PRODUCTION OF $K\pi\pi$ RESONANCES AT HIGH ENERGY*

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The previously observed enhancement between 1100 and 1400 MeV in the $K\pi\pi$ mass spectrum is interpreted as a $T=\frac{1}{2}, J^P=1^+$ resonance at 1280 ± 20 MeV and width of 130 ± 15 MeV which decays into $\pi+K^*$ and into $K+\rho$. Evidence is also presented supporting the existence of the newly reported L meson.

Several experimental groups have recently reported on the existence of possible resonant states in the $K\pi\pi$ mass system below 2 GeV.[1-5] We wish to present preliminary results of an investigation of K^+p interactions at 12.7 GeV/c [6] which provide further evidence on such $K\pi\pi$ states.

In Fig. 1(a) we show the invariant-mass distribution for the $(K\pi\pi)^+$ system as obtained from the final states[7]

$$K^+p\pi^+\pi^- \quad (395\text{ events}), \tag{1}$$

and

$$K^0p\pi^+\pi^0 \quad (359\text{ events}). \tag{2}$$

The outstanding feature of these distributions is the dominance of the wide peak at 1300 MeV.[4] Subtracting those events which have large momentum transfers to the proton and events which contain π^+p effective masses in the 3, 3 isobar band yields the shaded distribution.[8] The solid curve in Fig. 1(a) is our estimate of the predominant $K^*\pi$ background; the curve is normalized to the shaded events in the region between 2 and 3 GeV.[9] The dashed curve is the sum of the background and two Breit-Wigner denominators centered at 1320 MeV and at 1780 MeV with natural full widths of 140 and 80 MeV, respectively.[10] We identify the peak at 1780 MeV with the recently reported L meson,[4] and note that we expect less than a total of 12 events in Fig. 1(a) from the $K^*(1420)$ decay through the $K\pi\pi$ mode.[11]

An enhancement at 1300 MeV has been observed in several of the other experiments given in Refs. 1-5; in particular, Shen et al.[2] report the existence of a $K\pi\pi$ resonance at 1320 MeV with a width of 80 MeV. Our own data give support for a single resonance centered at 1280 ± 20 MeV but with a width of 130 ± 15 MeV; this is detailed below. For our analysis we consider only the shaded events of Fig. 1(a) contained in the $K\pi\pi$ mass region between 1100 and 1400 MeV, which for brevity we call the Q events.

(1) A scatter plot of the square of the momentum transfer from the incident to the emerging proton (Δ^2) versus the square of the momentum transfer from the incident proton to the

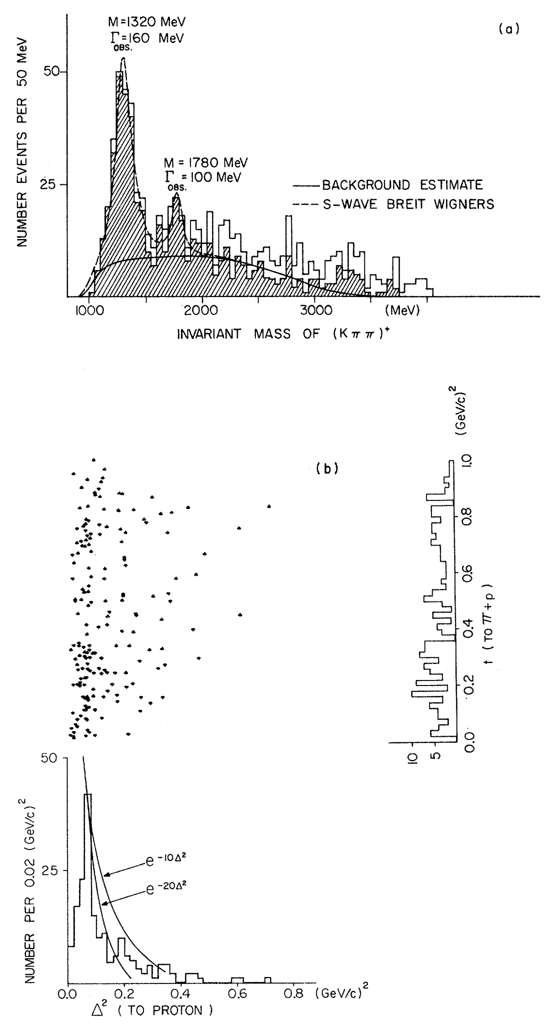

FIG. 1. (a) Mass of $(K\pi\pi)^+$ system for Reactions (1) and (2). For the shaded area we have excluded events which have large momentum transfers and events which have the π^+p mass in the 3, 3 isobar region. (b) Momentum transfer to the π^+p system versus the momentum transfer to the proton for the $K\pi\pi(1300)$ mass region.

