7] we write the amplitudes for nonresonant production as

$$i\sigma_{\pi\pi}\frac{1}{\Delta^0}e^{-(\beta_{\pi\pi}/2)|t_{\pi\pi}|},$$

where

$$\Delta^0 = \frac{M^{*2} - M^2}{2|P_{\text{lab}}|}$$

and M^* is the mass of the dissociated system. The inverse diffractive width, $\beta_{\pi\pi} \approx 8-12$ $(\text{GeV}/c)^{-2}$, was obtained from $\pi\pi$ scattering data proceeding via the diagram shown in Fig. 1(d).[11]

This amplitude yields a $d\sigma/dM^*$ with a broad Deck-type enhancement as shown in Fig. 2(a). It is a shape calculation only, and no attempt was made to calculate absolute rates with it. While the calculation shows that our data around 1.5 GeV/c^2 cannot be explained as entirely kinematic in origin, it does manage to explain the gross features of the $\Delta^{++}\pi^-$ background. Using this model as a background, we calculated the $N^*(1500)$ and $N^*(1700)$ production characteristics. They are presented in Table I.

DECAY CHARACTERISTICS

(a) *Two-body mass spectra.* The low-mass $p\pi^+\pi^-$ system is dominated by $\Delta^{++}(1238)$ production, and the $p\pi^-$ mass spectrum shows only a very small Δ^0 signal. In Fig. 4 we present the π^+p mass spectrum for the $N^*(1500)$, $N^*(1700)$, and three adjacent $p\pi^+\pi^-$ control regions for the 7.0-GeV/c π^-p data. Note that in all $p\pi^+\pi^-$ mass regions a strong Δ^{++} signal is present. Similar strong Δ^{++} signals are also present in the 25-GeV/c data.

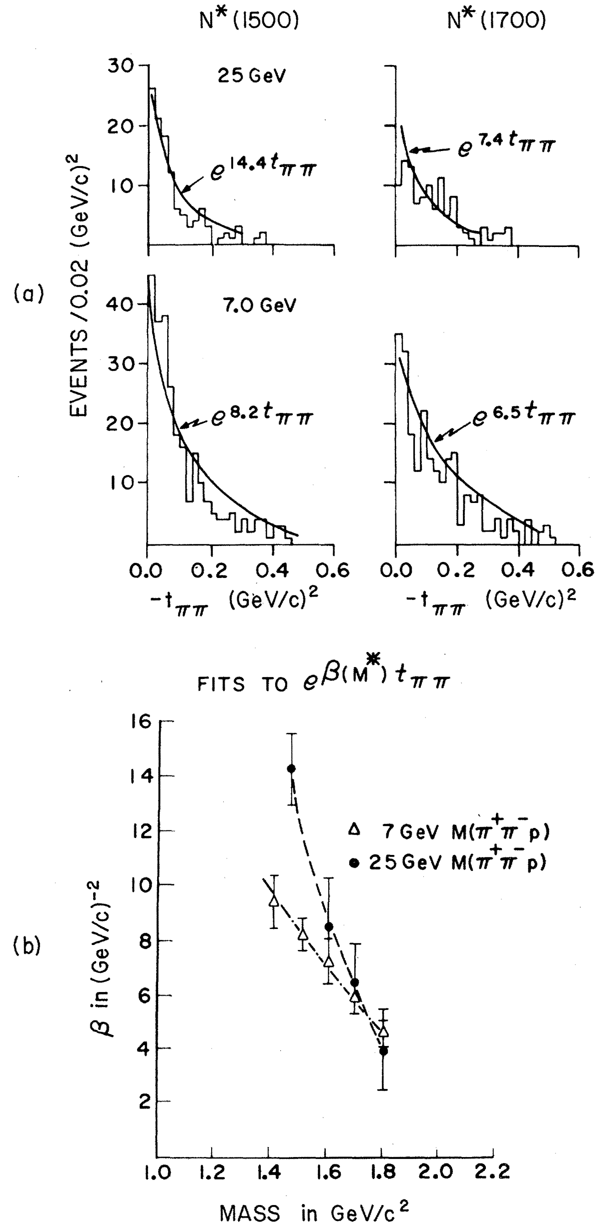

FIG. 3. (a) $d\sigma/dt$ distribution for the $N^*(1500)$ and $N^*(1700)$ at both 7.0 and 25.0 GeV/c; (b) plot of $\beta(M^*)$ vs M^*, obtained when the data were fitted with $\exp[\beta(M^*)t_{\pi\pi}]$.

