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Gerald A. Smith

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ABSTRACT

An analysis of π^-N interactions at 1.5 to 2.4 BeV/c, and K$^-$N interactions at 1.0 to 1.7 BeV/c in the 72-inch liquid-hydrogen bubble chamber has been completed recently. The $T = 2$ $\Sigma\pi$ system, the Y_1^*(1660 MeV) resonance, and the 725-MeV Kπ resonance, or "kappa meson," is discussed with reference to both experiments.

STRANGE-PARTICLE RESONANCES IN π^-p AND K$^-$p INTERACTIONS[*][†]

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We have been analyzing π^-p and K$^-$p interactions in the 72-inch liquid-hydrogen bubble chamber at Berkeley. The exposure amounted to approximately 250,000 pictures of π^- at 1.5 to 2.4 BeV/c and about 600,000 pictures of K$^-$ at 1.0 to 2.0 BeV/c. I would like to discuss primarily the π^- data; however, some reference to the K$^-$ data is necessary for sake of consistency. The topics I will cover are (a) the T = 2 $\Sigma\pi$ system, (b) the Y_1^*(1660 MeV) resonance, and (c) the 725-MeV Kπ resonance or "kappa meson." The people involved in the Berkeley experiments are (π^-) G. Alexander, O. Dahl, L. Jacobs, G. Kalbfleisch, D. Miller, J. Schwartz, and G. Smith, and (K$^-$) M. Alston, G. Kalbfleisch, and S. Wojcicki.

Figure 1 is related to a discussion of the T = 2 $\Sigma\pi$ system. In this experiment in addition to the hydrogen film about 30,000 pictures of π^- in deuterium at 2.26 BeV/c were taken and have been analyzed for the reaction $\pi^- n \rightarrow \Sigma^- \pi^- K^+$. The obvious intent here was to look at the $\Sigma^-\pi^-$ system, which is in a pure T = 2 state. In the top portion of Fig. 1 we have plotted the square of the invariant mass for all outgoing particles (excluding the proton). This is a check to see if the reaction with the deuteron was an impulse type of collision in which the proton is a spectator. There is some smear due to the motion of the deuteron plus the intrinsic beam resolution, which was about $\pm$(2 to 3)%. However, it appears to be basically an impulse type of collision. In the middle portion of Fig. 1 we have plotted the K$^+\pi^-$ mass-squared distribution. One can see that in the region which corresponds to a mass of 885 MeV there is a very strong K* production. In the bottom portion of Fig. 1 appears the $\Sigma^-\pi^-$ mass-squared

distribution.   The curve reflects the effect of the K^* plus nonresonant phase space.
Although the statistics are somewhat restrictive, there is no evidence for any significant deviation from background in the $T = 2$ $\Sigma\pi$ system.

Table I lists the channels we have been studying in $\pi^- p$ collisions. I have listed only the two and three-body final states plus cross sections which are tentative in that corrections for only neutral decay loss have been applied where required. I would now like to discuss the Y_1^* (1660 MeV) resonance. Figure 2 shows a plot of the neutral $\Sigma\pi$ mass-squared distribution. One clearly sees in $\Sigma^+ K^0 \pi^-$ the effects of the 1405- and 1520-MeV resonances and, in addition, the Y_1^* resonance at 1660 MeV. The 1660-MeV resonance was first suggested in the data of Alexander et al.[1] and later given a positive definition by Alvarez et al.[2] In the $\Sigma^- K^0 \pi^+$ data we see the 1405- and 1520-MeV resonances, but no apparent enhancement in the 1660-MeV region. Based on charge independence, the amplitudes for the $\Sigma^+ \pi^-$ and $\Sigma^- \pi^+$ modes of the decay of the 1660-MeV resonances should be equal. However, an examination of the Dalitz plots ($\Sigma\pi$ vs $K\pi$) for these reactions is very informative. In the $\Sigma^+ K^0 \pi^-$ reaction the $K^0 \pi^-$ system is pure $T = 3/2$, thereby eliminating the possibility of interference with any known $K\pi$ resonances. The Dalitz plot for $\Sigma^- K^0 \pi^+$ indicates a very strong K^*(885-MeV) band which almost completely dominates the 1660-MeV region, suggesting possible interferences and thereby offering an explanation for the absence of this resonance on the projection.

Figure 3 shows the $\Lambda\pi$ system and the negatively charged $\Sigma\pi$ system; the latter includes only the isospin $T = 1$ and 2 states. In the $\Lambda\pi$ system (pure $T = 1$), one sees the Y_1^* (1385 MeV) resonances produced very copiously plus the Y_1^* (1660 MeV) resonance, thus confirming the $T = 1$ assignment for the latter. The $\Sigma^- \pi^0$ system clearly shows the 1660-MeV resonance; the 1385-MeV region has been indicated, since there is still some speculation as to how much it decays into the $\Sigma\pi$ mode. There is essentially no evidence for either the 1385- or 1660-MeV resonances in $\Sigma^0 \pi^-$. Again, the $\Sigma^- \pi^0$ and $\Sigma^0 \pi^-$ amplitudes for Y_1^* (1660 MeV) decay should be the same based on charge independence. An examination of the Dalitz plot for $\Sigma^0 K^+ \pi^-$ indicates a strong K^*(885 MeV) production. However, outside the K^*

band there is evidence for the 1660-MeV resonance. Also, there is a suggestion of

the 1385-MeV resonance; however, it should be pointed out that this particular reaction

is somewhat kinematically ambiguous with $\Lambda^0 K^+ \pi^-$. We have a confidence of about

90% in our separation; but since the 1385-MeV resonance is so strong in the Λ^0 events,

it is difficult to add any significant information to that aspect of the Y_1^*(1385 MeV)

decay. Since the strangeness of the 1660-MeV resonance is minus one, and the baryon

number plus one, we would expect it to decay into the $\overline{K}N$ mode.

