Results from 3.0-GeV/c K^+ Interactions in Hydrogen*

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The interaction of 3.0-GeV/c K^+ mesons on protons was studied in an exposure of the Brookhaven National Laboratory (BNL) 80-in. hydrogen bubble chamber at the alternating gradient synchrotron (AGS). Results are presented concerning a search for resonances requiring higher $SU(3)$ representations than 8 or 10, namely, an isotopic-spin-1 (K^+K^+) or -$\frac{3}{2}$ $(K^+\pi^+)$ boson, and an isotopic-spin-0 or -1 (K^+n) baryon. Evidence is also given for the existence of the $N^*(1400)$ resonance, as well as a new $(K\pi)$ resonance with mass 1260±20 MeV and width 70 MeV.

1. INTRODUCTION

THE experimental results reported in this paper were derived from 100 000 photographs of 3.0-GeV/c positive kaons taken in the BNL 80-in. hydrogen bubble chamber at the AGS. The beam[1] has two stages of dc separation and a full momentum bite of 0.75%. It was designed to run up to 6 GeV/c and thus the separation at 3.0 GeV/c was very large. However, the length needed for the separation of the highest energies meant that a rather large proportion of the K^+ particles decayed in flight. For this reason, a relatively large proton beam intensity was required on the target (3×10^{11} protons per pulse) in order to obtain an average of 10 K^+ tracks in the chamber. Contamination in the beam was small (~15%) and consisted almost entirely of muons resulting from the earlier decay of K's in the beam. Because of this μ contamination, the K-beam flux was determined from a count of τ decays rather than a beam track count. Angle and position criteria were set, defining tracks that were "in the beam" and a fiducial volume was defined. Both τ decays and events were required to lie within these criteria. 4200 τ's were found, corresponding to 5.75 events per μb.

The events were scanned and measured, using image plane digitizers employing a movable puck attached by wires to two measuring heads. The measuring heads wound the wires onto digitized drums whose position indicates, in a semipolar coordinate system, the location of the puck and thus of the track on which the puck fiducial is set. The accuracy of the machines was better than 5μ on the film. Each machine was connected "on line" to an SDS 920 computer which performed a three-view check on the data before accepting the event and writing the measured coordinates onto magnetic tape. The system is described in more detail elsewhere.[2]

The analysis of these photographs has been spread over nearly two years as new interests have given cause to reexamine the data and make new measurements. In this introduction, the steps in this analysis will be briefly described. In the following sections the individual results will then be reported in greater detail.

The original object of the experiment was to confirm or disprove an observation made at CERN[3] of a (K^+K^+) meson. For this purpose it was required to observe reactions of the type

$$K^+ + p \to K^+ + K^+ + \Lambda^0. \quad (1)$$

The film was, therefore, scanned for two-prong events with an associated V whose geometry was compatible with its being a Λ^0. About 40% of all two-prong events with V's were measured. No (K^+K^+) meson was in fact found, as is reported in Sec. 2.

The measurements used for the (K^+K^+) meson search were also used to look at the reaction

$$K^+ + p \to p + \pi^+ + K^0. \quad (2)$$

Events that fitted this reaction were found to contain an enhancement in the $(K^0\pi^+)$ effective mass spectrum at 1260 MeV. In order to increase the data and remove the danger of biases, the remaining 60% of all two-prong and V events were measured. The enhancement was still present and compilations with the data from other groups appear to further confirm the effect. These results are reported in Sec. 3.

At this time in the analysis, reports had been made[4] of the possible existence of one or more positive strangeness baryons. A search for an enhancement in the (K^0p) effective mass spectrum in reaction (2) is complicated by the presence of a strong $K^*(890)$ and $N^*(1238)$. A more promising reaction appeared to be

$$K^+ + p \to \pi^+ + K^+ + n. \quad (3)$$

A sample of two-prong events was therefore selected that did not contain an obvious proton track; these were measured and events selected that fitted reaction (3). As reported in Sec. 4, no evidence of a positive strangeness baryon was observed in the (nK^+) effective mass spectrum, nor was evidence seen of any $I=\frac{3}{2}$ K^* in the $(K^+\pi^+)$ effective mass spectrum.

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[1] I. Skillicorn and M. Webster, Brookhaven National Laboratory Bubble Chamber Group Report H-10, 1962 (unpublished).

[2] D. Hill and R. B. Palmer, Rev. Sci. Instr. (to be published).

[3] M. Ferro-Luzzi *et al.*, Phys. Letters **17**, 155 (1965).

[4] R. L. Cool *et al.*, Phys. Rev. Letters **17**, 102 (1966); R. J. Abrams *et al.*, *ibid.* **19**, 259 (1967).

Using the same events fitting reaction (3), the $(n\pi^+)$ effective mass spectrum was examined. Here, evidence is seen for the well-established N^* resonances at 1238, 1500, and 1688 MeV. Evidence is also seen for the N^* at 1400 MeV, thus confirming results from phase-shift analysis. This result is reported in Sec. 5.

2. EVIDENCE AGAINST A MESON WITH STRANGENESS +2 AT 1280 MeV

Among the many bosons observed to date, the states with spin and parity 0^-, 1^-, and 2^+ are composed of nine particles each and have the isotopic spin I and hypercharge Y properties that can be associated with the constituent states of the representations 1 and 8 of the $SU(3)$ group. Although no representations of larger dimensions have been definitely established, it is of importance in the study of strong interactions to determine whether such states actually exist in nature. This question has special relevance with respect to composite quark models as to whether the presently known bosons are in reality composed of two quarks with increasing angular momentum to account for higher-spin states or multiple-quark states, i.e., 4, 6, etc., with zero angular momentum, the higher spin coming from the addition of the individual quark spins. To this end the existence or nonexistence of an $I=1$, $Y=2$ resonance, such as a (K^+K^+) state, is significant since the 27 is the smallest representation which can accommodate such a particle, and its existence would require the multiple-quark approach. In this section we report our results, as well as a world compilation obtained from a study of the following reactions:

$$K^+ + p \to K^+ + K^+ + \Lambda^0, \quad (4)$$

$$K^+ + p \to K^+ + K^+ + \Sigma^0, \quad (5)$$

$$K^+ + p \to K^+ + K^0 + \Sigma^+, \quad (6)$$

$$K^+ + p \to K^+ + K^+ + \Lambda^0 + \pi^0, \quad (7)$$

$$K^+ + p \to K^+ + K^0 + \Lambda^0 + \pi^+. \quad (8)$$

The evidence for the possible existence of a (K^+K^+) resonance comes from part of the CERN data for the above reactions obtained with K^+'s of momenta of 3.0, 3.5, and 5.0 GeV/c.[3] If one examines each final state individually, one notes that the main contribution to the effect comes from the data at the two lower energies. It was for this reason, therefore, that we repeated the experiment with K^+'s at 3.0 GeV/c. The pictures were scanned for all topologies involving one hyperon decay, either a Λ^0 or Σ^+ decay. In the case of V events it was further required that the line of flight of the V be closer to the positive than the negative track. This had the desired effect of eliminating $\approx 40\%$ of the K^0 decays. It was difficult to detect short decays, and a cutoff of 1 cm was applied amounting to an $\approx 5\%$ correction. Similarly, tracks which interacted within 5 cm of their origin were difficult to measure with the necessary precision and were therefore eliminated at the scanning phase, this corresponding to a 2% correction. For each event the χ^2 probability and expected track ionizations were determined. All events which fit reactions (4) through (8) were reexamined by a physicist for consistency with ionization. In almost all cases the calculated χ^2 probability for the different reactions were widely different, and this, coupled with the estimated ionization, allowed a selection to be made. The minimum accepted χ^2 probability was 1%. The only possible sources of difficulty were π^+ contamination and $(\Lambda^0\Sigma^0)$ ambiguities.