p-π^+ system (t) for the Q events is shown in Fig. 1(b). The Δ^2 spectrum is narrower by almost a factor of 10 than the t spectrum.[12] The distribution in Δ^2 is as steep as or steeper than that in any K^+p final state we have studied.[13] The large values observed for t speak against a production process for Q based on a Deck type of mechanism.[14]

(2) By comparing our data with that of the CERN-Brussels collaboration[5] it appears that the cross section for Q events is constant from 3 GeV/c up to our energy. This is to be contrasted with the cross sections for other quasi-two-body final states, such as K^*p, K^0N^*, and $K^{*0}N^*$, which decrease by a factor of 10 in the same energy interval.[15]

(3) The Q events are made up almost entirely of $K\rho$ or $\pi K^*(890)$ combinations. In Figs. 2(a) and 2(b) we show the distributions in the square of the $K\pi$ ($T_3=\pm\frac{1}{2}$) and $\pi\pi$ effective masses for these events. For an isospin $T=\frac{1}{2}$ resonance decaying into $\pi+K^*$ and $K+\rho$ we expect the following branching rates (neglecting all interference effects):

$$\frac{Q^+\to(\pi K^*)^+\to K^0+\pi^++\pi^0}{Q^+\to(\pi K^*)^+\to K^++\pi^++\pi^-}=\frac{1}{1}$$

and

$$\frac{Q^+\to(K\rho)^+\to K^0+\pi^++\pi^0}{Q^+\to(K\rho)^+\to K^++\pi^++\pi^-}=\frac{2}{1}.$$

The observed ratios are 0.85 ± 0.22 and 1.8 ± 0.6, respectively, hence our data are fully consistent with a $T=\frac{1}{2}$ resonance interpretation[16] for Q and are inconsistent with a $T=\frac{3}{2}$ assignment by more than 3.5 standard deviations.

(4) The Treiman-Yang angle distributions for the ρ events (mass 630-890 MeV) in the Q region are shown in Figs. 2(c) and 2(d).[17] If the Deck mechanism were appropriate neglecting background we would expect isotropy in φ_{Kp}. Instead we observe isotropy in $\varphi_{K\rho}$ suggesting that Q production proceeds through spin-0 exchange in the Δ^2 rather than in the t variable.

(5) There is no evidence for Q^{++} production in the final state $K^0\pi^+\pi^+n$ (<2 % of Q^+). This speaks against a $T=\frac{3}{2}$ assignment as well as against a Deck type of mechanism.[14] A similar conclusion is reached from the data on K^-p interactions[5,4] at 5 and 10 GeV/c: The amount of $K\pi\pi$ enhancement at 1300 MeV in the $K^0\pi^+\pi^-n$ state is typically <2 % of that ob-