In Fig. 4 we have plotted the two reactions which involve a kaon and nucleon

in the final state, $K^0 \overline{K}^0 n$ and $K^0 K^- p$. Since the K^0 and $\overline{K}^0$ are indistinguishable, there

are two points plotted for each event. In the $K^- p$ data we see the 1520-MeV resonance

plus an enhancement in the 1660-MeV region, whereas in the $\overline{K}^0 n$ data the 1660-MeV

resonance appears to be shifted to a slightly lower mass. Some time ago it was

reported by this group (π^-) that there is a rather large enhancement at low $K^0 \overline{K}^0$ mass

($\sim$ 1020 MeV). We interpreted this as a final-state S-wave scattering of the $K\overline{K}$

system.[3] We are looking at K_1^0 pairs only and an argument based on CP invariance

leads to the fact that only even angular-momentum states of the $K\overline{K}$ system are involved.

A comparison with $K^- K^0$ which is pure T = 1, lead us to believe that it is a T = 0

effect. The quantum numbers would then be 0^{++}. Nevertheless, such a strong effect

in the final state again could modify the presence of the 1660-MeV resonance in the

$\overline{K}^0 n$ mode. It is energetically possible for the 1660-MeV resonance to decay into

$\Lambda 2\pi$ and $\Sigma 2\pi$. An examination of the mass plots for these triplets made in four-body

final states indicates enhancements in the region of 1660 MeV in both cases (several

$\Sigma 2\pi$ modes are missing because they are underconstrained in kinematic fitting).

We may summarize the branching ratios for all Y_1^* decays (neutral and

negative charge) by expressing the ratios $\Lambda\pi$: $\Sigma\pi$: $\Lambda 2\pi$: $\Sigma 2\pi$: $\overline{K}N$ = 7:6:1: (undeter-

mined) : $>3\pm1.5$ in the $\pi^- p$ experiment. These are to be compared with the results of

Alvarez et al. in the $K^- p$ experiment which are 7:6:4:4: < 1. There are perhaps two

inconsistencies between the experiments: (a) the $\Lambda 2\pi$ mode and (b) the $\overline{K}N$ mode.

We cannot take the former too seriously, because our statistics in the $\pi^- p$ experiment

are very poor in the $\Lambda 2\pi$ channel. The only significant difference lies in the $\bar{K} N$ channel, which was essentially unobserved in the $K^- p$ experiment. However, this is probably not too surprising, since we are observing a resonant state with an extra particle in the final state in both experiments. The resonance is wide-- ~ 40 MeV-- giving a short-lived particle, and in the final state there may be interactions with the other "spectator" particle.

Lastly, I would like to comment that the recent work of Bastien and Berge at Berkeley[4] relating to the direct production of the resonances in $K^- p$ interactions at 760 MeV/c has indicated that the spin definitely is greater than 1/2. It is most likely 3/2, but 5/2 has not been ruled out. According to the hypothesis of spin-3/2, their data suggest that the $\bar{K} N$ mode could be as large as 50% of all the channels involved. It is clear that an experiment should be done to observe the resonance production in $K^- p$ interactions in the region 710 to 720 MeV/c. Such an experiment could measure the correct branching ratios and presumably even the spin and parity of the state.

I would now like to discuss the 725-MeV $K\pi$ resonance. Last summer at the CERN conference we (π^-) presented evidence for such a resonance and have since added about 70% more data to the analysis.[1] Figure 5 shows the $K\pi$ mass spectrum for the $\Sigma^- K^0 \pi^+$ and $\Sigma^- K^+ \pi^0$ reactions combined. We see clearly the $K^*(885$ MeV), plus a large enhancement with mass centered at ~ 721 MeV. The resolution of the system is 24 MeV. Where one would expect to see about 38 events, one actually observes 68; a Monte Carlo type of analysis indicates that the effect is at least three standard deviations. Note that this is at 1.90 and 2.05 BeV/c only. In Fig. 6 we have the $\Lambda^0 K^{0+} \pi^{0-}$ and $\Sigma^+ K^0 \pi^-$ events plotted separately at and above 1.90 BeV/c. The data are qualitatively similar in this momentum range and thus have been combined for increased statistical significance. The $\Sigma^+ K^0 \pi^-$ events show no effect, either at 885 MeV or 725 MeV, and since the $K^0 \pi^-$ system is pure $T = 3/2$, this leads us to believe that the 725-MeV isotopic spin is 1/2. There is a very weak effect in the Λ^0 events at slightly higher mass, but it is hardly significant enough to discuss any further. A plot of the Σ^- events above 2.05 BeV/c indicates little if no effect in the region of 725 MeV.