However, the presence of such strong Δ^{++} signals should not be interpreted to mean that the N^* decays principally via $\Delta^{++}\pi^-$.[12] Due to the limited Q value for the $N^*(1500)$ decay, the two-body mass projection of the Dalitz plot is useless, since it is almost impossible to differentiate between the Δ^{++} signal and phase space. In addition, the strong Δ^{++} signal could also be partially due to background from the reaction $\Delta^{++}\pi^-\pi^-$ proceeding by one-pion exchange (OPE) [Fig. 1(d) or Fig. 1(b)]. These two sources of background make it quite difficult to draw any sound conclusions concerning the decay modes of the N^*'s from analysis of the π^+p mass spectrum. In fact, in the case of the $N^*(1700)$, a noticeable reduction of signal occurs when a Δ^{++} is demanded. This effect obtains at both 7.0 and 25.0 GeV/c, as shown in Figs. 2(a) and 2(b), suggesting decay modes of the $N^*(1700)$ other than $\Delta^{++}\pi^-$.[13]

(b) *Isospin analysis.* Additional information about the decay modes of the $N^*(1500)$ and $N^*(1700)$ can be obtained from an isospin analysis of the $p\pi^+\pi^-/p\pi^-\pi^0$ ratios once the initial isospin is established as $I=\frac{1}{2}$. As is well known, the $p\pi\pi$ system can be formed in an $I=\frac{1}{2}$, or $\frac{3}{2}$ isospin state which

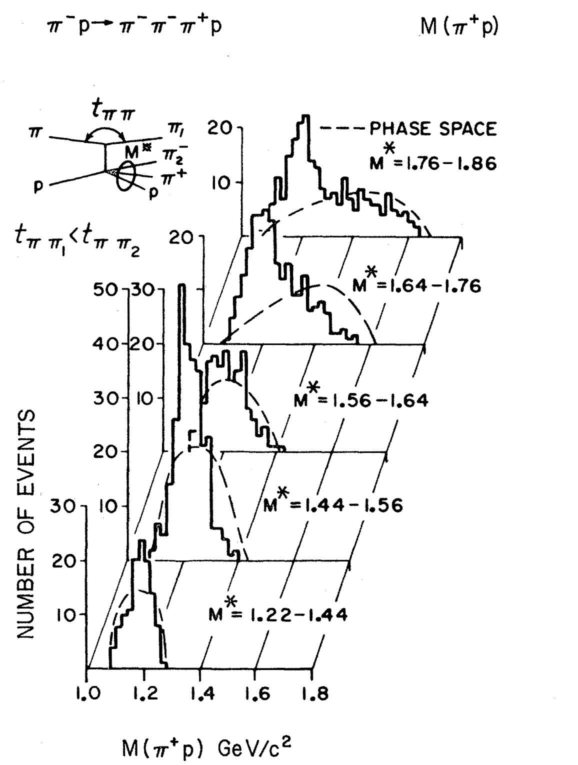

FIG. 4. π^+p mass spectrum for events with $\pi^+\pi^-p$ mass in the $N^*(1500)$, $N^*(1700)$, and three adjacent control regions for the 7.0-GeV/c data.

then decays via $\Delta\pi$, $p\rho(I=1, J=1)$, or directly to $p\pi\pi$. In addition, the $I=\frac{1}{2}$ state can also decay to $p\sigma(I=0, J=0)$. Now the $I=\frac{3}{2}$ assignment can probably be ruled out because of the small amount of $p\pi^-\pi^0$ decay observed, since it requires that $p\pi^+\pi^-/p\pi^-\pi^0=1.6$, or 2.0 depending on whether the decay is $\Delta\pi$ or $p\rho$. From Table I we estimate $p\pi^+\pi^-/p\pi^-\pi^0=3.1\pm 2$ for the $N^*(1500)$, and 2.4 ± 1.2 for the $N^*(1700)$.