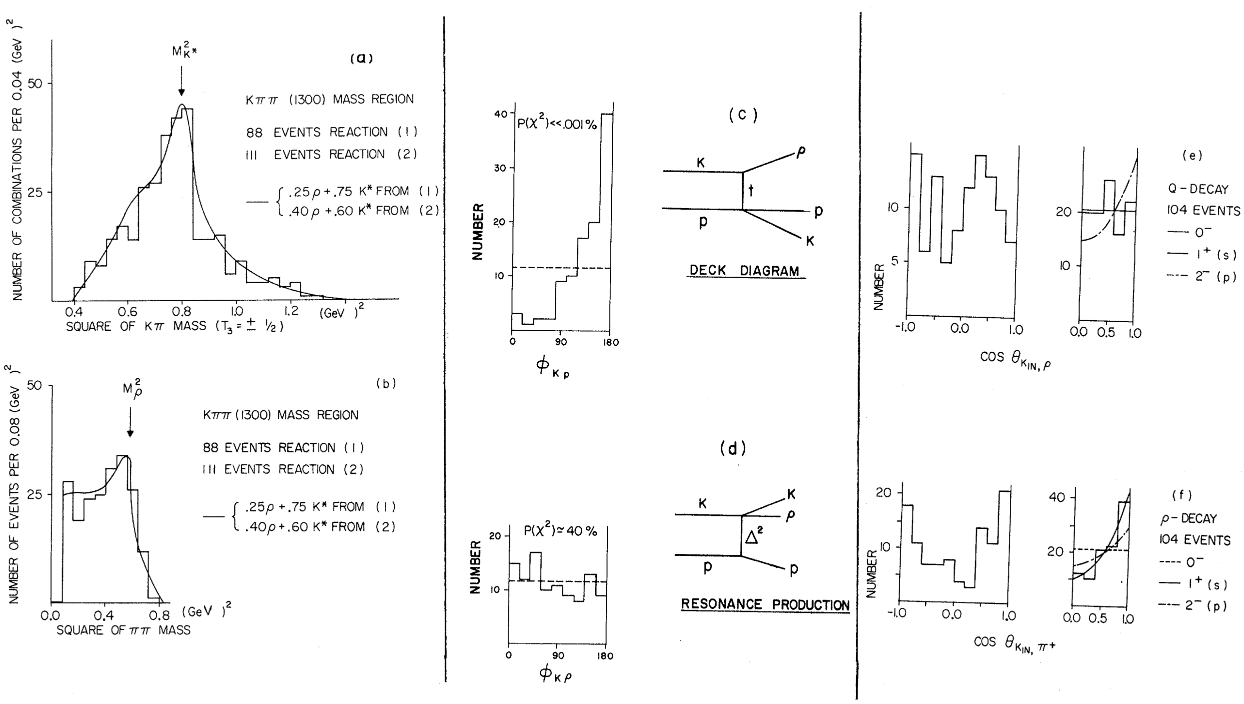

FIG. 2. (a), (b) Square of the invariant mass of the $K\pi$ ($T_3=\pm\frac{1}{2}$) and the $\pi\pi$ mass combinations for the Q events (see text). (c), (d) The Treiman-Yang angular distributions for the Q events, assuming a Deck process (c), and assuming a resonance production process (d). (e), (f) Angular distributions for the decay of Q into $K+\rho$, and the decay of ρ into $\pi+\pi$, respectively. Axis of quantization is the beam direction (see text for explanation of curves).

served in the $K^0\pi^-\pi^0p$ state.[18] This observation is also in contradiction with a Deck-type interpretation of the data and suggests an isoscalar-exchange process for Q production.

(6) The observed branching rates of Q into $K+\eta$, $K+\omega$, and $K+\pi$ are less than 2% (all at the 60% confidence level).[19] The low $K\omega$ mode speaks against an ω-exchange mechanism for Q production. The low decay rates into $K+\omega$ and $K+\eta$ indicate that the J^P assignment for Q is likely to be 0^-, 1^+, 2^-, $\cdots$.

(7) The vector mesons [$K^*(890)$ and ρ] are aligned along the beam axis. This suggests that Q production may not proceed through vector-meson exchange. Indeed from the evidence presented we conclude that Q production proceeds most probably through the exchange of a 0^+ isoscalar[20] (quantum numbers of the vacuum). In this model there is no component of angular momentum along the direction of the incoming K^+ meson, and the J^P assignment for Q can be only 0^-, 1^+, 2^-, $\cdots$; this is in agreement with the conclusions of the previous paragraph.

To study the spin-parity of the Q we consider the simplest assignments, and presently only the $K\rho$ decay mode.[21] Figures 2(e) and 2(f) show the angular distributions for the decay of Q into $K+\rho$, and the decay of the ρ into two pions; each decay angle is calculated with respect to the incident beam direction in the rest frame of the Q and ρ, respectively. There is about 50% background under the ρ peak; we assume that these background events are isotropically distributed. Under this assumption and for the exchange of a spinless particle (see items above) the best fit to both distributions is obtained assuming a 1^+ (s wave) assignment for the Q meson. The odds against a pure 2^- (p wave) are 80:1; a 0^- or a pure 1^+ (d wave) interpretation is inconsistent with the distributions in Fig. 2 by more than three standard deviations.

Having clearly observed the πK^* and the $K\rho$ decays of Q (Fig. 2) we have plotted separately (not shown here) the πK^* and the $K\rho$ mass spectra.[22] The πK^* mass spectrum peaks at 1280 ± 20 MeV, while the $K\rho$ mass distribution shows a peak centered at approximately 1320 MeV. Below we interpret this mass shift as resulting from purely kinematic effects.