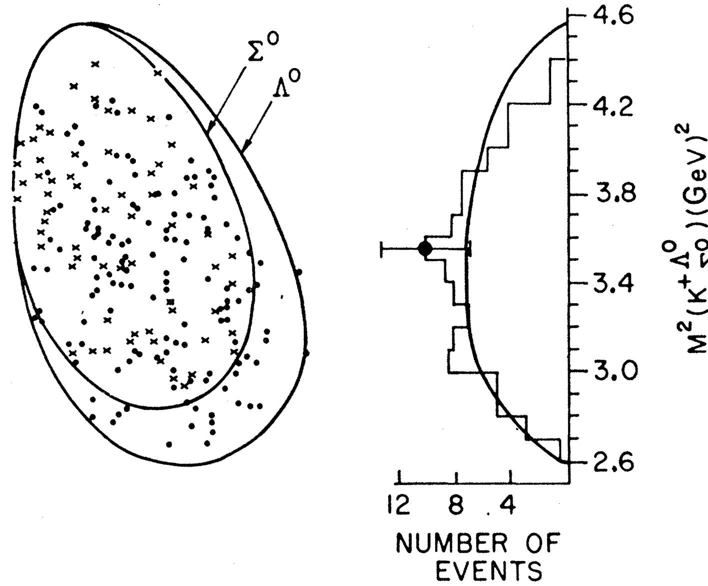
TABLE I. Channel cross sections obtained in this experiment, compared with those reported by the CERN group.[a]

Final state	Number of events	BNL cross section (μb)	CERN cross section (μb)
$K^+K^+\Lambda$	71	22.3±3.3	23.0±4.5
$K^+K^+\Sigma^0$	31	9.8±2.0	7.5±2.5
$K^+K^0\Sigma^+$	51	19.4±4.7	15.0±5.0
$K^+K^+\Lambda\pi^0$	15	4.7±1.3	7.5±2.5
$K^+K^0\Lambda\pi^+$	29	9.1±1.9	12.5±3.5
		65.3±6	65.5±6

[a] Reference 3.

At this energy, the cross section for Λ^0's produced by π's is a factor of 6 greater than that by K^+'s. Therefore, a π^+ contamination as small as 10% can cause appreciable difficulty. In the present case we believe that the π^+ contamination was small, <2%. This was determined from beam design considerations and from measurements on well-constrained events, i.e., 4-constraint fits. The K^+ and π^+ separation at 3.0 GeV/c in the dc separated beam is very large, the image width being only one-quarter of the K^+ to π^+ separation. This ensures that essentially no π^+'s pass the separator slit, so that any π^+'s that arrive at the chamber must arise from K^+'s that decay between the slit and the bubble chamber. Fifteen percent of all K^+'s decay in this distance, 20% of which decay via the $K^+ \to \pi^+\pi^0$ mode, thereby giving a maximum π^+ yield of 5%. However, these resultant π^+'s have a very broad momentum distribution, ranging from a maximum momentum of 3.0 GeV/c to a few hundred MeV/c. At most, 25% of these decays have the proper momentum and decay angle to survive the effects of sweeping magnets and angular and momenta limits placed on the measurement of the beam track in the chamber. This gives a calculated upper limit $\simeq$1–2%. This number was verified from a study of the (4-constraint) reaction $\pi^+p \to \Lambda K^+\pi^+$. No events were found making this fit unambiguously, and four events were ambiguous with the above π^+ interpretation and the reaction $K^+p \to \Lambda^0 K^+K^+$. If one assumes that all four of the ambiguous cases are due to a π^+ initiated reaction, then knowing the cross section for this reaction[5] we

[5] S. S. Yamamoto *et al.*, Phys. Rev. **134**, B383 (1964).



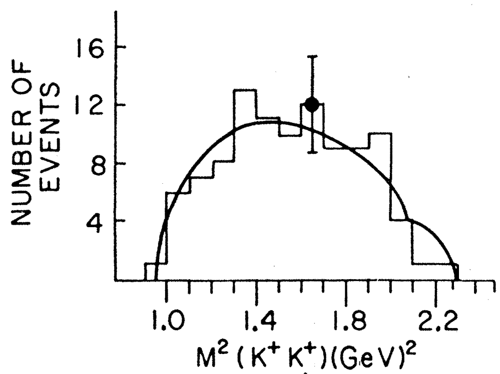


FIG. 1. Dalitz plot for 102 BNL events for the reactions $K^+p \to K^+K^+\Lambda^0$ and $K^+p \to K^+K^+\Sigma^0$ at 3.0 GeV/c. The dots correspond to 71 $K^+K^+\Lambda^0$ events and the crosses to 31 $K^+K^+\Sigma^0$ events. Each event is plotted twice due to the indistinguishability of the two K^+ mesons. Also shown are the two projections. The solid curves are the respective phase-space distributions for the two cases.

obtain a π^+ contamination of 2%. However, we believe this to be an upper limit due to the fact that there were no unambiguous π^+ fits, while there were four ambiguous K^+ fits. This is consistent with a zero measurable π^+ contamination since true K^+ events will be ambiguous with a π^+ interpretation in a small fraction of the cases, since this merely involves a change of a K^+ to a π^+ in both initial and final states.

As an aid in resolving the Λ^0 and Σ^0 ambiguity, two tantalum plates, each 1.5 radiation lengths thick, were inserted into the chamber for half of the run. By detecting the γ rays from Σ^0's, which were produced in a forward direction in the laboratory system, we were able to confirm that the kinematics-fitting correctly distinguished between the two hypotheses. Nine events remained ambiguous between reactions (4) and (5) and these were apportioned in the same ratio as the unambiguous events. The total number of events for each channel as well as the corrected cross sections for both the BNL and CERN data are shown in Table I. One notes the excellent agreement between the two measurements.

The Dalitz plot for our sample of events for reactions (4) and (5) are shown in Fig. 1. They are combined because individually they show the same behavior. There are two points per event because of the indistinguishability of the two K^+ mesons. Also shown are the two projections, namely, the mass square M^2 of the $(K^+\Lambda^0)$ or $(K^+\Sigma^0)$, and the (K^+K^+) final states with their respective phase-space distributions. There is no evidence for a resonance in either system. In Fig. 2(a), the (K^+K^+) and (K^+K^0) effective mass is plotted for all 156 events of reactions (4)–(6), including Σ^+ events. The charged Σ events are of lesser value, since we miss a significant fraction ($\approx 30\%$) of the $\Sigma^+ \to p\pi^0$ decays in which the proton makes a very small angle ($<3^0$) with respect to the Σ^+. However, since the previous evidence[3] for a possible (K^+K^+) enhancement included this channel, they are also included here. Again there is no evidence for any resonance. In Figs. 2(b) and 2(c) the same distributions are shown as published by CERN[3] and Wisconsin.[6] In Fig. 2(d), the compilation is shown

[6] A. R. Erwin *et al.*, Phys. Rev. Letters **16**, 1063 (1966).

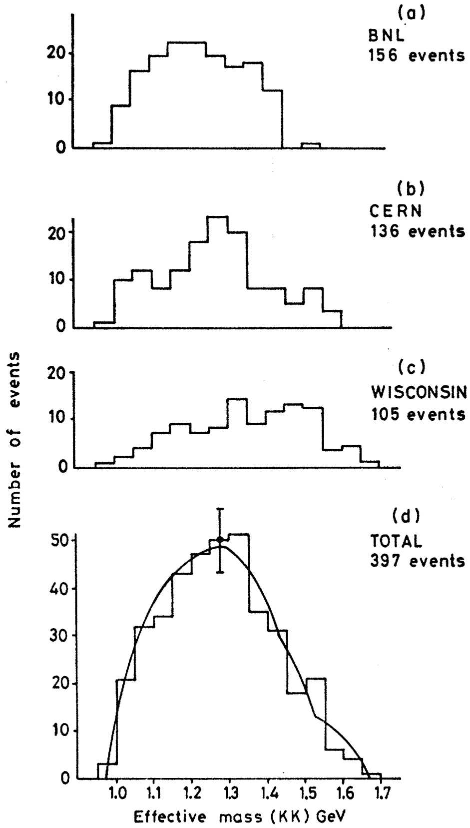


FIG. 2. Plots of the effective mass of the two positive-strangeness kaons in the following data: (a) $K^+p \to K^+K^+\Lambda$, $K^+p \to K^+K^+\Sigma^0$, and $K^+p \to K^+K^0\Sigma^+$ reported from Brookhaven with a K^+ beam momentum of 3.0 GeV/c; (b) $K^+p \to K^+K^+\Lambda^0$, $K^+p \to K^+K^+\Sigma^0$, and $K^+p \to K^+K^0\Sigma^+$ reported from CERN with K^+ beam momenta of 3.0, 3.5, and 5.0 GeV/c; (c) $K^+p \to K^+K^+\Lambda$ and $K^+p \to K^+K^+\Sigma^0$ reported from Wisconsin with K^+ beam momentum of 3.5 GeV/c; (d) the sum of the distributions (a), (b), and (c).

and is seen to agree well with the phase-space curve given in the figure. The χ^2 probability for a fit to the phase space is 40%.