The $I=\frac{1}{2}$ assignment, which is in agreement with previous studies[12–15] and the NDD model,[5] requires $p\pi^+\pi^-/p\pi^-\pi^0=2.5$ or 0.5 for $\Delta\pi$ or $p\rho$, and no $p\pi^-\pi^0$ signal for the $p\sigma$ decay. Table I allows us to rule out the $p\rho$ decay, but the $p\pi^-\pi^0$ data [Fig. 2(c)] are unfortunately not enough to single out either the $\Delta^{++}\pi^-$ or the $p\sigma$ mode, though the small $p\pi^-\pi^0$ signal at 1.5 GeV/c^2 suggests that the $N^*(1500)$ decays mainly via $p\sigma$.

(c) *Spin-parity analysis.* If the NDD mechanism dominates the N^* production, as well as the Deck background, then we expect ρ_{ij}, the density matrix describing the production process, to have $\rho_{\frac{1}{2}\frac{1}{2}}=0.5$ and all other entries to be zero.[16] Following the analysis scheme of Berman and Jacob,[17] we plot the polar angle distributions β_N, defined as the angle between the normal to the $p\pi^+\pi^-$ decay plane and the target nucleon in the $p\pi^+\pi^-$ rest frame. In Fig. 5(b), β_N is defined graphically, along with the distributions expected assuming that the states in this mass region have spin $\frac{1}{2}$, $\frac{3}{2}$, or $\frac{5}{2}$.[18–20]

In Fig. 6 we present the $\cos\beta_N$ distributions for the $N^*(1500)$ and $N^*(1700)$ regions, for both the 7.0- and 25.0-GeV/c $p\pi^+\pi^-$ final states. Requiring a Δ^{++} has very little effect on these distributions below 1.75 GeV/c^2.

$N^*(1500)$. The $N^*(1500)$ normal distribution for the 7.0-GeV/c data exhibits a mixture of $J=\frac{1}{2}$ and $\frac{3}{2}$, and a χ^2 fit yields $(34\pm 10)\%$ $J=\frac{1}{2}$. The 25.0-GeV/c data are consistent with a $(85\pm 10)\%$ $J=\frac{1}{2}$ signal. A Deck mechanism leads naturally to a $\Delta^{++}\pi^-$, $J^P=\frac{3}{2}^-$ state which decays isotropically in both $\cos\theta_\Delta$ and $\cos\xi$. A $J^P=\frac{1}{2}^+$ state decaying via $\Delta\pi$ is isotropic in $\cos\theta_\Delta$, but we expect to see a $(1+3\cos^2\xi)$ helicity distribution[17] which is experimentally not observed. The 7.0-GeV/c $N^*(1500)$ data presented in Fig. 6(a) thus appear consistent with a $J^P=\frac{1}{2}^+$ object decaying via $p\sigma$, sitting on a $\frac{3}{2}^-$ $\Delta^{++}\pi^-$ Deck background. This interpretation is possible, not unique, since no attempt has been made to account for the interference effects between states of different spin-parity. However, it seems safe to rule out a $J^P=\frac{1}{2}^+$ decay via $\Delta^{++}\pi^-$. This conclusion is consistent with the results of Rhode *et al.*[18]

The 25.0-GeV/c $N^*(1500)$ $\cos\beta_N$ distribution is quite different from the 7.0-GeV/c data [see Fig. 6(a)]. As noted previously, it appears to be mostly $J^P=\frac{1}{2}^+$, and the $\cos\theta_\Delta$ distribution is isotropic, consistent with a $\frac{1}{2}^+$ or $\frac{3}{2}^-$ state decaying via $\Delta^{++}\pi^-$. However, the $\cos\xi$ distribution is not entirely consistent with the $(1+3\cos^2\xi)$ expected for the $\Delta^{++}\pi^-$ decay, and the resulting distribution could be due to interference from the competing $p\sigma$ channel. As to why the 25-GeV/c $N^*(1500)$ data appear to be nearly totally $J^P=\frac{1}{2}^+$, one might conjecture that at higher energies the same M^* is obtained at much smaller $t_{\pi\pi}$, thus favoring the $\Delta l=0$, $\frac{1}{2}^+\to\frac{1}{2}^+$ NDD transitions over the $\Delta l=1$, $\frac{1}{2}^+\to\frac{3}{2}^-$ transitions observed at 7.0 GeV/c. The amount of $\frac{3}{2}^-$ is related to the total π^--π^- cross section for the mass range sampled. The result found might indicate a small $I=2$ π-π cross section. Note also that the respective β's are 14.0 and 8.0 $(\mathrm{GeV}/c)^{-2}$.