Figure 3 shows a scatter plot of the $\pi\pi$ mass versus the $K\pi\pi$ mass for the shaded events in Fig. 1(a). We see that the strong ρ enhancement in the Q occurs essentially at the very edge of phase space.[23] The solid curve in the $K\pi\pi$ mass projection of Fig. 3 is the distribution expected for the $K\pi\pi$ mass spectrum if the Q were a resonance located at 1280 MeV with a width of 130 MeV which decayed into $\pi+K^*$ and into $K+\rho$ with equal strengths, as predicted by SU(3) octet coefficients.[24] Our data are completely consistent with this hypothesis.[25]

Finally, although the statistics are poor, we have supporting evidence for the recently reported L meson.[4] Furthermore, in the $K^0\pi^+\pi^+n$ final state we observe less than three events above background in the L region, where we expect 40 for a $T=\frac{3}{2}$ assignment.[26] Thus we have an independent determination of the isospin of the L meson as $T=\frac{1}{2}$.

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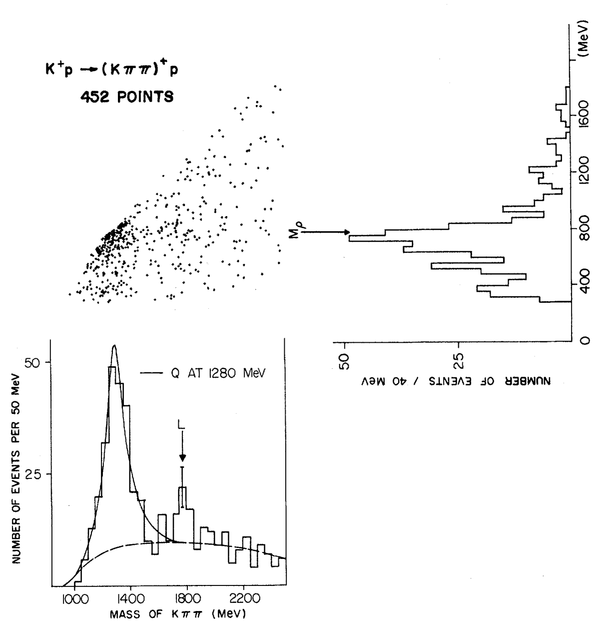

FIG. 3. Invariant mass of the $K\pi\pi$ versus the mass of the $\pi\pi$ system. Dashed curve is the background estimate of Fig. 1(a). The solid curve is the expected spectrum for a $K\pi\pi$ resonance at 1280 MeV, with a total width of 130 MeV, decaying with equal strength into $\pi+K^*$ and into $K+\rho$ (see footnote 23).

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[1]For comprehensive reviews of the experimental situation see A. H. Rosenfeld, University of California Radiation Laboratory Report No. UCRL-16462, 1965 (unpublished), and G. Goldhaber, University of California Radiation Laboratory Report No. UCID-2873, 1966 (unpublished).

[2]B. C. Shen et al., Phys. Rev. Letters 17, 726 (1966).

[3]J. M. Bishop et al., Phys. Rev. Letters 16, 1069 (1966).

[4]J. Bartsch et al., Phys. Letters 22, 357 (1966). These authors observe for 10-BeV/c K^-p interactions an enhancement, in the $K\pi\pi$ system of 1300 MeV, very similar to ours.

[5]W. De Baere et al., CERN Report No. CERN/TC/ Physics 66-19, 1966 (unpublished); Y. Goldschmidt-Clermont et al., CERN Report No. CERN/TC/ Physics 66-17, 1966 (unpublished); B. Goz et al., Bull. Am. Phys. Soc. 12, 44 (1967).

[6]The Brookhaven National Laboratory radio-frequency separated beam was used in conjunction with the 80-inch liquid-hydrogen chamber. For details on the rf beam see H. Foelsche et al., Alternating Gradient Synchrotron Report No. HF/JL/JS/MG-1, 1964 (unpublished).

[7]We estimate that the background due to misidentification of events in Reactions (1) and (2) is less than 15%. Separately, the events from Reactions (1) and (2) have the same characteristics; we have therefore added the two samples of data to improve the statistics. We have also examined the effects of escape corrections and found them to be negligible.

[8]The square of the four-momentum transfer from incoming to emerging proton is required to be <1 (GeV/c)^2, and the π^+p isobar band is defined as 1160 to 1280 MeV.

[9]The smooth curve is a modified phase-space calculation which takes into account the severe distortions into the $K\pi\pi$ mass spectrum by the highly peripheral nature of the K^+p interaction. The events in the $K\pi\pi$ mass spectrum past 3000 MeV are essentially all due to the remaining $N^*(1238)$, hence we normalize the background curve to data below 3000 MeV.