In Fig. 7 we have broken down the Σ^- events into the $\Sigma^- K^0 \pi^+$ and $\Sigma^- K^+ \pi^0$ channels.
Charge independence would require a K^0/K^+ branching ratio of 2/1 for isotopic spin
$T = 1/2$, and 1/2 for $T = 3/2$. Since the isotopic spin of the K^*(885 MeV) is known to
be $T = 1/2$, we may use this resonance as a test of our ability to use the branching-ratio
argument for an isotopic-spin determination of the 725-MeV resonance. We clearly
see effects of interference in both the width and shape of the K^* in these two channels;
this, plus the subjectivity required in estimating the background curves, leads us to
believe that such arguments lead to inconclusive results on the isotopic spin of the
725-MeV resonance. Assuming that the 725-MeV effect is a resonance, we may in-
quire about its spin properties. Figure 8 shows the breakup of the $K\pi$ system in its
own rest frame with respect to its line of flight in the production center of mass at
1.90 and 2.05 BeV/c. On the left side of the figure we see the $\Sigma^- K^0 \pi^+$ events and on
the right the $\Sigma^- K^+ \pi^0$ events. We have defined two control regions, one immediately
below 725 MeV and one immediately above it. The anisotropies in the $\Sigma^- K^0 \pi^+$ data
can be understood in terms of reflections of the strong Y^* resonances on this angular
distribution. However, in the $\Sigma^- K^+ \pi^0$ channel there are no known strong resonances
in the $T = 1$ or 2 $\Sigma \pi$ system (we are below threshold for 1660-MeV production). In the
control regions, the data are consistent with isotropy, whereas in the 725-MeV region,
isotropy fits the data with only 1% confidence. A $\sin^2 \beta$ curve gives a 52% probability
for a fit; we don't mean to suggest that this is a vector meson by such arguments, but
rather want to emphasize that isotropy is not a particularly good fit to the data.

I would now like to report on the work of Wojcicki, Alston, and Kalbfleisch
(K^-) in the $K^- p$ experiment. Figures 9 and 10 summarize their efforts in the re-
action $K^- p \rightarrow \bar{K}^0 \pi^- p$. Figure 9 shows the complete $\bar{K}^0 \pi^-$ mass spectrum at incident
momenta of 1.0 to 1.7 BeV/c. One sees a very striking K^*(885 MeV) resonance, and
the only statistically significant enhancement aside from the 885-MeV resonance is
found in the 725-MeV mass region. To put the effect into the right perspective, we
show in Fig. 10 a portion of the same data in the lower mass region. In the interval
from 720 to 725 MeV there is an effect of approximately four standard deviations.

The resolution in this system is 6 MeV. A plot of the same data in smaller intervals indicates that the width of the resonance could be as much as 12 MeV.

To summarize the 725-MeV resonance, in two independent experiments we have observed significant effects at this mass in the $K\pi$ system, thereby obtaining very strong evidence for its existence as a resonant state. Because of the better resolution in the K^-p experiment, an upper limit of 12 MeV is placed on the width of the resonance. The results of the π^-p experiment indicate that the isotopic spin is 1/2. There is no clear evidence for a spin assignment, although the π^-p experiment very weakly suggests $J > 0$. No decays of the type $\kappa \rightarrow K\gamma$ or $K\pi\gamma$ have been observed.

ACKNOWLEDGMENTS

DISCUSSION

S. Goldhaber: In the Dalitz plot for $\Sigma^- K^0 \pi^+$ do you have an interference region between the K^*(725 MeV) resonance and the Y^*?

Smith: When one looks at the Dalitz plot in the region of the 1405- and 1520-MeV resonances, there indeed appears to be a sharp increase in density, particularly in the 725-MeV Kπ region. One might argue that this is evidence for a finite width to the 725-MeV resonance, since the effect could arise from interferences with the Y^*'s. I would like to comment that we are currently running at the Bevatron in this region and hopefully increased statistics will help to clarify this point.

E. Fowler: I'm encouraged to ask a similar question about the T = 2 $\Sigma\pi$ system. Do you have enough events that you could see any effect in the Dalitz plot if you looked outside the K^* band.

Smith: As far as I can tell, there's nothing outside the K^* band to indicate an interaction.

FOOTNOTES AND REFERENCES

1. G. Alexander, L. Jacobs, G. Kalbfleisch, D. Miller, J. Schwartz, and G. Smith, Proceedings of the 1962 International Conference on High-Energy Physics at CERN, p. 320.

2. 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).

3. G. Alexander, O. Dahl, L. Jacobs, G. Kalbfleisch, D. Miller, A. Rittenberg, J. Schwartz, and G. Smith, Phys. Rev. Letters 9, 460 (1962).

4. P. Bastien and P. Berge, Phys. Rev. Letters 10, 188 (1963).

Table I. Strange-particle events in π^-p collisions at 1.5 to 2.4 BeV/c (3-body final state)

Final state	Total No. events (observed)	Cross sections (μb) (corrected)		
		1.69 BeV/c	2.05 BeV/c	2.36 BeV/c
$\Lambda^0 K^0$	2110	170 ± 30	150 ± 30	110 ± 20
$\Sigma^0 K^0$	555	96 ± 12	90 ± 12	90 ± 12
$\Sigma^- K^+$	1376	130 ± 20	63 ± 8	37 ± 5
$\Lambda^0 K^+ \pi^-$	1009	69 ± 9	140 ± 20	100 ± 10
$\Lambda^0 K^0 \pi^0$	403	77 ± 18	120 ± 20	120 ± 20
$\Sigma^0 K^+ \pi^-$	530	10 ± 3	48 ± 9	56 ± 8
$\Sigma^0 K^0 \pi^0$	not analyzed	—	—	—
$\Sigma^- K^+ \pi^-$	575	17 ± 4	45 ± 8	37 ± 5
$\Sigma^- K^0 \pi^+$	1257	36 ± 5	85 ± 10	95 ± 14
$\Sigma^+ K^0 \pi^-$	425	15 ± 4	25 ± 5	37 ± 5
$K^0 \overline{K^0} n$	101	29 ± 11	65 ± 18	99 ± 18
$K^0 K^- p$	137	3 ± 1	30 ± 9	30 ± 3
Total	8478			

FIGURE LEGENDS

Fig. 1. (a) Square of the invariant mass of all outgoing particles (excluding the spectator) for the reaction $\pi^- n \to \Sigma^- \pi^- K^+$ at 2.26 BeV/c;

(b) square of the $K^+ \pi^-$ invariant mass;

and (c) square of the $\Sigma^- \pi^-$ invariant mass.