We conclude that if the observed enhancement at 1500 is the P_{11} isobar $N^*(1470)$, then it decays principally via $p\sigma$. This is reasonable in that a $\Delta\pi$ decay would go via p wave, and would thus be suppressed by the centrifugal barrier. Finally, inspection of the region below the $N^*(1500)$ for the

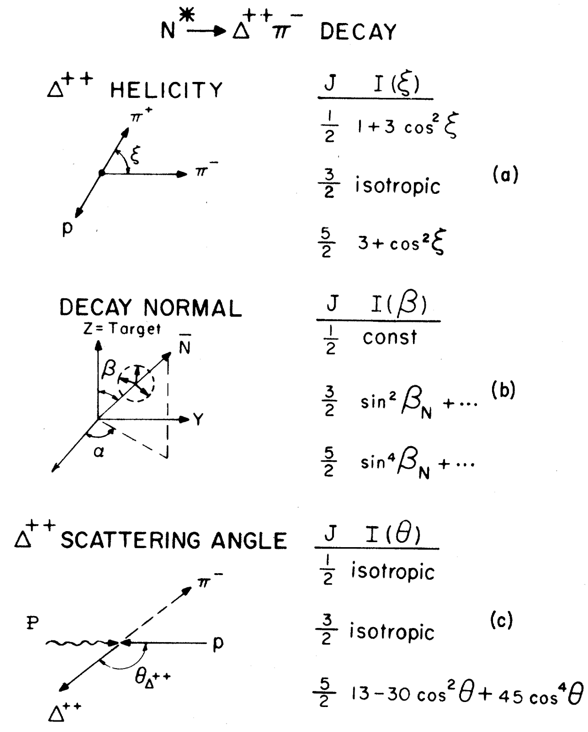

FIG. 5. Coordinate systems used for angular distributions: (a) Δ^{++} helicity angle ξ, the angle between the π^+ and the direction of the Δ^{++} in the Δ^{++} rest frame. On the right are shown the expected distributions for various J^P assignments. (b) decay normal β, the angle between the $N\pi\pi$ decay normal and the target in the $N\pi\pi$ rest frame, (c) Δ^{++} scattering angle θ_Δ in the $N\pi\pi$ rest frame. The distributions shown assume sequential decay.

