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Evidence for the Existence of a $K\pi$ Resonant State at 726 MeV*

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In a classic investigation of the three- and four-body final states produced in 1.15-BeV/c $K^- + p$ interactions, Alston et al.[1] obtained evidence for the existence of three resonant states: $Y_1^*(1385) \rightarrow \Lambda + \pi$; $K^*(885) \rightarrow K + \pi$; and $Y_0^*(1405) \rightarrow \Sigma + \pi$; where the numbers in parentheses are the energies in MeV. Since this work, other experiments have demonstrated the existence of many additional unstable baryon states as well as five (or more) strangeness $S = 0$ unstable meson states. Thus far, a satisfactory classification of the incomplete experimental data[2] has been possible within the framework of the unitary symmetry model of Gell-Mann[3] and Ne'eman.[4] Consequently, the unambiguous observation of a new $K\pi$ resonant state would be of particular interest, since it would imply the existence of either a complete new unitary multiplet whose other members remain to be discovered, or a phenomenon whose explanation must be sought outside the conventional unitary symmetry scheme.[5,6]

In order to search for possible $S = +1$ unstable meson states, we have studied the effective-mass distributions for $K\pi$ systems produced in $\pi^- + p$ interactions over a wide momentum interval. In this Letter we report evidence that strongly indicates the existence of a weakly coupled unstable state of the $K\pi$ system[7] with mass $\sim 726 \pm 3$ MeV and full-width $\Gamma \lesssim 20$ MeV. No determination of the spin or parity was possible although the data indirectly support the isotopic spin assignment $I = 1/2$.

The data were obtained during an extensive exposure of the Lawrence Radiation Laboratory's 72-inch hydrogen bubble chamber to a secondary π^- beam at seven momentum settings ranging from 1.51 to 2.36 BeV/c. A total of 250,000 pictures with 10 to 20 pions each were taken and scanned for visible production of strange particles. Of the 11,000 strange-particle events observed, 4200 were successfully fitted kinematically to one of the hypotheses

$$\pi^- + p \to \Sigma^+ + \pi^- + K^0 \quad (1a)$$

$$\to \Sigma^- + \pi^+ + K^0 \quad (1b)$$

$$\to \Sigma^- + \pi^0 + K^+ \quad (1c)$$

$$\to \Sigma^0 + \pi^- + K^+ \quad (1d)$$

$$\to \Lambda + \pi^0 + K^0 \quad (1e)$$

$$\to \Lambda + \pi^- + K^+ \quad (1f)$$

by means of the IBM program PACKAGE. In general, events could be properly identified on the basis of the adequacy of fit (as measured by χ^2) to both the production and decay vertices. In ambiguous cases, a decision was frequently possible after track ionization was checked on the film.[8] The distribution of events used in our analysis is summarized in Table I. For statistical considerations, the data are grouped into three momentum intervals: 1.51 and 1.69 BeV/c, the two momenta below the $K^*(885)$ threshold; 1.90 and 2.05 BeV/c; and 2.17, 2.25, and 2.36 BeV/c.

The major correlations in reactions (1a) through (1f) have already been discussed in some detail.[7,9] Whenever possible, the final states are dominated by the sequences $\pi^- + p \to Y^* + K$ or $Y + K^* \to Y + \pi + K$. At lower momenta, the $\Sigma^+ \pi^- K^0$ and $\Sigma^- \pi^+ K^0$ events arise predominantly from decay of $Y_0^*(1405)$ and $Y_0^*(1520)$. The $\Lambda \pi^0 K^0$ and $\Lambda \pi^- K^+$ final states are dominated by $Y_1^*(1385)$, since it decays weakly via the $\Sigma\pi$ mode. At higher momenta, a significant contribution is observed in all $Y\pi$ channels from the recently established $Y_1^*(1660)$.[9, 10] The $I = 1/2$ $K^*(885)$ appears strongly in all final states except $\Sigma^+ \pi^- K^0$.