[10]The mass resolution functions for these regions appear to be more Breit-Wigner rather than Gaussian in character, with full widths at half-maximum of ~20 MeV.

[11]This is based on our observation of $K^*(1420)$ production in the final state $K^0p\pi^+$, in conjunction with the branching rates into three bodies given in A. H. Rosenfeld et al., University of California Radiation Laboratory Report No. UCRL-8030, 1967 (unpublished).

[12]This behavior is reminiscent of that observed for the analogous distributions in the reactions $\pi+p\to A_1+p$. See, for example, G. Goldhaber and S. Goldhaber, University of California Radiation Laboratory Report No. UCRL-16744, 1966 (unpublished). Taking account of the kinematic limits in the Δ^2 and in the t spectra makes the two distributions more similar.

[13]This includes the K^*p, N^*K, and K^*N^* final states. The distribution in the forward Δ^2 region for Q events goes as $e^{15\Delta^2}$. The data for $\Delta^2<0.05$ are depleted due to a scanning bias.

[14]We fell that although a Deck type [R. T. Deck, Phys. Rev. Letters 13, 169 (1964)] of model can be used to explain some features of our data, it is generally inadequate for explaining all the features of our data as well as the previous results at lower energies [see Ref. 12 and De Baere et al., Ref. 5). We point out that the Deck model predicts a smaller Q enhancement in the neutron events because of a smaller charge-exchange scattering cross section at the nucleon vertex. Although we cannot predict with certainty the size for this enhancement, a signal >2% of the Q^+ events is a reasonable estimate.

[15]For quasi-two-body final states we observe the following cross sections in millibarns: K^*p (in $K^0\pi^+p$), 0.06 ± 0.01; K^0N^* (in $K^0\pi^+p$), 0.05 ± 0.01; $K^{*0}N^*$ (in $K^+\pi^+\pi^-p$), 0.11 ± 0.03; and $Q(\to K^*+\pi)p$ (in $K^+\pi^+\pi^-p$), 0.18 ± 0.04.

[16]Taking into account unobserved decays, the cross section for one event of Reaction (2) is 2.3 μb. One event is equivalent to 3.3 μb for Reaction (1). The ratios given in the text correspond to those indicated in Figs. 2(a) and 2(b).

[17]The Treiman-Yang angle φ_{Kp} is defined as follows:

$$\cos\varphi_{Kp}=\frac{(\vec{k}_{\text{inc}}\times\vec{k}_\rho)\cdot(\vec{k}_K\times\vec{k}_p)}{|(\vec{k}_{\text{inc}}\times\vec{k}_\rho)|\cdot|(\vec{k}_K\times\vec{k}_p)|},$$

where $\vec{k}_{\text{inc}}$, $\vec{k}_\rho$, $\vec{k}_p$, and $\vec{k}_K$ are the momenta of the incident K^+ and the emerging ρ, proton, and K meson, respectively. All vectors are defined in the laboratory system. An analogous expression holds for $\varphi_{K\rho}$ when calculated in the rest frame of the incident K^+. Similar angles can be defined for the $K^*(890)$ events; these show the same characteristics as their ρ-event analogs. There are also other Treiman-Yang angles which can be defined for other than the simple pseudoscalar-exchange Deck diagram; however, there exists no unique prediction for their behavior. In our data the Treiman-Yang angles for the vector-meson-exchange Deck diagrams exhibit behavior similar to that of φ_{Kp}.

[18]This is particularly clear for K^-+p at 10 GeV/c from the data of Bartsch et al., from which we estimate an upper limit of <1%. See Goldhaber's report in Ref. 1 for the compiled data.

[19]In calculating the upper limit for the $K\pi$ rate we have assumed that Q has $T=\frac{1}{2}$.

[20]It is not at all clear what the energy dependence for such production mechanisms might be; it is also unclear whether a combination of several processes is not needed to explain these data (for example, a 0^+-particle exchange at lower energies and a diffraction or Pomeranchuk-exchange mechanism at higher energies); a detailed calculation is required. We wish to thank Dr. Das, Dr. Kikkawa, Dr. Mathur, and Dr. Okubo for a discussion of this point. See also the discussion of Goldhaber, Ref. 1; D. R. O. Morrison, Phys. Letters 22, 226 (1966); and the data for a process analogous to ours in pp scattering in E. W. Anderson et al., Phys. Rev. Letters 16, 855 (1966).