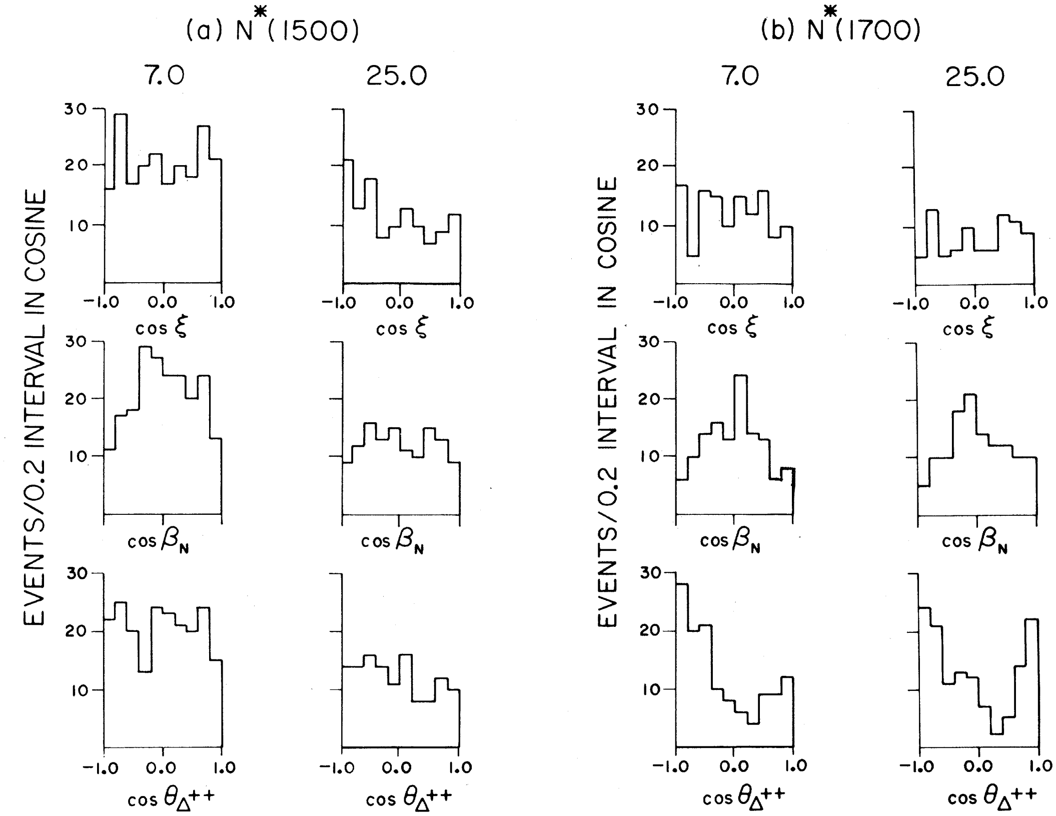

FIG. 6. (a) $\cos\xi$, $\cos\beta$, and $\cos\theta_\Delta$ for the $N^*(1500)$ at 7.0 and 25.0 GeV/c; (b) same as (a) for the $N^*(1700)$ isobar.

7.0-GeV/c data shows this region to be consistent with an almost pure $\Delta^{++}\pi^-$ $J^P=\frac{3}{2}^-$ diffractively produced state, that is, $I(\cos\beta_N)=\sin^2\beta_N$, and the $\cos\theta_\Delta$ and $\cos\xi$ distributions are isotropic. In addition, the very peripheral production, $e^{-12|t_{\pi\pi}|}$, strongly suggests we are seeing a $\frac{1}{2}^+\rightarrow\frac{3}{2}^-$ NDD transition, and this process is likely to be most responsible for the $\frac{3}{2}^-$ $\Delta^{++}\pi^-$ background seen in the $N^*(1500)$ region.

$N^*(1700)$. The $N^*(1700)$ normal distribution shown in Fig. 6(b) is suggestive of $J^P=\frac{3}{2}^-$ or $\frac{5}{2}^+$ for both the 7.0- and 25.0-GeV/c data; one might tentatively identify this enhancement with either the $N^*(1670)$ $J^P=\frac{5}{2}^-$ or the $N^*(1688)$ $J^P=\frac{5}{2}^+$ isobar. The $N^*(1688)$ state is preferred, since it should be easier to produce in a NDD process requiring $\Delta l=2$, whereas $\Delta l=3$ is required for the $\frac{5}{2}^-$ state. Finally, the $\frac{5}{2}^-$ state can be ruled out if we believe the stronger $\Delta P=(-1)^{\Delta J}$ selection rule of Morrison.[8]

If the $N^*(1700)$ state decays mostly into $\Delta\pi$, then the nonisotropic $\cos\theta_\Delta$ distribution [see Fig. 6(b)] allows us to rule out the $J=\frac{3}{2}$ state since it predicts isotropy. The $\cos\theta_\Delta$ distribution agrees best with the $\frac{5}{2}^+$ distribution [see Fig. 5(c)], but the over-all agreement is not that good, and interference effects seem to be present. The $\cos\xi$ distributions are not incompatible with these results, the data being consistent with either the $\frac{3}{2}^-$ or $\frac{5}{2}^+$ hypotheses.