The distributions in effective-mass-squared, $M^2(K\pi)$, for the pure $I = 3/2$ $K^0 \pi^-$ system [reaction (1a)] are given in Fig. 1. Since the $\Sigma^+ \pi^- K^0$ final state results almost entirely from Y^* decay, the $M^2(K^0 \pi^-)$ distribution is determined by the net alignments of the Y^*'s along their production directions in the $\pi^- + p$ c.m. system. For example, if the $D^{3/2}$ $Y_0^*(1520)$ MeV were produced from an initial $S^{1/2}$ $\pi^- + p$ state, the decay distribution with respect to the production direction would be $1 + 3\cos^2\theta$. Since the data were taken over a range of momenta, this decay distribution would be reflected as a bump at low $K\pi$ effective mass, with a smeared enhancement at high effective mass. In other final states, the higher mass enhancement could be masked by $K^*(885)$ so that the low-mass bump simulates the decay of an unstable state. It is important then, that the $K^0 \pi^-$ distributions show no evidence of structure and appear adequately represented by the smooth curves shown.[11]

The combined $M^2(K\pi)$ distributions for the $K^0 \pi^+$ and $K^+ \pi^0$ systems produced in association with Σ^-'s [reactions (1b) and (1c)] are plotted in Fig. 2a. A striking feature of the data is the strong $K^*(885)$ production (particularly at higher momenta), although the reaction $\pi^- + p \to \Sigma^- + K^{*+}(885)$ cannot occur in peripheral collisions involving either K or $K^*(885)$ exchange. In addition, the distributions exhibit a prominent peak in the interval 0.51 to 0.55 BeV^2 (714 to 742 MeV). In order to examine the structure of this peak in more detail, an alternative representation of the data is provided in Fig. 2b and c, where the $K^0\pi^+$ and $K^+\pi^0$ events have been plotted separately. It is apparent that the peak persists in each distribution over essentially the same mass interval. To illustrate the approximate size of the effect, we have attempted to draw plausible and mutually consistent curves through the data. No obvious enhancements were observed in the 1.51- or 1.69-BeV/c data (not shown), although at these momenta the situation is unfavorable because phase space peaks at low $K\pi$ mass.

The observed peaks cannot result from decay of aligned Y^*'s, since the Y^*'s leading to $\Sigma^-\pi^+$ also lead to $\Sigma^+\pi^-$, where we find no effect. In addition, the major contribution to each peak appears in the 1.90- and 2.05-BeV/c data. These momenta are below threshold for production of $Y_1^*(1660)$, the only resonant state that could contribute significantly to both $\Sigma^-\pi^+$ and $\Sigma^-\pi^0$ final states. For similar reasons the peaks cannot be attributed to interference between $K^*(885)$ and Y^* background. Considering the peak in Fig. 2a as a statistical fluctuation in the 1.90- and 2.05-BeV/c data, we estimate a probability less than 1/500 for the occurrence of a peak as large as observed. Consequently, a statistical origin for the peak cannot be conclusively discounted on the basis of the present experiment alone. However, in view of the remarkable coincidence in mass with the peak observed by Wojcicki et al.,[12] we conclude that the data almost certainly represent the decay of a new unstable state (hereafter called the κ meson) with strangeness $S = +1$ and mean mass $\sim 726 \pm 3$ MeV.[13]

Resolution functions have been calculated by using events with $M^2(K\pi)$ of 0.50 to 0.56 BeV^2. The full width at half-maximum is 0.04 BeV^2 for $K^+\pi^0$

and 0.02 BeV^2 for $K^0\pi^+$. From this we estimate that the full width of the κ is $\lesssim 20$ MeV. If the width is several MeV or more, interference between κ and Y^* decay may be expected. Some evidence for the existence of such an effect is provided by both the marked tendency for the κ decays to populate the Y_0^* bands in the $\Sigma^-\pi^+K^0$ final state, and the apparent difference in widths for the $K^+\pi^0$ and $K^0\pi^+$ decay modes.[14]

A straightforward interpretation of the data favors the assignment $I = 1/2$ for the κ. Most important, perhaps, is the absence of an enhancement in the $I = 3/2$ $K^0\pi^-$ system (Fig. 1). If the I - spin of the κ were 3/2, both the $I = 1/2$ and $I = 3/2$ components of the initial $\pi^- + p$ system could contribute to its production. In this case, the observed $M^2(K^0\pi^-)$ distribution would imply essentially complete destructive interference between the two production amplitudes, a possibility that appears unlikely over the wide momentum interval studied. Alternatively, if the decay $\kappa \rightarrow K + \pi$ represents an allowed transition, the I - spin of the κ may be deduced directly from the branching ratio $R = (\kappa^+ \rightarrow K^0\pi^+)/(\kappa^+ \rightarrow K^+\pi^0 + \kappa^+ \rightarrow K^0\pi^+)$. However, the presence of interference between κ and Y^* decay and an incomplete understanding of the background preclude a rigorous determination on this basis. Nevertheless, in drawing the curves in Fig. 2a, b, and c, we have imposed the somewhat arbitrary additional requirement[15] that the relative areas in the $I = 1/2$ $K^*(885)$ peaks give the correct branching ratio, $(K^* \rightarrow K^0\pi^+)/(K^* \rightarrow K^0\pi^+ + K^* \rightarrow K^+\pi^0) = 2/3$. A reasonable extrapolation of the background curves through the 0.70- to 0.40-BeV^2 interval suggests a branching ratio $R \simeq 37/55$, consistent with the $I = 1/2$ assignment. It must be emphasized however, that this branching ratio estimate cannot in itself provide evidence against the $I = 3/2$ assignment, because of statistical limitations and obvious background uncertainties.