A similar negative effect is concluded from a study of the four-body final states [reactions (7) and (8)]. These channels are much more complicated to analyze due to the multiple resonances that can be produced among the four particles, i.e., Y^*, N^*, K^*, etc. However, in the present case we only find evidence for the production of $Y_1^*(\Lambda\pi)$ with mass of 1385 MeV, the $(K\pi)$ and $(K\Lambda)$ distributions essentially fitting phase space. The (KK) effective mass plot for the 44 four-body events is shown in Fig. 3(a). It is evident that the events show no evidence for any (KK) resonance. In Fig. 3(b) the same distribution is given as published by the CERN group. The much larger statistics arise from the larger cross section for this channel at the higher energy. Figure 3(c) shows the sum of the two previous distributions. The deviation from a smooth curve at 1280 MeV is not found to be more than 1.5 standard deviations.

From this total study we conclude that any previous evidence for any (K^+K^+) resonance is negated by the accumulation of additional data at similar energies.

3. EVIDENCE FOR A $(K^0\pi^+)$ ENHANCEMENT AT 1260 MeV

Three strange-meson states have now been known for some years, namely, the $K(494)$ (0^-), the $K^*(890)$ (1^-), and the $K^*(1425)$ (2^+). Since the discovery of these three, there have been many publications pertaining to other strange mesons with masses below 1500 MeV, yet none have been satisfactorily identified. The $\kappa(720)$ was reported, but has not been confirmed and is now in considerable doubt. Enhancements[7–9] in the $(K\pi\pi)$ effective mass spectra around 1300 MeV have been widely reported but their number, masses, and widths have not been unambiguously identified. Their spin and parity, however, has usually been reported as $J^P = 1^+$.

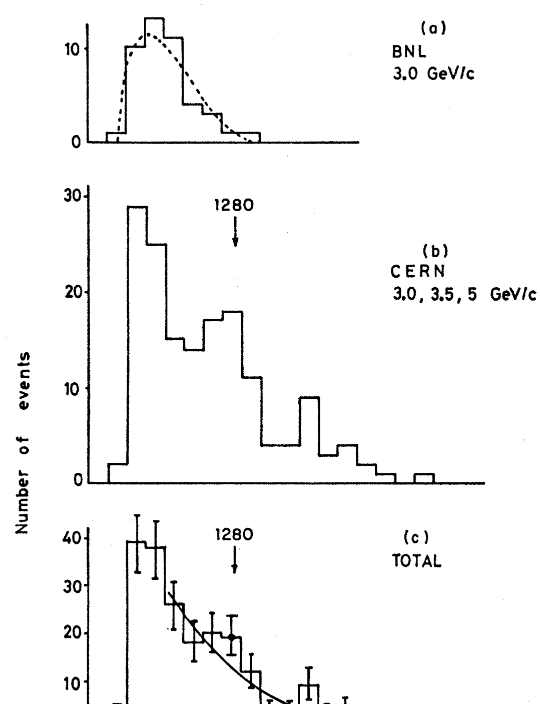


FIG. 3. Plots of the effective mass of the two positive-strangeness kaons in the reactions $K^+p \to K^+K^+\Lambda\pi^0$ and $K^+p \to K^+K^0\Lambda\pi^+$ obtained from (a) data reported from Brookhaven with K^+ beam momentum of 3.0 GeV/c; (b) data reported from CERN with K^+ beam momenta of 3.0, 3.5, and 5.0 GeV/c; (c) the sum of the distributions (a) and (b).

[7] G. Goldhaber *et al.*, Phys. Rev. Letters **19**, 972 (1967).
[8] J. Berlinghieri *et al.*, Phys. Rev. Letters **18**, 1087 (1967).
[9] Y. Goldschmidt-Clearmont *et al.*, Nuovo Cimento **46**, 539 (1966).

Further $(K\pi)$ enhancements have been reported at masses of 1300 MeV[10] and 1080 MeV,[11] neither of which have been confirmed. Evidence will be presented here for a $(K\pi)$ resonance at a mass of 1260 MeV, a mass within the range covered by the broad $(K\pi\pi)$ enhancements. It will be argued, however, that it is unlikely to be associated in the broad $(K\pi\pi)$ region. In addition, a compilation of various experiments shows some indication of an excess of events at a $(K\pi)$ effective mass of 1080 MeV.

The data used in this analysis are taken from measurements of all two-prong events with a V seen. These events were fitted to the reaction

$$K^+ + p \rightarrow K^0 + p + \pi^+, \tag{2}$$

where the probability was 10% or greater. The only ambiguities occurred when two different fits were obtained to this same reaction, the second fit having the p and π^+ exchanged. These ambiguities were removed by a visual estimation of the track ionizations.

The $(p\pi^+)$ effective mass spectrum is plotted in Fig. 4 and is seen to contain a strong $N^*(1238)$. Figure 5(a) shows the distribution of the effective mass of the $(K^0\pi^+)$ system for the BNL data at 3.0 GeV/c. Besides a strong $K^*(890)$, some evidence is seen for the $K^*(1420)$. Evidence of this had not been previously seen at this energy.[12] A broad and not very significant enhancement is also observed with a peak around 1260.

In order to investigate this 1260 enhancement, events were selected which did not contain an $N^*(1238)$ (effective mass $p\pi^+$ excluded between 1160 and 1320 MeV). These events are plotted in Fig. 6(a). The background is significantly reduced and the bumps at 1260 and 1430 are enhanced. An enhancement is also seen at 1080 in the compiled data [Fig. 6(e)], which may be taken as some confirmation of the existence[11] of a resonance at this mass. A fit to the data plotted in Fig. 6(a) allowing Breit-Wigner resonances at 890, 1080, 1260, and 1430 MeV gave 106 events in the 1260-MeV bump, corresponding to a cross section of 55 μb for the reaction

$$K^+ + p \rightarrow K^*(1260) + p$$
$$\searrow \pi^+ + K^0 \text{ (seen and unseen)}. \tag{9}$$

After correction for the removal of the $N^*(1238)$

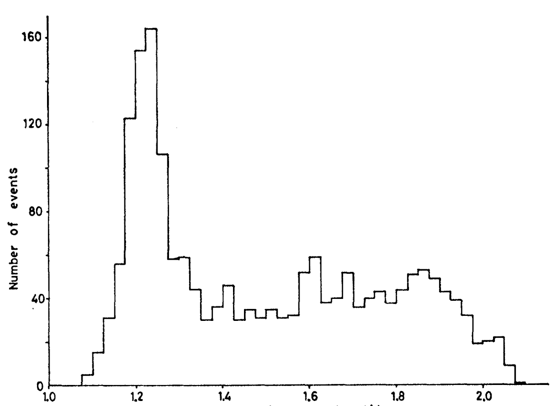


FIG. 4. Plot of the effective mass of the $(p\pi^+)$ system in the reaction $K^+p \rightarrow K^0p\pi^+$ at a K^+ beam momentum of 3.0 GeV/c.