It should be noted from Figs. 2(a) and 2(b), however, that the $N^*(1700)$ displays a sizable non-$\Delta\pi$ mode, and the $\frac{5}{2}^+$ signal could be due entirely to the nonresonant NDD process, which means that the $N^*(1700)$ could also be the $N^*(1700)$ $\frac{1}{2}^-$ above a large $\frac{5}{2}^+$ Deck background. Such a hypothesis is not inconsistent with the angular distributions and agrees with other results.[13] We conclude that if the $N^*(1700)$ decays via $\Delta\pi$, it is $\frac{5}{2}^+$, but one cannot rule out the $J=\frac{1}{2}$ assignment on a $\frac{5}{2}^+$ Deck background. The $\frac{1}{2}^-$ assignment is very interesting in that NDD production of this isobar is forbidden by Morrison's $\Delta p=(-1)^{\Delta J}$ rule.[8]

STRANGE-PARTICLE DECAY MODES

We now investigate the possibility of alternative strange-particle decay modes of the $N^*(1700)$. In Fig. 7 we present the ΛK mass spectrum for the reactions $\pi N\rightarrow\pi K\Lambda$ between 6 and 7 GeV/c.[10] A low-mass ΛK enhancement is clearly seen in Fig. 8(a) in the reaction $\pi^{-,+}N^{+,0}\rightarrow\pi^{-,+}K^{+,0}\Lambda$ centered

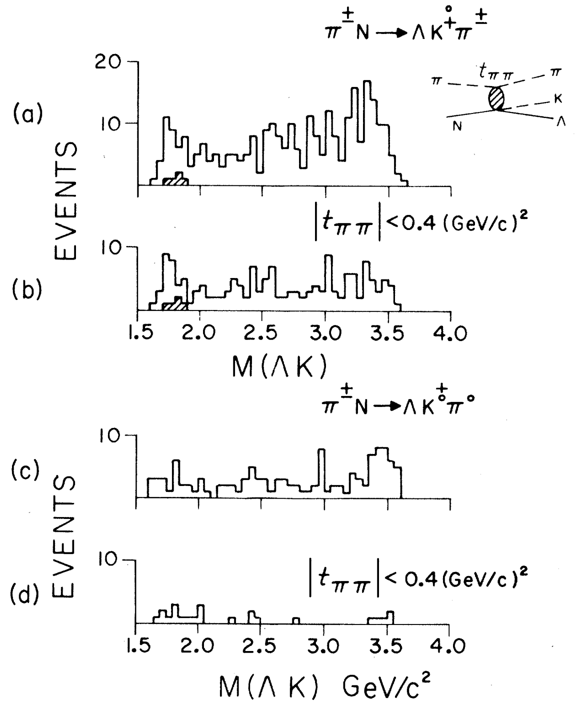

FIG. 7. (a) $\Lambda K^{+,0}$ mass spectrum; (b) same as (a) for $|t_{\pi\pi}| < 0.4$ $(\mathrm{GeV}/c)^2$; (c) $\Lambda K^{+,0}$ mass spectrum for events requiring a charge exchange; (d) same as (c) for $|t_{\pi\pi}| < 0.4$ $(\mathrm{GeV}/c)^2$. Shaded events show $K^*(1400)$ overlap.

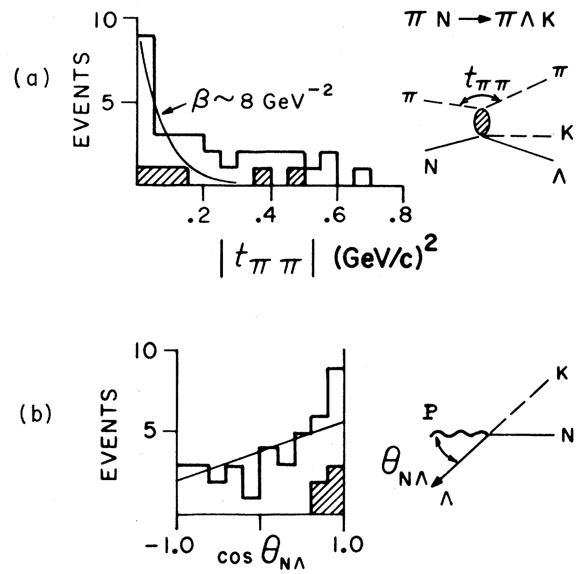

FIG. 8. (a) $t_{\pi\pi}$ distribution for ΛK events in the $N^*(1750)$ region; (b) $\cos\theta$, the $N\Lambda$ scattering angle. Shaded events show $K^*(1400)$ effects.

around 1750 MeV/c^2 with a width of $\simeq 100$–200 MeV/c^2. Its production is very peripheral, since the signal remains almost undiminished when $|t_{\pi\pi}| \leq 0.4$ $(\mathrm{GeV}/c)^2$ is demanded [Fig. 8(b)]. There is no possibility of $K^*(890)$ overlap, and the events which overlap with $K^*(1400)$ are shaded. Their small number demonstrates that we are seeing a bona fide effect and not a kinematic enhancement. Finally, the very peripheral nature of the interaction strongly suggests that we are seeing a NDD process $N \to \Lambda K$.