We have also looked for any decay correlations that might be present if the spin of the κ were ≥ 1. In the $K^0\pi^+$ final state the correlations merely reflect the accumulation of the κ decays in the Y_0^* bands. For the more favorable $K^+\pi^0$ final state, a polar-to-equatorial ratio of 5/21 is observed for decay with respect to the production direction. Because of the difficulty in assessing background effects with the limited experimental data, we do not feel that this anisotropy provides a serious argument for spin ≥ 1.

It is of interest to determine whether the neutral component of the κ is produced in the present experiment. The $M^2(K\pi)$ distributions for all $K^+\pi^-$ and $K^0\pi^0$ systems are given in Fig. 3. We find no indication for any enhancement at 726 MeV. However, a surplus of ~18 events occurs at 747 ± 5 MeV,[16] again arising predominantly in the 1.90- and 2.05-BeV/c data. Since the net detection efficiency in reactions (1d) and (1e) would be 14/27 for an $I = 1/2$ κ (or 10/27 for $I = 3/2$), this is approximately the size of the effect one would expect if the cross sections for $\kappa^0 + \Lambda$ and $\kappa^+ + \Sigma^-$ were similar. Unfortunately, the effect is of marginal statistical significance, so that we cannot conclude whether the κ^0 is simply produced very weakly in reactions (1d, e, and f), or alternatively, is produced at about the same rate, but has a mass 21 ± 6 MeV higher than the κ^+.

In conclusion, the existence of an unstable meson with strangeness $S = +1$, mass 726 ± 3 MeV, and full width $\Gamma \lesssim 20$ MeV appears reasonably established from a study of the $K\pi$ effective-mass distributions observed in $\pi^- + p$ and $K^- + p$ interactions. The simplest interpretation of these data suggests the isotopic spin assignment $I = 1/2$. No unambiguous evidence for a determination of the spin and parity was obtained. Since we were not able to identify this unstable $K\pi$ system with any clearly predicted particle, it has been called the κ meson. Production cross sections are summarized in Table II.

We are indebted to Mr. Max Leavitt for his extensive programming support in the reduction of the data. In addition, we thank Professors Sheldon Glashow, Gyo Takeda, and J. John Sakurai for interesting conversations regarding possible interpretations of the κ.

It is a pleasure to acknowledge the support and encouragement of Professor Luis Alvarez throughout the course of this experiment. Finally, without the skill and patience of the operators of the Bevatron and 72-in. bubble chamber, as well as the efforts of our scanning and measuring staffs, this experiment would not have been possible.

FOOTNOTES AND REFERENCES

* Work supported by the U. S. Atomic Energy Commission.

† Now at the Israel Atomic Energy Commission Laboratories, Rehovoth.

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3. M. Gell-Mann, California Institute of Technology Synchrotron Laboratory Report CTSL-20, 1961, (unpublished) and Phys. Rev. 125, 1067 (1962).

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6. G. Takeda, Phys. Rev. Letters 10, 167 (1963).

7. G. Alexander, G. R. Kalbfleisch, D. H. Miller, and G. A. Smith, Phys. Rev. Letters 8, 447 (1962), already have discussed preliminary evidence for such a state based upon an analysis of a small fraction of the present data. See also reference 9.

8. The major ambiguity arises in the correct assignment of events to the $\Sigma^- \pi^0 K^+$ and $\Sigma^- \pi^+ K^0$ final states, since about one-half of the Σ^- events have acceptable fits to both hypotheses. Using ionization information, one can uniquely identify about one-half of the ambiguous events. The remainder are assigned to the fit with the lowest χ^2. We estimate

that less than 10% of the events are improperly assigned. This was checked by using the same procedure on 393 $\Sigma^- \pi^+ K^0$ events with visible K^0 decay, where the K^0 information was suppressed during fitting.