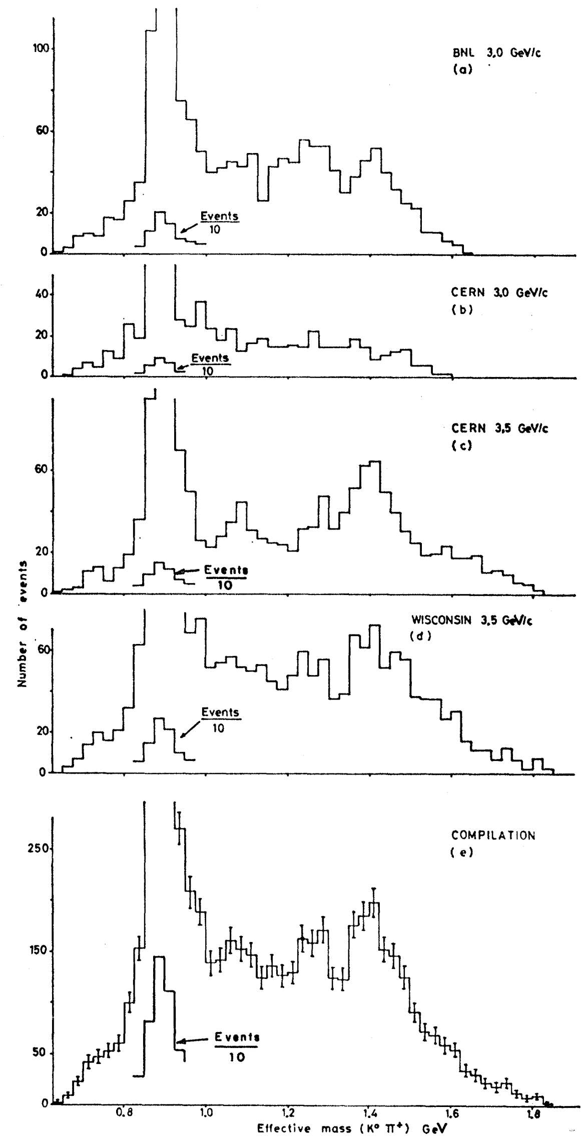


FIG. 5. Plots of the effective mass of the $(K^0\pi^+)$ system in the reaction $K^+p \rightarrow K^0p\pi^+$: (a) data obtained at BNL with K^+ beam momentum of 3.0 GeV/c; (b) data obtained at CERN with K^+ beam momentum of 3.0 GeV/c; (c) data obtained at CERN with K^+ beam momentum of 3.5 GeV/c; (d) data obtained at Wisconsin with K^+ beam momentum of 3.5 GeV/c; (e) the compilation of (a) through (d).

[10] J. M. Bishop *et al.*, Phys. Rev. Letters **16**, 1069 (1966).
[11] W. DeBaere *et al.*, Nuovo Cimento **51A**, 401 (1967).
[12] M. Ferro-Luzzi *et al.*, Nuovo Cimento **36**, 1101 (1965).

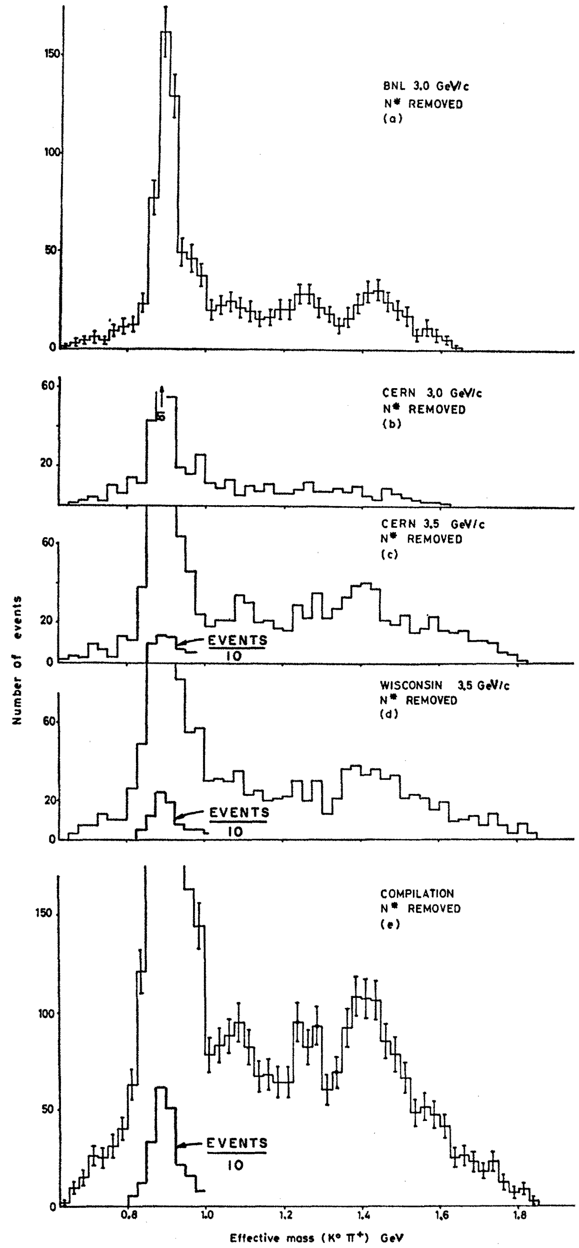


FIG. 6. Plots of the effective mass of the $(K^0\pi^+)$ system in the reaction $K^+p \rightarrow K^0p\pi^+$ for events in which the effective mass of the $p\pi^+$ system does not lie between 1160 and 1320 MeV: (a) data obtained at BNL with K^+ beam momentum of 3.0 GeV/c; (b) data obtained at CERN with K^+ beam momentum of 3.0 GeV/c; (c) data obtained at CERN with K^+ beam momentum of 3.5 GeV/c; (d) data obtained at Wisconsin with K^+ beam momentum of 3.5 GeV/c; (e) the compilation of (a) through (d).

band, the estimate for the cross section for reaction (9) becomes 70 ± 25 μb.

In a further attempt to improve the resonance to background ratio, events were selected for which the cosine of the center-of-mass angle between the incoming K^+ and outgoing $K^0\pi^+$ was less than 0.6, i.e., peripherally produced $K^0\pi^+$ events. These events are plotted in Fig. 7. The dip between the 1260 and 1430 bumps is now deeper and, if the bump is assumed to be real, the background under the 1260 peak is only about 30%.

Since the statistical significance of the 1260 bump in the BNL data corresponds to only about 3 standard deviations, an attempt has been made to improve the statistics by forming a compilation of published K^+p data at K^+ beam momenta of 3.0 GeV/c [12] and 3.5 GeV/c.[11,13] Since Dalitz plots are published in each case, it has been possible to form compilations with and without the N^* removed. The published data do not allow a compilation of events with both the N^* removed and $\cos\theta(K\pi) < 0.6$.

The unselected data from all sources are plotted in Figs. 5(a)–5(d) and the unselected compilation is shown in Fig. 5(e). All individual distributions show some slight bump in the 1260 region and the compilation shows a substantial bump between 1225 and 1300 containing at least 100 events above a background of approximately 400 events; this is greater than a 4-standard-deviation effect. The resonance to background ratio is 1:3.

The data after N^* removal are plotted in Figs. 6(a)–(d), and the compilation with the N^* removed is shown in Fig. 6(e). Once again the compiled plot shows a significant bump between 1225 and 1300 MeV. The bump contains at least 75 events on a background of 190 events. The significance is 4.6 standard deviations and the signal-to-background ratio 1:2.5.

It should be noted that in both compilations, with and without N^* removal, the excess of events is seen at a $(K\pi)$ mass of 1080 MeV. The effect is not overwhelming because of the near proximity of the $K^*(890)$, which makes it difficult to estimate a background curve reliably.

Data have also been examined from K^+p reactions at 4.6,[14] 5,[15] and 10 GeV/c.[16] Little evidence for the $K^*(1260)$ was seen, but the statistics in these experiments were not sufficient to allow any conclusion to be drawn from them as to the possible existence of the resonance. K^-p data at 3.0 GeV[17] and at 3.5 GeV[18] have also been examined. No evidence is seen in the former. In the latter, a 2-standard-deviation bump is seen at 1240 MeV in the sum of the $(K\pi)$ effective mass distributions from the following reactions:

$$K^-+p\rightarrow K^-+\pi+n\,, \tag{10}$$

$$K^-+p\rightarrow K^-+\pi^0+p\,, \tag{11}$$

$$K^-+p\rightarrow \bar{K}^0+\pi^-+p\ (K^0\text{ seen and unseen})\,. \tag{12}$$

[13] J. M. Bishop *et al.*, University of Wisconsin, reported at Heidelberg International Conference on Elementary Particles, 1967 (unpublished).
[14] B. C. Shen *et al.*, Phys. Rev. Letters **17**, 726 (1966).
[15] F. Verbeure, thesis, University of Leuven, Holland, 1967 (unpublished).
[16] Birmingham-Glasgow-Oxford Collaboration, CERN Report 68-7, page 121, 1968 (unpublished).
[17] S. Focardi *et al.*, Phys. Letters **16**, 351 (1965).
[18] B. Musgrave *et al.*, Rutherford Laboratory Report No. H29 (unpublished).