Fig. 2. The $\Sigma\pi$ mass-squared distributions at incident momenta of 2.17, 2.25, and 2.36 BeV/c for the reactions $\Sigma^+ K^0 \pi^-$ and $\Sigma^- K^0 \pi^+$.

Fig. 3. $\Lambda\pi$ and $\Sigma\pi$ mass-squared distributions at incident momenta of 2.17, 2.25, and 2.36 BeV/c for the reactions $\Lambda^0 K^{0+} \pi^{0-} \Sigma^- K^+ \pi^0$, and $\Sigma^0 K^+ \pi^-$.

Fig. 4. The $\overline{K}N$ mass-squared distributions at incident momenta of 2.17, 2.25, and 2.36 BeV/c for the reactions $K^0 \overline{K}^0 n$ and $K^0 K^- p$.

Fig. 5. The $K\pi$ mass-squared distribution for all Σ^- events ($\Sigma^- K^0 \pi^+$ and $\Sigma^- K^+ \pi^0$) at 1.90 and 2.05 BeV/c.

Fig. 6. The $K\pi$ mass-squared distributions for $\Sigma^+ K^0 \pi^-$ and $\Lambda^0 K^{0+} \pi^{0-}$ at incident momenta of 1.90 to 2.36 BeV/c.

Fig. 7. The $K\pi$ mass-squared distributions for $\Sigma^- K^+ \pi^0$ and $\Sigma^- K^0 \pi^+$ at 1.90 and 2.05 BeV/c.

Fig. 8. Decay of the $K\pi$ system with respect to its direction of flight in the production center of mass as seen in the $K\pi$ rest frame for Σ^- events at 1.90 and 2.05 BeV/c.

Fig. 9. The $K\pi$ mass distribution in the reaction $K^- p \to \overline{K}^0 p \pi^-$ at incident momenta of 1.0 to 1.7 BeV/c.