[21]The cleanest samples of πK^* and $K\rho$ events in the Q region show similar characteristics. The K^* in particular exhibits a clear $\cos^2\theta$ decay along the beam axis. We elect to show only the ρ-decay spectra for the following reasons: (1) The decay of Q into $K+\rho$ can be treated nonrelativistically. (2) Because the Q decays into $K+\rho$ at threshold, it is difficult to interpret, in a simple way, the effect of the ρ reflections in the K^* events in the ρ-K^* overlap region (the effect of the K^* events on the ρ decays is not as severe.) Finally, (3) there is only one possible ρ per event while two K^* are possible in Reaction (2). About half of the events in the ρ band of Fig. 2(b) from Reaction (1) occur in the K^*-ρ overlap region. For Reaction (2) about 80% of the events in the ρ band overlap the two K^* bands. Similarly the K^* events (830 to 950 MeV) come mainly from the K^*-ρ and K^*-K^* overlaps. A model for treating the decay of a meson into $K+\rho$ and $\pi+K^*$ has been developed by Dr. D. Griffiths; we thank Dr. M. Derrick and Dr. A. Cooper for bringing this to our attention.

[22]There is a substantial amount of $\pi K^*-K\rho$ overlap in the Q events (see footnote 21).

[23]This is what would be expected for a $K\rho$ state bound near threshold, and has motivated us to fit the $K\rho$ mass spectrum (not shown) with an s-wave effective-range scattering formalism. A satisfactory fit to the data can be obtained with a scattering length $a_0 \sim 2$ F and an effective range $r_0 \sim 2$ F. The expression used for the effective range approximation is (phase space)/$\{k^2+[-(1/a_0)+\frac{1}{2}r_0k^2]^2\}$, where k is the momentum of the K in the $K\rho$ rest frame; the ρ is treated as a simple Breit-Wigner resonance.

[24]Combining our results for Reaction (1) and (2) we get for the phase-space-corrected (2.0 ± 0.2) decay rates $(Q\rightarrow K+\rho)/(Q\rightarrow\pi+K^*)=0.91\pm0.25$, consistent with SU(3) predictions. The phase-space correction is obtained by integrating the product of the Q-resonance Lorentzian (Breit-Wigner denominator) with the decay vector-meson Lorentzian. We wish to note at this point the similarity between our effect and the C meson which was observed (only in the neutral mode) in $\bar{p}p$ annihilations at rest [R. Armenteros et al., Phys. Letters 9, 207 (1964), and N. Barash et al., in Proceedings of the Twelfth International Conference on High Energy Physics, Dubna, 1964 (Atomizdat., Moscow, 1966)]. Its interpretation was and still is unclear but we feel that it can be the same object that we observe. We thank Dr. N. Barash and Dr. L. Kirsh for reminding us of the C^0.

[25]If the Q is a member of a 1^+ nonet then its decay into $K+\omega$ is anomalously low (by about a factor of 5).

[26]If the isospin of L is $\frac{3}{2}$ then using the previously determined $\pi K^*(890)$ decay rate of L (Ref. 4) and our observed L-production rate in Fig. 1 we expect >40 L^{++} events in the state $nK^0\pi^+\pi^+$. From our data we can exclude $T=\frac{3}{2}$ by $\gtrsim 2.4$ standard deviations.

CONTRIBUTION OF VECTOR MESON EXCHANGE TO ρ^- PRODUCTION AT 4.2 GeV/c*

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We have been studying π^-p two-prong interactions obtained from an exposure of the Lawrence Radiation Laboratory 72-inch hydrogen bubble chamber to an incident beam of 4.2-GeV/c π^- mesons. From a total sample of about 43 000 measured events we have identified 2900 of the type

$$\pi^- + p \rightarrow p + \pi^- + \pi^0. \qquad (1)$$

The aim of this Letter is to present the results of an analysis of the reaction

$$\pi^- + p \rightarrow \rho^- + p. \qquad (2)$$

We study the di-pion effective-mass distribution for different intervals of t, the negative invariant four-momentum transfer squared from the incident to the outgoing proton. As t increases beyond $10\mu^2$, where μ^2 is the pion mass squared, background contamination dominates the diminishing ρ^- peak. Therefore, we will limit our discussion to 304 events with di-pion effective mass between 0.7 and 0.82 GeV and $t<10\mu^2$, which corresponds to $\cos\theta^*$ >0.94 (θ^* is the ρ^- production angle in the overall center-of-momentum system).

The ρ^- decay angular distribution can be ex-