The background level in the K^-p data is much higher in the region than in the K^+p case and thus the bump, despite its small statistical significance, corresponds to the relatively large cross section of about 150 μb for the sum of all three of the above reactions.

It is concluded that there is some evidence for a $(K^0\pi^+)$ resonance with a mass of 1260 ± 20 MeV and a width of the order of 70 MeV. Its production by K^+p at 3.0 and 3.5 GeV/c K^+-beam momenta has a cross section of the order of 70 μb. If this resonance were to be associated with some part of the broad $(K^*\pi)$, $(K\rho)$ enhancement around 1320, then we would be forced to conclude that the spin parity of the resonance is 1^-, 2^+, 3^-, etc. This is not in agreement with the preferred assignment for the $(K^*\pi)$ enhancement of 1^+. A further argument against associating the $(K\pi)$ bump with any $(K^*\pi)$ enhancement is obtained from a consideration of branching ratios. The cross section for the $K^*(1320)$ enhancement in the reaction $K^++p\rightarrow K^{*0}+\pi^++p$ is found[8,19] to be almost independent of K^+ energy from 3.5 to 12.6 GeV and equal to about 180 μb. Thus, although it is not easy to distinguish the $K^*(1320)$ enhancement at 3.0 GeV, we may assume that it is produced with about 180-μb cross section. The observed branching ratio $K^0\pi^+/K^{*0}\pi$ at this energy is of the order of 1. This is in disagreement with the failure to observe any $(K^0\pi^+)$ decay mode of the 1320 seen at higher energies. The quoted[8] limit for the branching ratio is

$$\frac{K^*(1320)\rightarrow K^0\pi^+}{K^*(1320)\rightarrow \text{all}}<2\%\ (90\%\ \text{confidence}).$$

It is concluded, therefore, that the resonance, if real, is not associated with the $(K^*\pi)$ enhancement at 1320 MeV.

One can speculate that the $K^*(1260)$ could have $J^P=0^+$ and thus be a member of the last of the four positive-parity K^*'s predicted[19a] by Dalitz and others on the basis of a quark-antiquark bound state with angular momentum 1. If this were so it seems not unreasonable that its mass lies near the mass of the other three positive-parity K^*'s: $K^*(1400)$, C meson (1230), and $K_A(1320)$. With the limited statistics available, the decay angular distribution of the $K^*(1260)$ is isotropic and thus consistent with 0^+. If a 0^+ assignment were true, then the resonance could not be produced by Pomeranchon exchange, and thus its production cross section would, instead of being constant, fall with increasing beam energy in a way similar to that of the $K^*(890)$ production. The two-body production of $K^*(890)$ in the reaction $K^++p\rightarrow K^*(890)^++p$ is approximately[9] 1.3 mb at 3.0 GeV and falls to only 0.06 mb by 12.6 GeV.[2] If the two-body production of

[19] W. DeBaere *et al.*, Nuovo Cimento **49**, 373 (1967).

[19a] R. H. Dalitz, in *Proceedings of the Thirteenth Annual International Conference on High-Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967), p. 215.

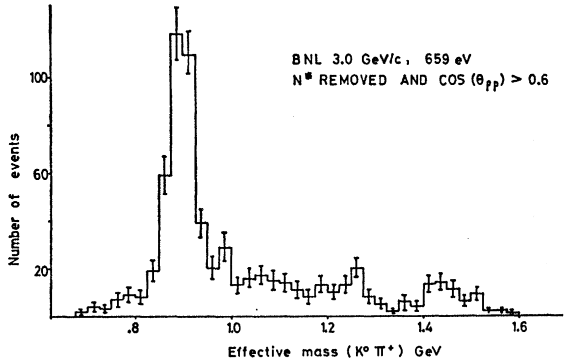


FIG. 7. Plot of the effective mass of the $(K^\circ\pi^+)$ in the reaction $K^+p\rightarrow K^0p\pi^+$ for events in which (1) the $p\pi^+$ effective mass does not lie in the region 1160–1320 MeV and (2) the cosine of the center-of-mass angle between the incoming K^+ and outgoing $K^0\pi^+$ system is less than 0.6.

$K^*(1260)$ fell at the same rate we would predict a production cross section of only 3 μb at 12.6 GeV. This may be compared with the observed upper limit of 4 μb derived from the branching-ratio limit[8] quoted above. Thus, although the evidence for a $K^*(1260)$ is not conclusive, its existence is not excluded by the results obtained at higher energies, and if its spin-parity is 0^+, it would fit nicely into the quark-antiquark shell model.

4. SEARCH FOR $S=+1$ BARYONS AND $I=\frac{3}{2}$ MESONS

Almost all reported strongly interacting baryons have quantum numbers consistentwith the model that supposes them to be formed of three quarks (QQQ). There is no theoretical reason why an antiquark-plus-four-quark baryon state $(\bar{Q}QQQQ)$ should not exist, but little evidence for such a state has been seen, and such evidence as has been presented has remained largely unconfirmed. An exception to this might have to be made in the case of positive-strangeness baryons. Since quarks have only zero or negative strangeness it follows that a simple three-quark model does not fit such a baryon. An antiquark-plus-four-quark system is, however, possible (e.g., $\bar{\lambda}\mathcal{P}\mathfrak{N}\mathfrak{N}\mathfrak{N}$).

Evidence for the existence of such positive-strangeness baryons was first seen in measurements of the total cross section[4] of K^+ mesons on protons and deuterons. In each of these cross sections, a considerable peak is seen at K^+ momenta near 1–2 GeV/c and some smaller fluctuations are seen at higher momenta. The larger peaks can be fitted by an $I=1$ resonance at 1910 MeV and an $I=0$ resonance at 1863 MeV. Some supporting evidence for the $I=1$ resonance was obtained in a missing-mass photoproduction experiment.[20] But evidence[21] from a pion missing-mass experiment

[20] J. Tyson *et al.*, Phys. Rev. Letters **19**, 255 (1967).

[21] D. Birnbaum *et al.*, in *Proceedings of the Heidelberg International Conference on Elementary Particles*, edited by H. Filthuth (Wiley-Interscience Publishers, Inc., New York, 1968).

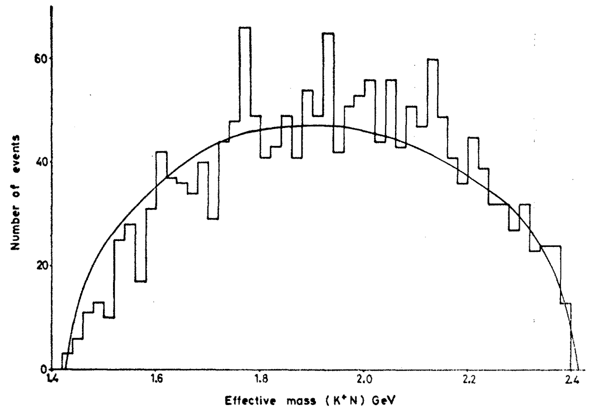


FIG. 8. Plot of the effective mass (K^+n) from the reaction $K^+p \to \pi^+K^+n$, 1845 events. The smooth curve represents a normalized phase space.

that had been interpreted as supporting either $I=0$ or $I=1$ resonance was later[22] explained as a kinematic effect. Although the narrowness of the bumps in the total cross section are hard to explain without a resonance, it is nevertheless desirable to observe the production and decay of the resonances. We have, therefore, searched for an enhancement in (Kp) effective mass spectra in reactions in which the K, p, and one pion are produced.

As has been noted, the reaction

$$K^+ + p \to K^0 + \pi^+ + p \qquad (2)$$

is dominated by $K^*(890)$ and $N^*(1238)$ production. In fact, 70% of all events in this channel lie in either one or the other band. Of the remaining 30% a significant fraction contains a $K^*(1400)$, leaving only a relatively small number of events which might contain a (K^0p) resonance. A plot of the (K^0p) effective mass distribution with K^* and N^* removed was nevertheless examined and found to show no enhancement. Even though the sample was small and the phase space distorted by the cuts, a strong production of a (K^0p) resonance should have been observed.

A better channel in which to look for the production of a positive strangeness baryon is

$$K^+ + p \to K^+ + \pi^+ + n. \qquad (13)$$

In this channel, there can be no $K^*(890)$ production and isotopic spin considerations reduce the cross section for $N^*(1238)$ production.