If the NDD process dominates, then one should not observe similar enhancement in the reaction $\pi^{-,+}N^{+,0} \to \pi^0 K^{0,+}\Lambda$ which requires an $I=1$ exchange. Inspection of Figs. 7(c) and 7(d) shows no such enhancement. This is especially clear when a $|t_{\pi\pi}| < 0.4$ $(\mathrm{GeV}/c)^2$ is demanded, indicating that the dominant process at low ΛK masses is NDD. If this is true, then we expect to fit the $d\sigma/dt$ distribution with an $e^{\beta t}$ form. In Fig. 8(a) is presented the $t_{\pi\pi}$ distribution for the $N^*(1700)$ region. Although the data are poorly fitted by this form, yielding a value of $\beta = 8 \pm 2.1$ $(\mathrm{GeV}/c)^{-2}$ for $|t_{\pi\pi}| < 0.3$ $(\mathrm{GeV}/c)^2$, they do suggest a very peripheral process.[21]

The isospin is established as $I = \frac{1}{2}$ by virtue of the ΛK decay mode. To establish the J^P, we look at the N-Λ scattering angle $\cos\theta_{N\Lambda}$. The results are shown in Fig. 8(b) along with the definition of $\cos\theta_{N\Lambda}$. The distribution is fitted with $1 + 0.47 \cos\theta_{N\Lambda}$. If one removes the events associated with the $K^*(1400)$, then the results are consistent with isotropy. We might be seeing either a $J^P = \frac{1}{2}^+$ or $\frac{1}{2}^-$ state.[22] With this result it is tempting to identify the ΛK enhancement with the decay of either the $S_{11}(1700)$ or $P_{11}(1780)$, or possibly both with interference. Identification of the ΛK enhancement with the $\frac{1}{2}^-$ $N^*(1700)$ isobar would represent a violation of Morrison's $\Delta P = (-1)^{\Delta J}$ rule.[8] Other evidence for a possible violation of Morrison's rule has also been seen in $p\pi^+\pi^-$ data.[13]

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*Work supported in part by the U. S. Atomic Energy Commission under Contract AT(11-1)-881, COO-881-195.

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[1] R. Ehrlich *et al.*, Phys. Rev. Letters 21, 1839 (1968), provides a complete reference for π-, K-, and p-initiated reactions. In addition, a review of the 1.5-GeV/c^2 enhancement is provided by J. G. Rushbrooke in *Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, 1968,* edited by J. Prentki and J. Steinberger (CERN, Geneva, Switzerland, 1968).

See also V. E. Barnes *et al.*, Phys. Rev. Letters 23, 1516 (1969); R. A. Jespersen *et al.*, Phys. Rev. Letters 21, 1368 (1968); P. Antich *et al.*, Phys. Rev. Letters 22, 39 (1969).

[2]G. Belletini *et al.*, Phys. Letters 18, 167 (1965); C. Ankenbrandt *et al.*, Nuovo Cimento 35, 1052 (1965); E. W. Anderson *et al.*, Phys. Rev. Letters 16, 855 (1966); K. J. Foley *et al.*, Phys. Rev. Letters 19, 397 (1967).

[3]R. T. Deck, Phys. Rev. Letters 13, 169 (1964); M. H. Ross *et al.*, Phys. Rev. Letters 19, 546 (1967).

[4]E. Gellert *et al.*, Phys. Rev. Letters 17, 884 (1966). By "kinematic effect," one means that the $\pi^+\pi^-p$ spectrum is determined by a two-vertex diagram ($\pi^- - p$ and $\pi^+ - p$, in this case).

[5]A mechanism using the Deck effect plus a final-state πN interaction, to produce the sharper $N^*(1470)$ structure on the broad Deck kinematic background, has been put forth by J. G. Rushbrooke in Phys. Rev. 177, 2357 (1969).