Fig. 10. The $K\pi$ mass distribution in $K^- p \to \overline{K}^0 p \pi^-$ in the 600-to-850-MeV mass interval.
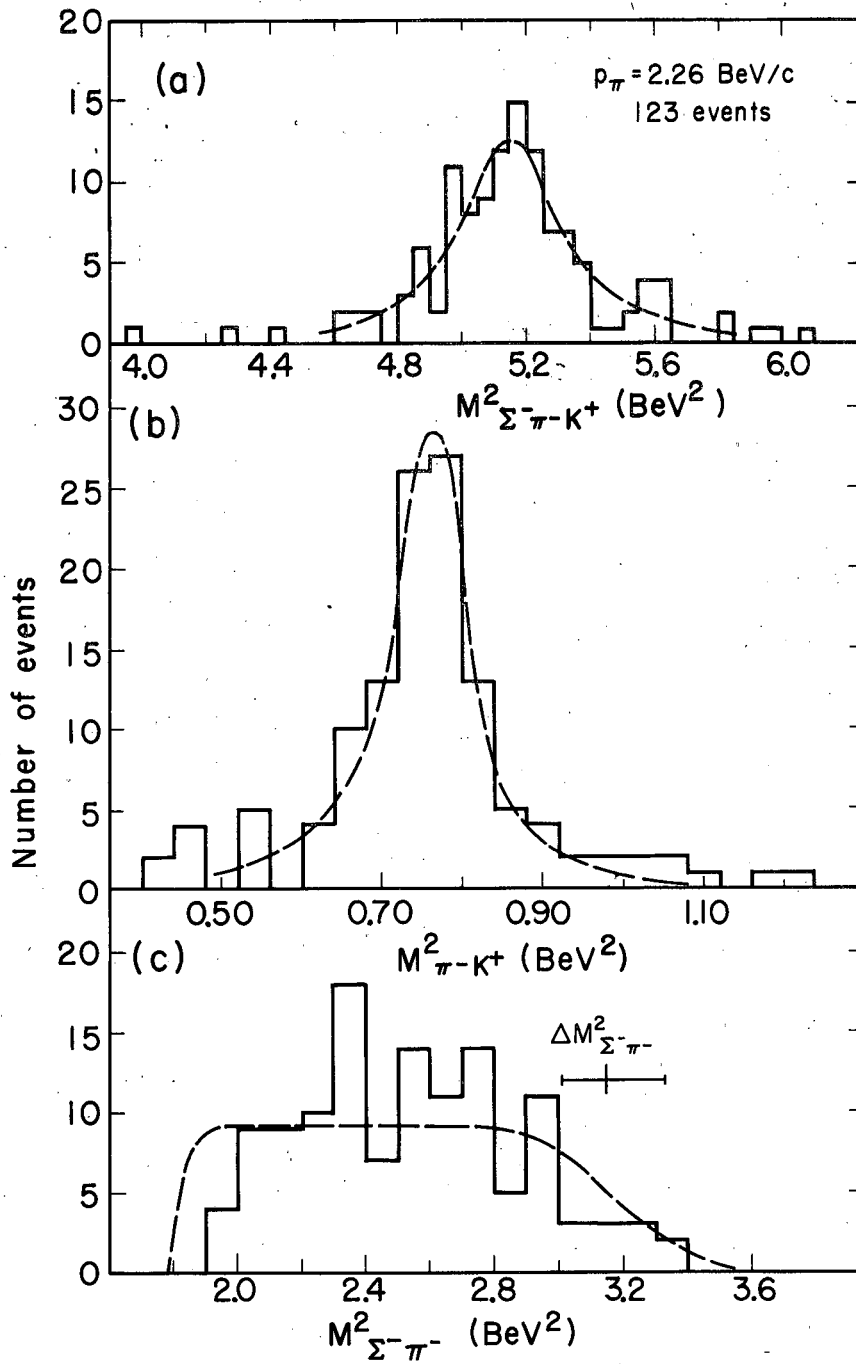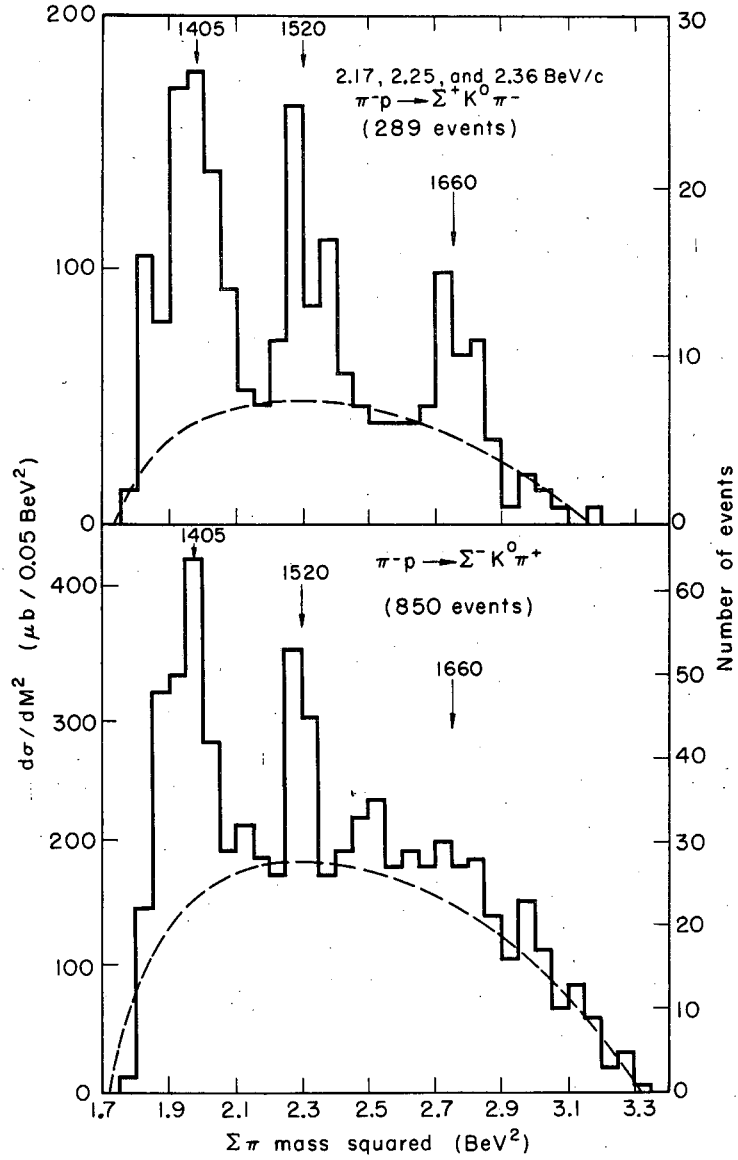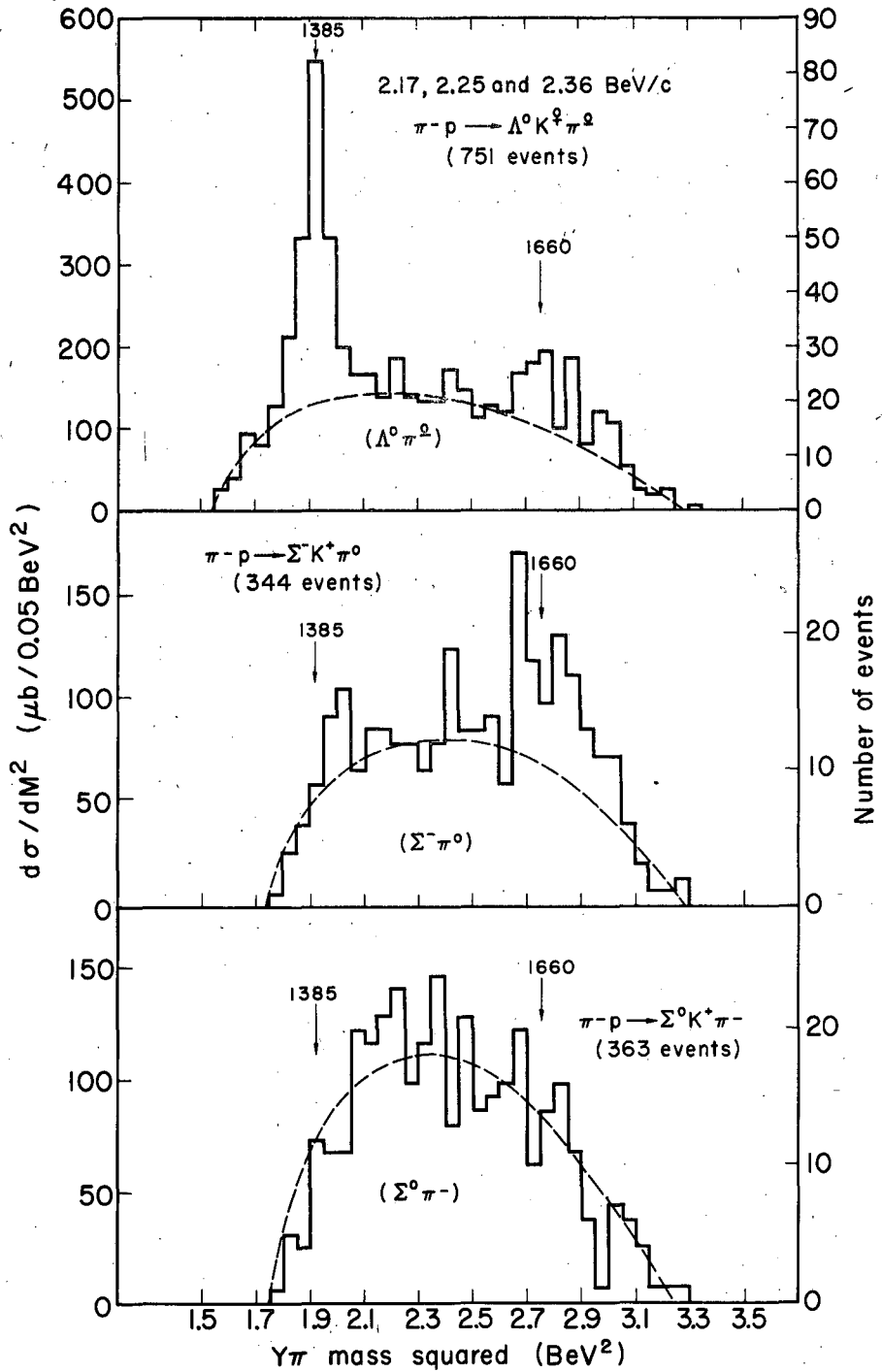