About a third of the film, selected on the basis of quality, was scanned for two prongs, and all those not containing an identified proton track were measured. This selection was aimed at eliminating most of the elastic events and had the effect of reducing the number of events measured by a factor of 2. A total of 15 000 events were measured, and 1883 were selected whose kinematics and ionizations fitted reaction (13).

Figure 8 shows the effective mass distribution for the (K^+n) system for these events. No enhancement is seen near 1.8 GeV. The data fit the phase-space curve well, which is indicated by the smooth line.

From these results we conclude that the production of a Z^{*+} whose width is less than 200 MeV in the reaction

$$K^+ + p \to Z^{*+} + \pi^+ \qquad (14)$$

at 3.0 GeV/c, followed by its decay into K^0+p or $K^+ + n$, proceeds with a cross section less than 30 μb with 90% confidence.

We will now consider the $I=\frac{3}{2}$ K^* mesons. As reviewed in Sec. 2, most mesons could be formed of a quark and an antiquark. In that section, negative evidence was presented for one meson (K^+K^+) that could not be so formed. An $I=\frac{3}{2}$ K^* would be another such meson that does not fit the scheme. Such a K^* cannot be formed of only two quarks because quarks have either $I=\frac{1}{2}(\mathcal{N},\mathcal{P})$ or $I=0$ (λ). Previous evidence has been presented for $I=\frac{3}{2}$ K^*'s, seen in the $(K\pi\pi)^{++}$ system, with masses at 1175 MeV [10,23] and at 1270 MeV.[24,25] The former evidence came from K^+p interactions at 3.5 and 10 GeV/c and might, thus, be expected in the present experiment.

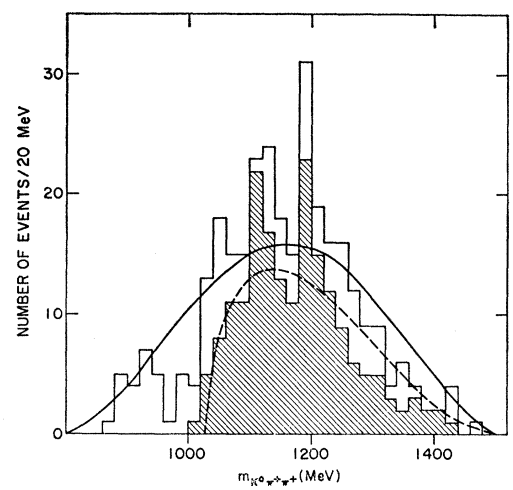


FIG. 9. Plot of the effective mass of the $(K^0\pi^+\pi^+)$ system in the reaction $K^+p \to K^0\pi^+\pi^+\pi^-p$. The unshaded histogram shows all events and the solid smooth curve indicates normalized five-body phase space. The shaded histogram is of those events containing $K^*(890)$ and the lower dashed curve indicates the four-body phase space for the reaction $K^+p \to K^*(890)^+\pi^+p\pi^-$.

[22] D. Birnbaum (private communication, 1968).

[23] Birmingham-Glasgow-Oxford Collaboration, in *Proceedings of the Heidelberg International Conference on Elementary Particles*, edited by H. Filthuth (Wiley-Interscience Publishers, Inc., New York, 1968).

[24] G. Goldhaber, in *Proceedings of the Thirteenth Annual International Conference on High-Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967), p. 137.

[25] R. Böck *et al.*, Phys. Letters **12**, 65 (1964).

All four-prong events with a visible V were measured and those were selected that fitted the reaction

$$K^+ + p \rightarrow K^0 + \pi^+ + \pi^+ + \pi^- + p. \quad (15)$$

Three hundred and eight events fitting this reaction were found, corresponding to a cross section of 350 ± 40 μb. In Fig. 9 the $(K^0\pi^+\pi^+)$ effective mass distribution is shown for all events (unshaded), and with the requirement that one or the other π^+ forms a $K^*(890)$ with the K^0 (shaded). Although some structure is seen, it will be noted that at the mass value 1175 MeV there is a dip in the distribution and that no structure is seen at 1270 MeV. It is concluded that there is no supporting evidence for resonances at either of these mass values.

An $I = \frac{3}{2}$ K^* might also be observed in the $(K^+\pi^+)$ system and reaction (13) is a good channel in which to search for such a resonance. The unshaded histogram in Fig. 10 shows this mass distribution for reaction (13) with no selection criteria applied. No evidence of an enhancement at 1175 or 1270 is seen, but the distribution does seem to depart from the indicated phase space at higher effective masses. As will be reported in Sec. 5, we do find that the reaction contains production of a number of nucleon isobars. Since reflections of these could distort the $(K^+\pi^+)$ effective mass distribution, a selection was made in which the most strongly produced isobar events were removed. These isobars (see Sec. 5) were those at 1238, 1500, and 1688 MeV. All events were therefore removed whose $(n\pi^+)$ effective masses lay in the regions 1200–1320, 1460–1540, and 1620–1720 MeV. The remaining events are shown in the shaded histogram of Fig. 10 together with phase space. It is seen that the high mass departure from phase space has been removed and there is still no evidence for any $I = \frac{3}{2}$ K^*.

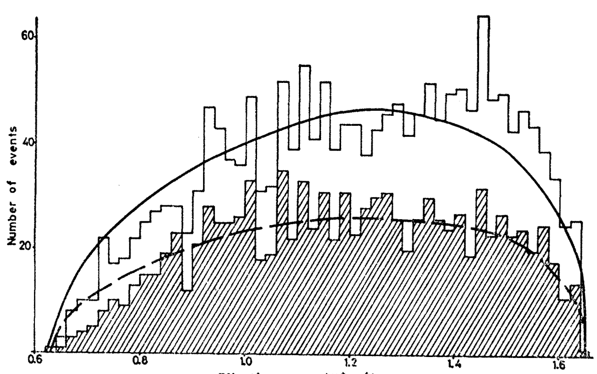


FIG. 10. The unshaded histogram represents the distribution of the effective mass $(K^+\pi^+)$ from the reaction $K^+p \rightarrow \pi^+K^+n$, 1845 events plotted. The solid smooth curve represents a normalized phase space. The shaded histogram represents the same distribution after removing all events for which the effective mass (π^+n) lies in any of the following regions: 1200–1320, 1460–1540, and 1620–1720 MeV, and the dashed curve represents a corrected phase space.

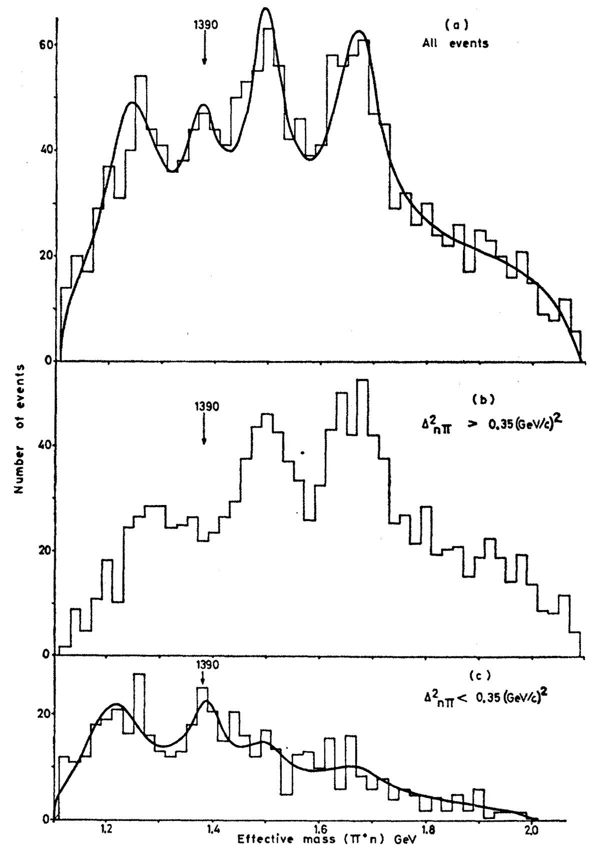


FIG. 11. Plots of the effective mass (π^+n) from the reaction $K^+p \rightarrow K^+\pi^+n$. All events are plotted in (a); those with momentum transfer to the (π^+n) system greater and less than 0.35 $(\mathrm{GeV}/c)^2$ are plotted in (b) and (c), respectively. The smooth lines in (a) and (c) represent a simultaneous fit to these two distributions allowing four Breit-Wigner resonances and phase space.