[6]David J. Crennell *et al.*, Phys. Rev. Letters 19, 1212 (1967).

[7]L. Stodolsky, Phys. Rev. Letters 18, 973 (1967).

[8]D. R. O. Morrison, Phys. Rev. 165, 1699 (1968).

[9]The exposures were: (a) 300 000 pictures, 0.33-μb/event π^-p exposure at 7.0 at ANL in the 30-in. bubble chamber; 100 000 pictures, 0.30-μb/event π^-p exposure at 25.0 at BNL in the 80-in. bubble chamber; and 650 000 pictures, 0.48-μb/event π^+d exposure at 7.0 at ANL in the 30-in. bubble chamber. This film yielded 5000 $\pi^-\pi^-\pi^+p$ events at 7.0, and 2100 events at 25.0 GeV/c. The π^+d exposure yielded 1949 events with visible spectators.

[10]Specifically, the reactions $\pi^-p \to \Lambda K^{0,+}\pi^{0,-}$ and $\pi^+d \to p_s\Lambda K^{0,+}\pi^{+,0}$ were studied. The data represent a Colorado, Ohio University, Toronto, and Wisconsin strange-particle collaboration. The actual collection was done by J. T. Lynch at Wisconsin, with assistance from A. Franklin at Colorado, J. Bishop at Ohio Univ., and J. Prentice at Toronto.

[11]$\pi\pi$ scattering data at $\pi\pi$ masses greater than 1.2 GeV/c^2 are fitted very well by $d\sigma/dt \sim e^{\beta t}$ with $\beta \simeq 8-12$ $(\mathrm{GeV}/c)^{-2}$. At these $\pi\pi$ masses, diagrams 1(b) and 1(d) are indistinguishable, so β is just our $\beta(M^*)$.

[12]P. Antich *et al.*, Phys. Rev. Letters 22, 39 (1969).

[13]V. E. Barnes *et al.*, Phys. Rev. Letters 23, 1516 (1969).

[14]R. Ehrlich *et al.*, Phys. Rev. Letters 21, 1839 (1968).

[15]R. A. Jespersen *et al.*, Phys. Rev. Letters 21, 1368 (1968).

[16]This is characteristic of NDD processes. One can view it as vacuon-nucleon scattering [see Fig. 5(e)]. Since there is only angular momentum exchanged, the maximum spin projection along the proton direction is $\lambda = \pm\frac{1}{2}$. This requires $\rho_{\frac{1}{2}\frac{1}{2}} = 0.5$, and all other $\rho_{ij} = 0$.

[17]S. M. Berman and M. Jacob, Phys. Rev. 139, B1023 (1965).

[18]J. Rhode *et al.*, Phys. Rev. 187, 1844 (1969).

[19]M. Jacob and G. C. Wick, Ann. Phys. (N.Y.) 7, 404 (1959).

[20]Only the terms expected to dominate are given. The complete expansions may be found in the Appendix of Ref. 18. These quoted distributions are independent of the parity of the decaying N^*. Parity information can be obtained through study of the polarization of the nucleon, a near-impossible task. If, however, a $\Delta^{++}\pi^-$ decay scheme obtains, then one can determine the parity from the decay distributions of the Δ^{++}. Again see the appendix of Ref. 18.

[21]This value of $\beta = 8 \pm 2.1$ $(\mathrm{GeV}/c)^{-2}$ agrees with the value of $\beta = 5.9 \pm 2.0$ $(\mathrm{GeV}/c)^{-2}$ found by Crennell *et al.* in the reaction $\pi p \to \Lambda K\pi$ at 6.0 GeV/c. See Ref. 6.

[22]A pure $J^P = \frac{1}{2}^+$, or $\frac{1}{2}^-$ state decaying to a $\frac{1}{2}^+$ and 0^- object, decays via either a p wave ($l = 1$) or s wave ($l = 0$). Either way, the $\cos\theta$ distribution is flat. However, an interfering $\frac{1}{2}^+$ and $\frac{1}{2}^-$ state will produce a $(1 + A\cos\theta)$ distribution. In fitting the data in Fig. 8(b) we have corrected for $K^*(1400)$ overlap.