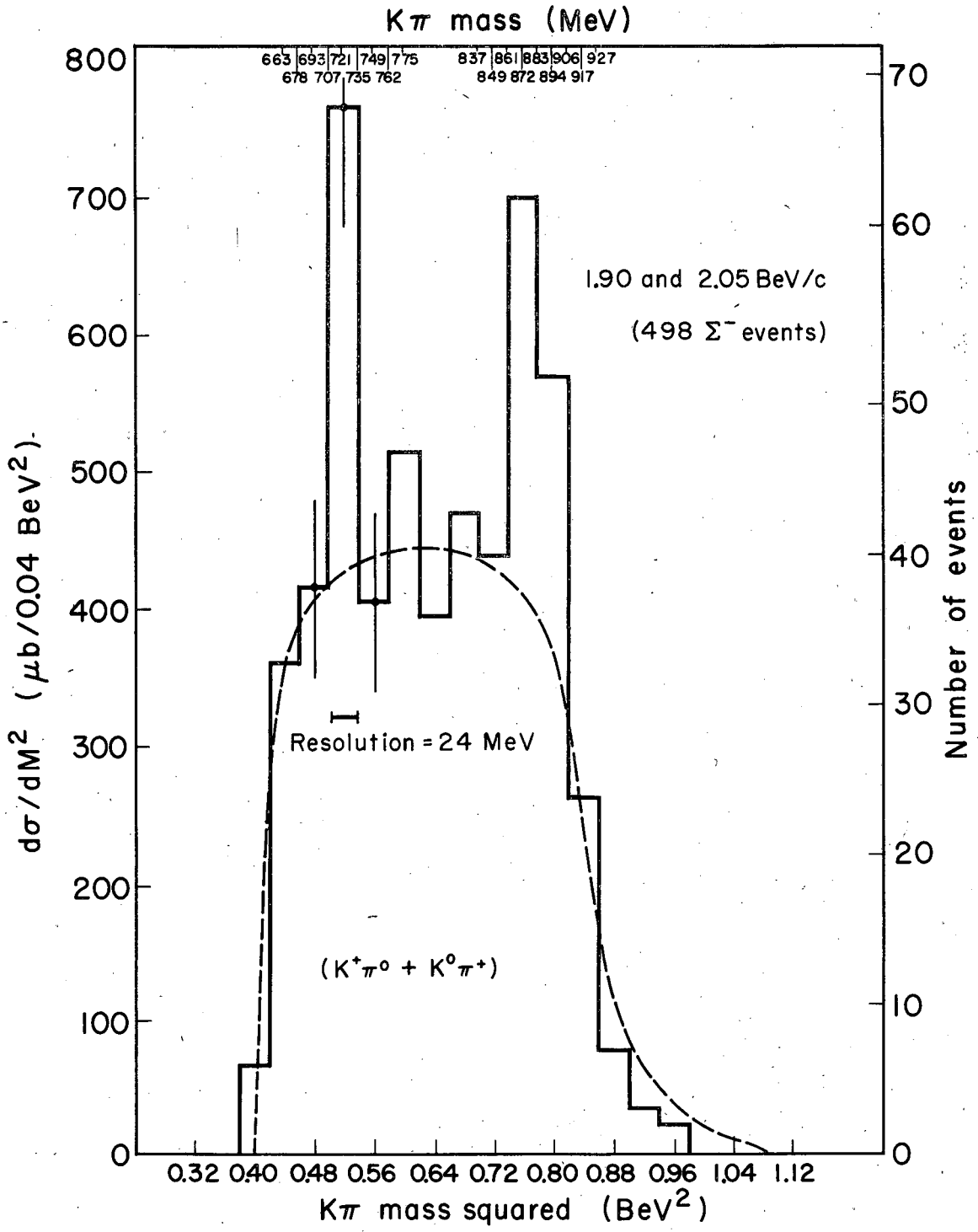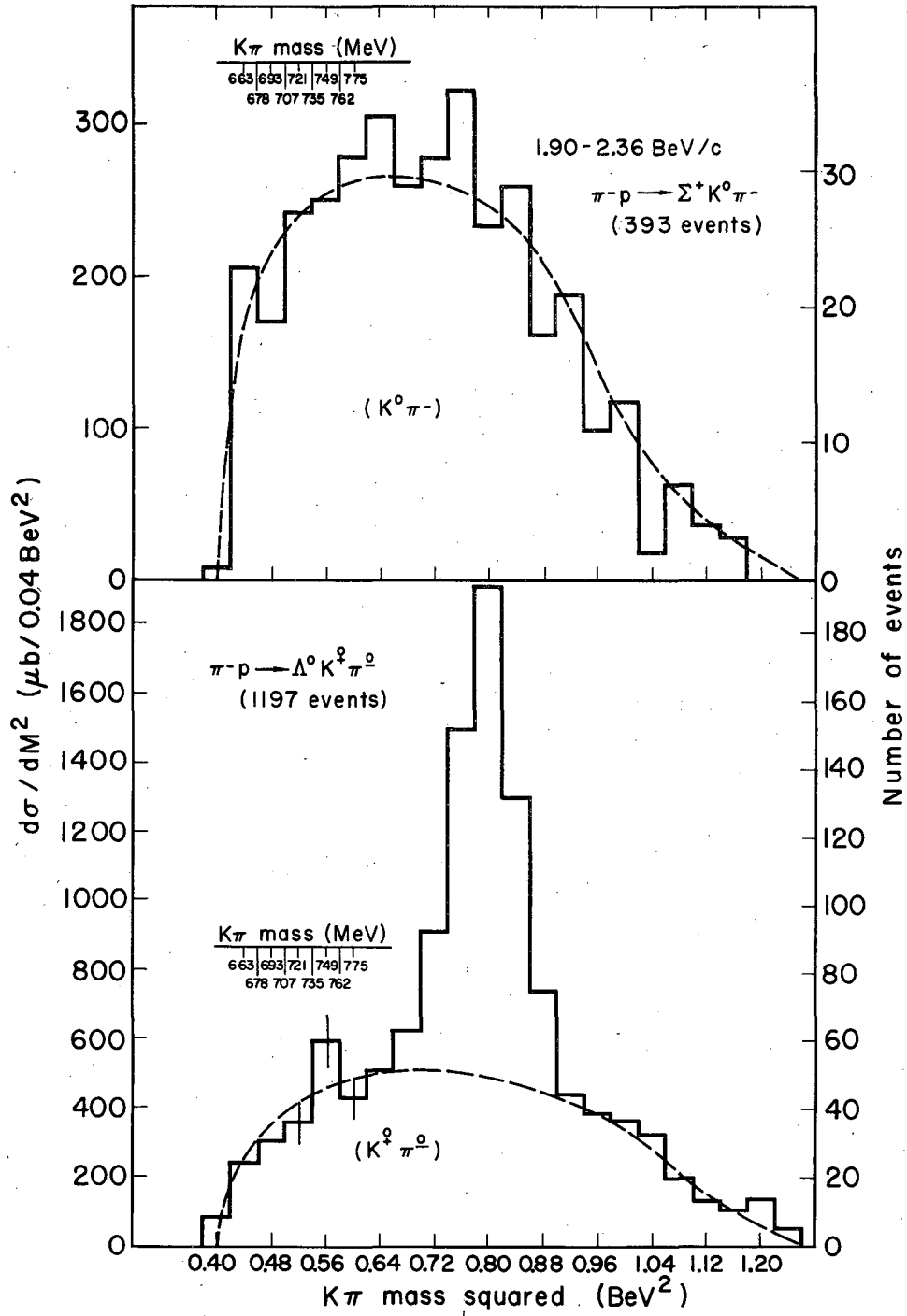
Fig. 1