9. G. Alexander, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, G. A. Smith, and J. Schwartz, "Study of Strange-Particle Resonant States Produced in 1.89-2.04 GeV/c $\pi^- + p$ Interactions," in Proceedings of the 1962 International Conference on High-Energy Physics at CERN (CERN, Geneva, 1962) p. 322.

10. L. W. Alvarez, M. H. Alston, M. Ferro-Luzzi, D. O. Huwe, G. R. Kalbfleisch, D. H. Miller, J. J. Murray, A. H. Rosenfeld, J. B. Shafer, F. T. Solmitz, and S. G. Wojcicki, Phys. Rev. Letters 10, 184 (1963).

11. Because of the known complexity of the final states, no systematic attempt was made to compare the data with predictions based upon pure phase-space considerations. Instead, smooth curves approximately consistent with known resonances were drawn through the data. Marked deviations from these curves were then studied as possible new phenomena.

12. S. G. Wojcicki, G. R. Kalbfleisch, and M. H. Alston, Phys. Rev. Letters, this issue.

13. J. Fisk, H. K. Ticho, D. H. Stork, W. Chinowsky, G. Goldhaber, S. Goldhaber, and T. F. Stubbs, "Pion Production by K^+ Mesons on H_2 and D_2," in Proceedings of the 1962 International Conference on High-Energy Physics at CERN (CERN, Geneva, 1962) p. 358. These authors observe a 2-standard-deviation enhancement at 730 MeV. The

effect would correspond to a cross section of about 100 to 120 μb for $K^+ + p \rightarrow \kappa^+ + p$.

14. If both these effects represent statistical fluctuations, the full width may be $\lesssim 1$ MeV, so that a large fraction of the decay proceeds through electromagnetic interactions. To check this possibility, we rescanned all pictures containing Σ^-'s for e^+e^- pairs which might be associated with the decay $\kappa \rightarrow K + \gamma$. Six pairs pointing back to production vertices were found, but all events were consistent with either $\Sigma^- \pi^0 K^+$ or $\Sigma^- \pi^+ K^0$. In addition, no kinks were observed in the positive tracks (K^+ or π^+), indicating that the lifetime is less than 10^{-12} sec.

15. The approximate equality of the contributions arising from Y_0^*(1405 and 1520) decay to the $\Sigma^+\pi^-$ and $\Sigma^-\pi^+$ effective-mass distributions indicates that, at least in some cases, the total decay rates are not seriously affected by interference effects, although the shapes of the resonances are markedly altered.

16. The possibility of systematic mass shifts between the $\Sigma \pi K$ and $\Lambda \pi K$ final states has been checked independently several times; no effects larger than 2 to 3 MeV were observed.

Table I. Summary of events used in analysis.

Final State	Pion momentum (BeV/c)		
	1.51, 1.69	1.90, 2.05	2.17, 2.25, and 2.36
$\Sigma^+ \pi^- K^0$	35	104	289
$\Sigma^- \pi^+ K^0$	95	322	850
$\Sigma^- \pi^0 K^+$	51	176	244
$\Sigma^0 \pi^- K^+$	23	145	263
$\Lambda \pi^0 K^0$	58	137	209
$\Lambda \pi^- K^+$	158	309	542

Table II. Estimated cross sections for $\pi^- + p \rightarrow \Sigma^- + \kappa^+$ and $\Sigma^- + K^{*+}(885)$.

Pion momentum (BeV/c)	κ^+ Observed events	κ^+ Cross section (μb)	$K^{*+}(885)$ Observed events	$K^{*+}(885)$ Cross section (μb)
1.51, 1.69	~0	~0	Below threshold	
1.90, 2.05	29	6 ± 2	105	20 ± 2
2.17, 2.25, and 2.36	26	3 ± 1	274	30 ± 2

FIGURE LEGENDS

Fig. 1. $M^2(K^0 \pi^-)$ distributions for $p_\pi \geq 1.90$ BeV/c. Since the ordinate represents the number of events per 0.04 BeV^2 (the resolution width), only every other point is independent. The shaded area indicates $p_\pi = 1.90$ or 2.05 BeV/c.