5. OBSERVATIONS OF $N^*(1400)$ AND OTHER NUCLEON ISOBARS

As has been stated in the previous section, the reaction

$$K^+ + p \rightarrow K^+ + \pi^+ + n \quad (13)$$

was found to contain strong production of several nucleon isobars. Besides the well-established $N^*(1238)$, $N^*(1500)$, and $N^*(1688)$, evidence was seen for the $N^*(1400)$. Previous phase-shift analysis[26] of (πn) elastic and charge-exchange scattering has indicated the possible existence of a P_{11} (πn) resonance with a mass around 1400 MeV. However, different analyses report masses as far apart as 1380 and 1471 MeV. The production of a baryon enhancement at a mass 1400 has

[26] L. D. Roper *et al.*, Phys. Rev. **138**, B190 (1965); P. Bareyre *et al.*, Phys. Letters **18**, 342 (1965); B. H. Bransden *et al.*, Phys. Rev. **139**, B1566 (1965); C. Lovelace, presented at the Thirteenth Annual International Conference on High Energy Physics, Berkeley, 1966 (unpublished).

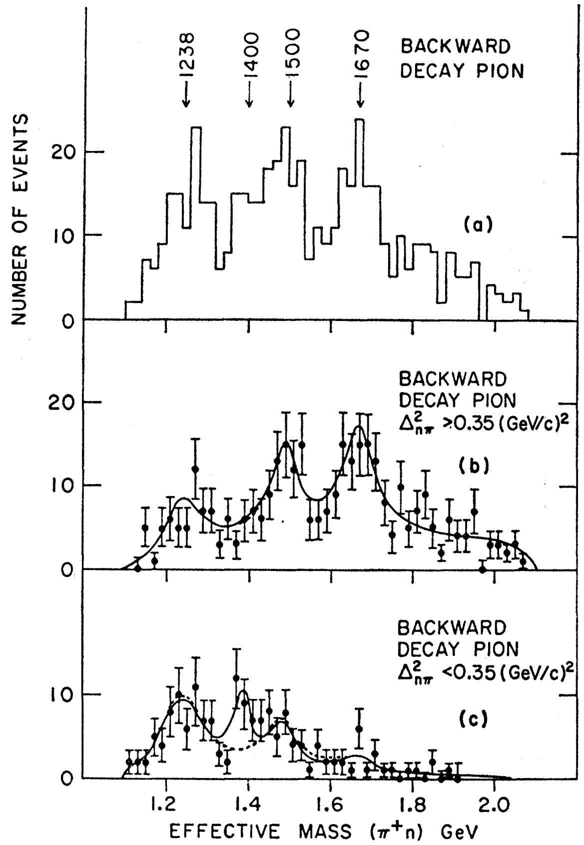


FIG. 12. Plots of the effective mass (π^+n) from the reaction $K^+p \to K^+\pi^+n$ in which the pion is required to be backward in the (π^+n) center-of-mass system, with respect to the incoming beam. All such events are plotted in (a); those with momentum transfer to the (π^+n) system greater and less than 0.35 $(\text{GeV}/c)^2$ are plotted in (b) and (c), respectively. The continuous lines in (b) and (c) represent the results of a simultaneous fit to the two distributions allowing four Breit-Wigner resonances and phase space.

also been reported[27] by many counter experiments which essentially measure the recoil proton momenta in pp interactions at high energy. In a subsequent bubble-chamber study[28] involving 6-GeV/c protons, an enhancement in the 1400-MeV mass region was explained as a kinematic effect of the Deck type,[29] thereby casting doubt on the interpretation of all the other deviations as resonances. The recent observation of the $N^*(1400)$ in πp reactions at high energies[30] has revived the resonance interpretation. However, since it again is a recoil measurement, it is once again subject to the same criticism as the p-p experiment, namely, the observed enhancement can also be explained by a kinematic effect. A recent bubble-chamber experiment[31] studying the interaction of 6-BeV/c $\pi^\pm$ on hydrogen has shown clear evidence for the $N^*(1400)$ in which it is extremely difficult to explain as a kinematic effect. In the experiment described in this section, the $N^*(1400)$ resonance is produced by a different particle, a K^+ meson, and in a final state where the enhancement cannot be ascribed to effects of dynamics. Both results confirm the existence of the $N^*(1400)$ as a baryon resonance.

Reaction (13) is well suited to the observation of resonances in the (π^+n) system. The final state can contain no known K^* or Y^* resonances and might, therefore, be expected to be dominated by N^* production. The (π^+n) effective mass distribution is shown in Fig. 11(a). Evidence is seen for the well-known N^* resonances at 1238, 1500, and 1688 MeV. There is also an enhancement at approximately 1390 MeV. If this enhancement were caused by the $N^*(1400)$ with spin and parity $\frac{1}{2}^+$ as predicted by phase-shift analysis, then it would be expected to be produced very peripherally. The same data are therefore divided into two samples: those with Δ^2 (momentum transfer squared to the $N\pi$ system) greater than 0.35 $(\text{GeV}/c)^2$ and those with Δ^2 less than 0.35 $(\text{GeV}/c)^2$. The $(N\pi)$ effective mass spectra for these samples are plotted in Figs. 11(b) and 11(c). It is seen that there is no enhancement at 1390 in the nonperipheral sample. In the peripheral sample it is noted that the strong N^* (1500) and $N^*(1688)$ signals have been greatly suppressed but the enhancement at 1238 remains.

The data presented above show evidence for the $N^*(1400)$, but the isobar is present over a considerable background. Before investigating the details of the Δ^2 dependence of the $N^*(1400)$, it is desirable to find some way of reducing this background. The following fact was utilized.

The angular distribution of the decay pion from an N^* which does not interfere with background is symmetric in the N^* center-of-mass system. In our data, this angular distribution, to be referred to as the pion decay angle, is found to be highly asymmetric for all (πn) effective mass values, with a preponderance of forward pions, i.e., pions which are emitted in the beam direction. Requiring the pion to be emitted backward in the N^* center-of-mass system with respect to the incoming beam, therefore, removed a large fraction of the background events while retaining about half of all true N^* resonance events. A plot of the (πn) effective mass for this sample is shown in Fig. 12(a).

Evidence is again seen for the $N^*(1238)$, $N^*(1500)$, and $N^*(1688)$. Although the number of events has been reduced, the valleys which separate the resonances are seen to be much deeper than in Fig. 11(a), thus indicating the presence of relatively little background. No clear separation is seen between the $N^*(1400)$ and $N^*(1500)$, but these can again be separated by observing the same data plotted for Δ^2 greater than 0.35 $(\text{GeV}/c)^2$, Fig. 12(b), and less than 0.35 $(\text{GeV}/c)^2$,

[27] G. Bellettini *et al.*, Phys. Letters **18**, 167 (1965); E. W. Anderson *et al.*, Phys. Rev. Letters **16**, 855 (1966); I. M. Blair *et al.*, Phys. Rev. Letters **17**, 789 (1966).
[28] E. Gellert *et al.*, Phys. Rev. Letters **17**, 884 (1966).
[29] R. T. Deck, Phys. Rev. Letters **13**, 169 (1964).
[30] K. J. Foley *et al.*, Phys. Rev. Letters **19**, 397 (1967).
[31] R. B. Bell *et al.*, Phys. Rev. Letters **20**, 164 (1968).

Fig. 12(c). The shape of the distributions in the region 1360 to 1540 is seen to be very different in the two Δ^2 regions and once again the $N^*(1400)$ is seen clearly in the small Δ^2 sample.

The curves in Figs. 11 and 12 represent the results of simultaneous fits to the data shown in the plots. The fits were made by resonances with Breit-Wigner shapes superimposed on a noninterfering phase-space background. The intensity of the resonances was adjusted for each distribution separately but the position and width of the resonance was constrained to be the same for all distributions. The broken curves in Fig. 12(c) represent a fit in which only three resonances were allowed. The continuous curves represent a fit in which four resonances were allowed. The best fit gave the following masses and widths:

for $N^*(1236)$, mass 1230 ± 10 MeV, width 140 ± 20 MeV;
for $N^*(1400)$, mass 1385 ± 10 MeV, width 42 ± 22 MeV;
for $N^*(1500)$, mass 1485 ± 10 MeV, width 80 ± 24 MeV;
for $N^*(1688)$, mass 1670 ± 10 MeV, width 90 ± 30 MeV.