Fig. 2. $M^2(K\pi)$ distributions for $Q = +1$ $K\pi$ systems with $p_\pi \geq 1.90$ BeV/c. The solid curves through the data are mutually consistent; the dashed background curves were drawn to give approximately the correct branching ratio for the $I = 1/2$ K^*(885 MeV). The shaded area indicates $p_\pi = 1.90$ or 2.05 BeV/c.

Fig. 3. $M^2(K\pi)$ distributions for $Q = 0$ $K\pi$ systems with $p_\pi \geq 1.90$ BeV/c. The shaded area is for events with $p_\pi = 1.90$ or 2.05 BeV/c.

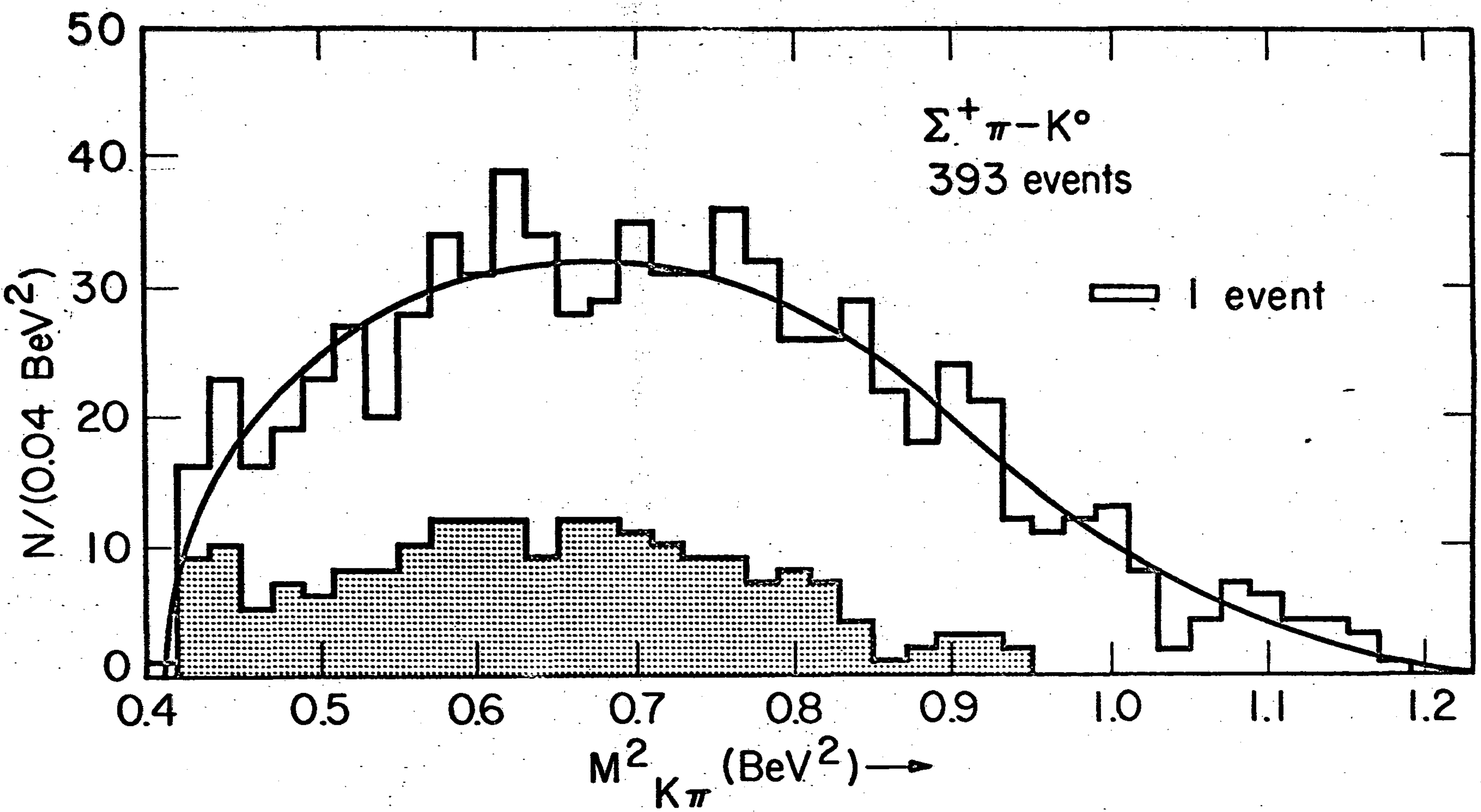
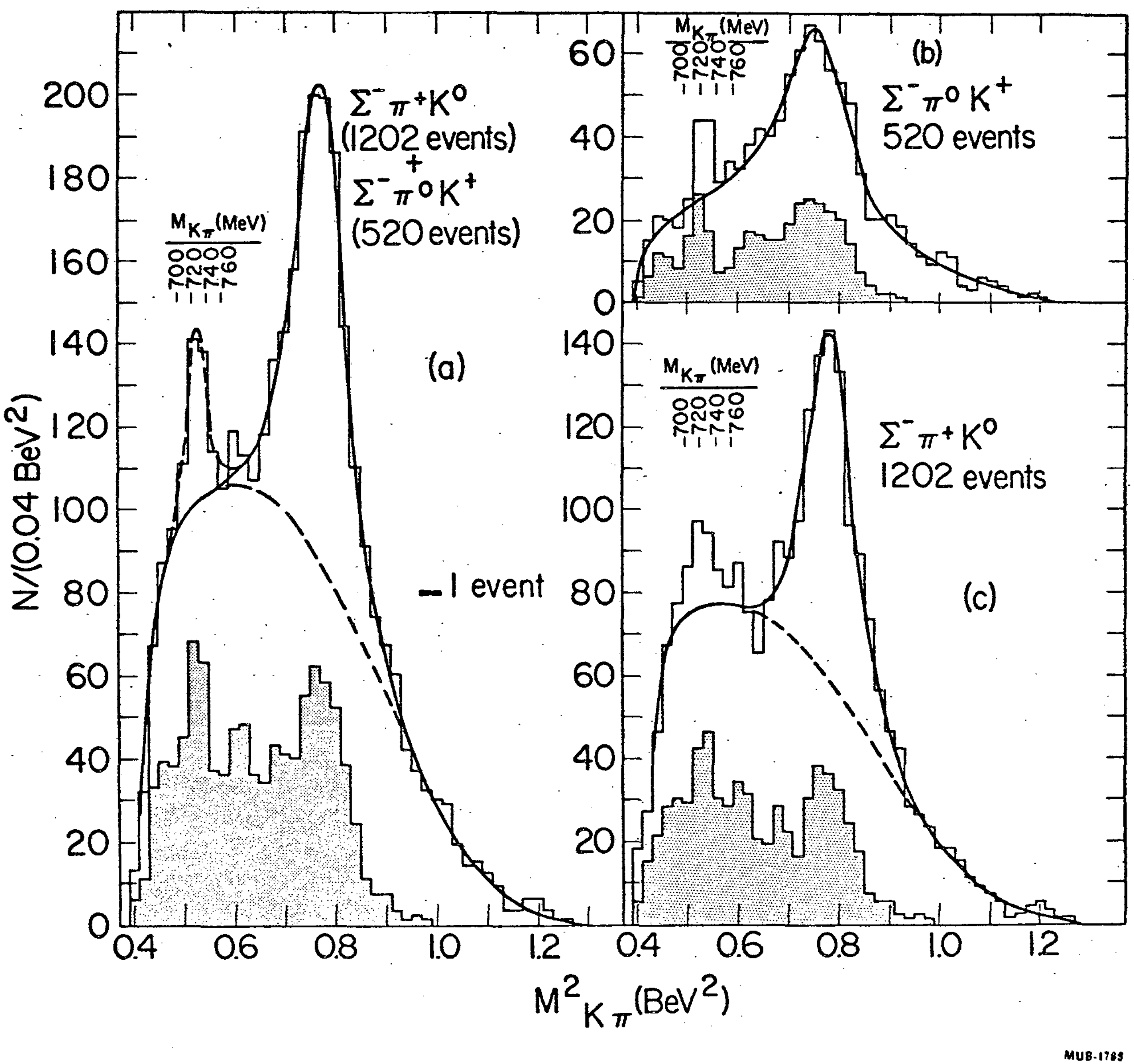


Fig. 1.

MU-30336



Σ⁻π⁺K⁰
(1202 events)
+
Σ⁻π⁰K⁺
(520 events)
M_Kπ (MeV)
700
720
740
760
(a)
1 event
(b)
Σ⁻π⁰K⁺
520 events
(c)
Σ⁻π⁺K⁰
1202 events
N/(0.04 BeV²)
M²Kπ (BeV²)
MUB-1788

Fig. 2.