It should be noted that the masses and widths of the $N^*(1236)$, $N^*(1500)$, and $N^*(1688)$ are all consistent with the accepted values. The mass of the $N^*(1400)$ is found to be somewhat lower than previously published values, and its fitted width is significantly narrower than the phase-shift results indicate. It must be emphasized, however, that the errors given above for both the mass and the width of the $N^*(1400)$ are purely statistical and take no account of possible interference and background effects.

Using the sample of events with backward decay pion, the Δ^2 dependences for the $N^*(1400)$ and $N^*(1500)$ are plotted in Fig. 13. The straight lines represent a dependence of the form

$$\sigma = ae^{-n\Delta^2},$$

where n equals 1.6 in the $N^*(1500)$ region and n equals 4.3 in the $N^*(1400)$ region. For comparison, the Δ^2 dependence for elastic events is also given. The indicated straight line for the elastic events corresponds to $n=6.6$, which agrees well with the values obtained with beams at energies from 6.8 to 14.8 GeV.[32] The exponent ($n\approx4.3$) used here to fit the $N^*(1400)$ distribution in production from K^+p may be compared with the much higher values reported from π^-p counter experiments ($n\approx12$), π^-p bubble chamber[31] ($n\approx6$), and pp ($n\approx18$).[33] A similar variation is well known in the Δ^2 distributions for elastic scattering, where an exponent of about 6 is found in K^+p reactions but an exponent of about 10 is observed for π^-p and pp reactions.

An attempt was made to determine the isotopic spin of the $N^*(1400)$ from an examination of the rate of its

[32] K. J. Foley *et al.*, Phys. Rev. Letters 11, 503 (1963).

[33] It should be noted that in this experiment the exponent is derived from fitting the data for $\Delta^2<0.5$ (GeV/c)^2 while the quoted counter experiment obtains the coefficient of the linear term from the region $\Delta^2<0.2$ (GeV/c)^2.

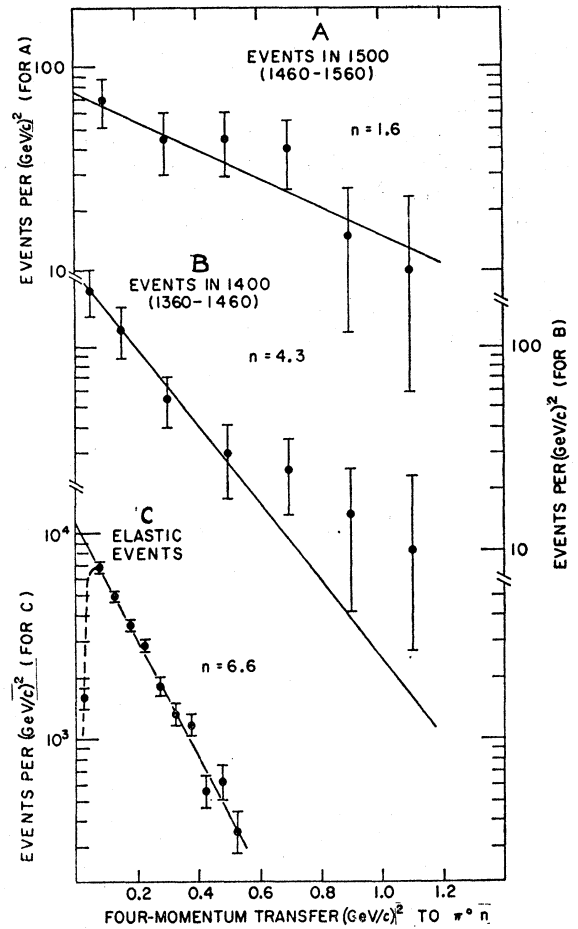


FIG. 13. Four-momentum transfer distributions. Plots (a) and (b) refer to four-momentum transfer to the (π^+n) system in the reaction $K^+p\rightarrow K^+\pi^+n$. Plot (c) refers to the four-momentum transfer to the proton in K^+p elastic scattering.

production in the reaction $K^++p\rightarrow K^++N^*$ with $N^*\rightarrow p\pi^0$. If its isotopic spin is $I=\frac{3}{2}$, then this rate should be twice that for the decay $N^*\rightarrow\pi^++n$, and if $I=\frac{1}{2}$, then it should be one-half the rate. The result was consistent with $I=\frac{1}{2}$ and 2 standard deviations from $I=\frac{3}{2}$.

We therefore conclude that (a) an N^* resonance exists with a mass less than 1400 MeV, our mass value being $M=1385\pm20$ MeV,[34] (b) it has a width Γ less than 100 MeV which is at variance with that predicted by phase-shift analysis of pion-nucleon interactions, and (c) it is peripherally produced with a Δ^2 dependence sharper than that for the $N^*(1500)$.

6. CONCLUSION

The results reported here have been in consistent agreement with a quark-antiquark composition for mesons and a three-quark composition for baryons.

[34] The error quoted here takes account of possible systematic effects.

No evidence was found for the previously indicated (K^+K^+) resonance, nor for any $I=\frac{3}{2}$ K^*, nor for a positive-strangeness baryon, all of which are inconsistent with such simple compositions. In contrast, we have some confirmatory evidence for a $(K\pi)$ resonance at 1080 MeV and evidence for a new $(K\pi)$ resonance at 1260 MeV. Either of these might well be the $J^P=0^+$ K^* predicted by a quark shell model.

ACKNOWLEDGMENTS

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Search for a Neutral Weak Interaction via $\bar{\nu}_e$ Dissociation of Deuterons*

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An attempt was made to observe the dissociation of the deuteron by electron antineutrinos in order to test the theory of the neutral weak-interaction current. This event could be recognized by the detection of both disintegration products, the neutron and the proton. A deuterated liquid scintillator loaded with gadolinium to provide energetic-neutron-capture γ rays was used in this search. The signature for the event would be a prompt "proton" pulse followed by a coincidence between two crystals which signaled neutron capture. The crystal energy gates were set between 0.75 and 6.25 MeV, and the liquid scintillator was set for a light output equal to that produced by electrons$>$0.20 MeV and $<$0.59 MeV. During 55.5 h of runs near one of the Savannah River Plant reactors, the cross section for this process was determined to be $<(1.7\pm1.4)\times10^{-42}$ cm^2, a limit which is to be compared with a maximum theoretical expectation of 1.3×10^{-44} cm^2 and a previous experimental limit of 10^{-40} cm^2.

INTRODUCTION

An interesting problem in the field of weak interactions is whether neutral weak-interaction currents exist.[1–4] One possible mode of detecting such a current would be via the interaction

$$\nu+N\rightarrow N^*+\nu. \quad (1)$$

If the nucleus were a deuteron and the ν sufficiently energetic, the process would involve the emission of a proton and a neutron, both of which could be easily detected. For $\nu=\bar{\nu}_e$, reaction (1) becomes in this case

$$\bar{\nu}_e+d\rightarrow p+n+\nu_e. \quad (2)$$

According to Gapanov and Tyutin[5] the cross section for (2) is of the order of 10^{-46} cm^2 as a minimum and 10^{-44} cm^2 as a maximum value for fission antineutrinos. The best experimental limit for this cross section prior to the present effort[6] is $<10^{-40}$ cm^2.

In the present experiment we attempted to detect the neutral weak-interaction current via (2) by searching for a delayed coincidence between the prompt pulse produced by the proton and neutron and the subsequent capture of the neutron. The target was a deuterated decalin scintillator[7] ($C_{10}H_8D_{10}$) to which gadolinium was added because it has a high thermal neutron-capture cross section and yields several energetic γ rays per capture.[8] These γ rays were detected by two NaI(Tl)

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[7] T. L. Jenkins and F. Reines, Proc. IEEE **NS-11**, No. 3, 1 (1964).
[8] *The Reactor Handbook* (Wiley-Interscience Publishers, Inc., New York, 1962), Vol. 3, Part B, p. 46.