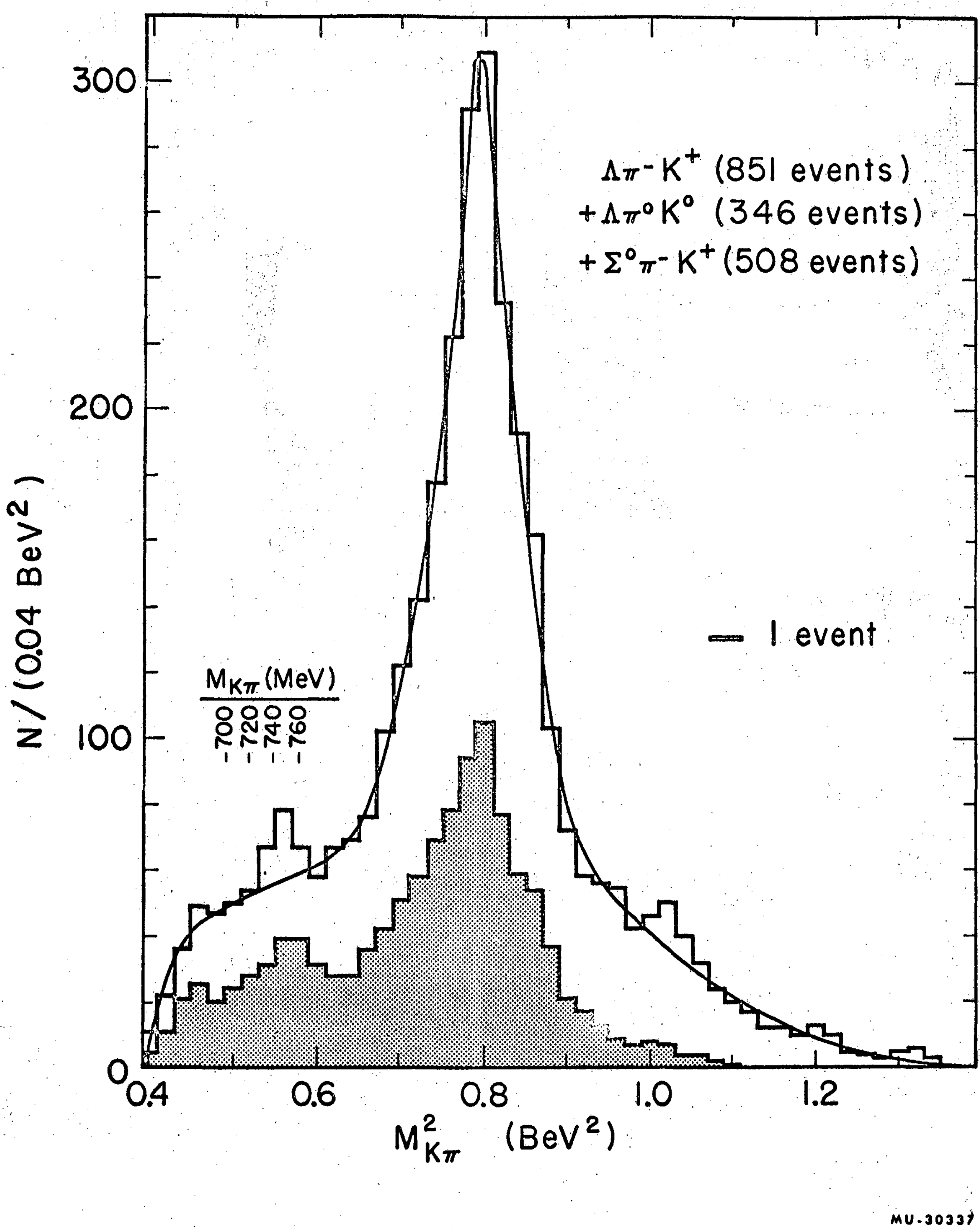

300
200
100
0
N/(0.04 BeV^2)
$\Lambda\pi^- K^+$ (851 events)
$+\Lambda\pi^0 K^0$ (346 events)
$+\Sigma^0\pi^- K^+$ (508 events)
1 event
$M_{K\pi}$ (MeV)
700
720
740
760
0.4
0.6
0.8
1.0
1.2
$M^2_{K\pi}$ (BeV^2)
MU-30337

Fig. 3.