MUB-1566

Fig. 2
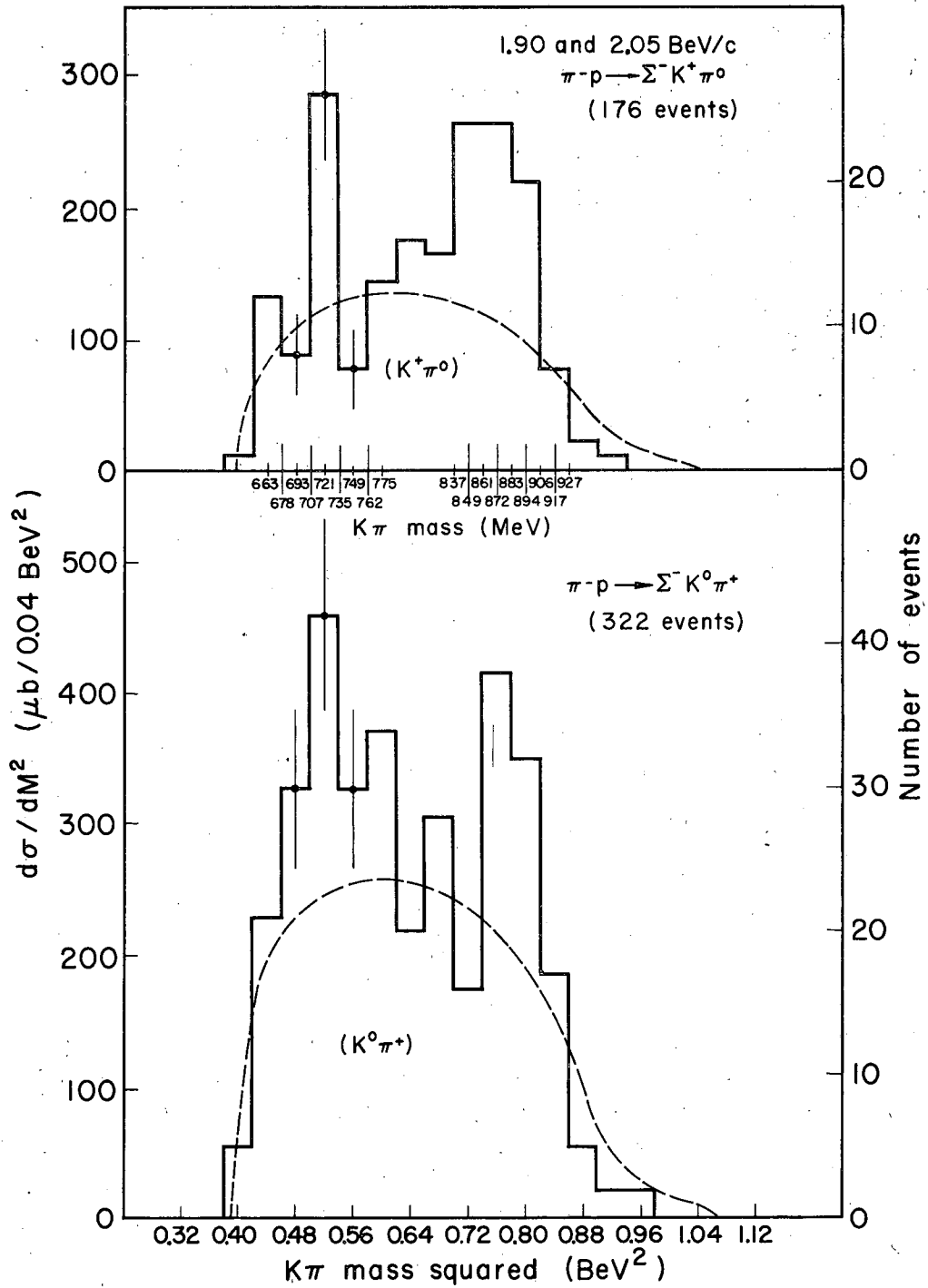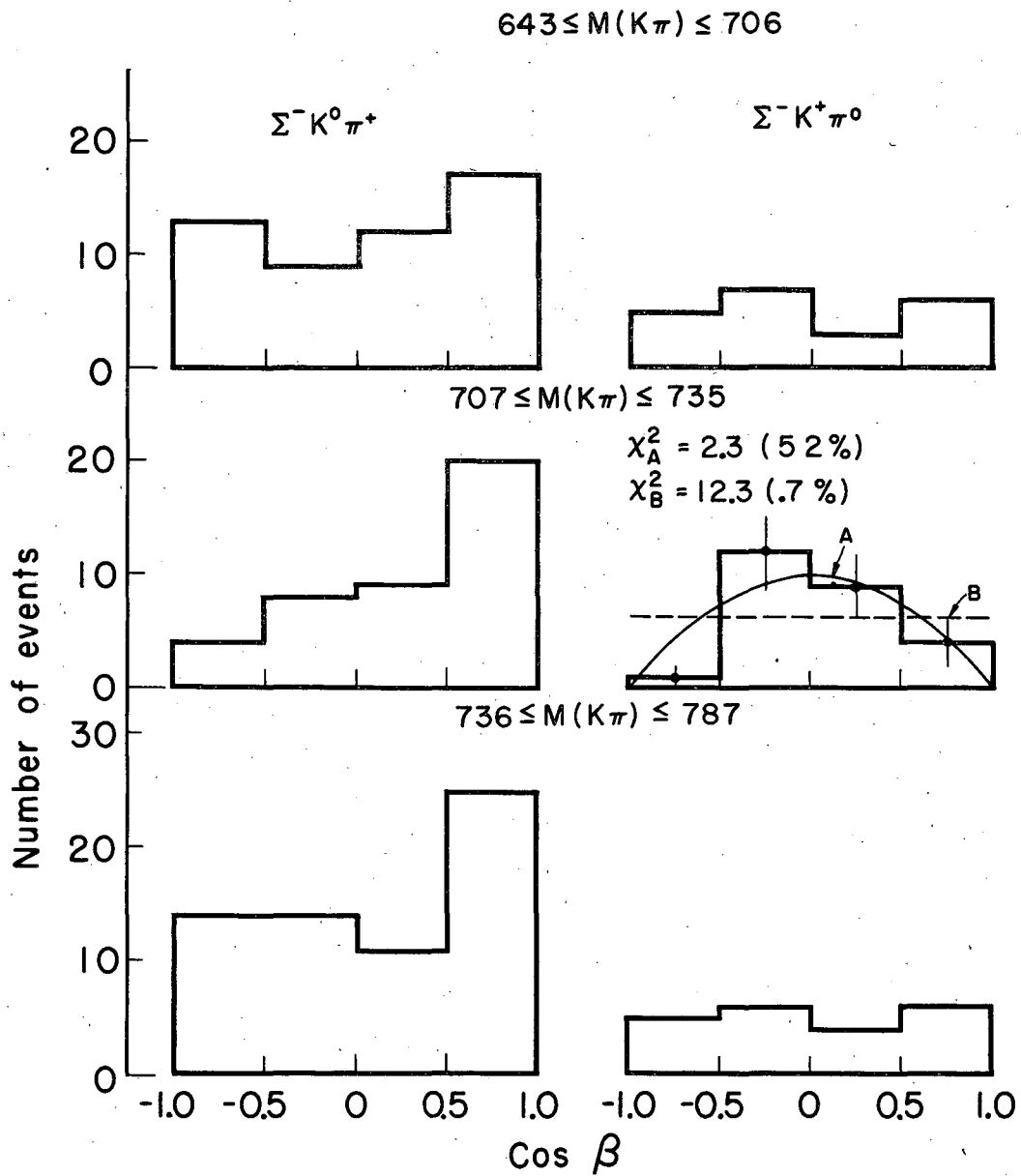
MU-30075

Fig. 3
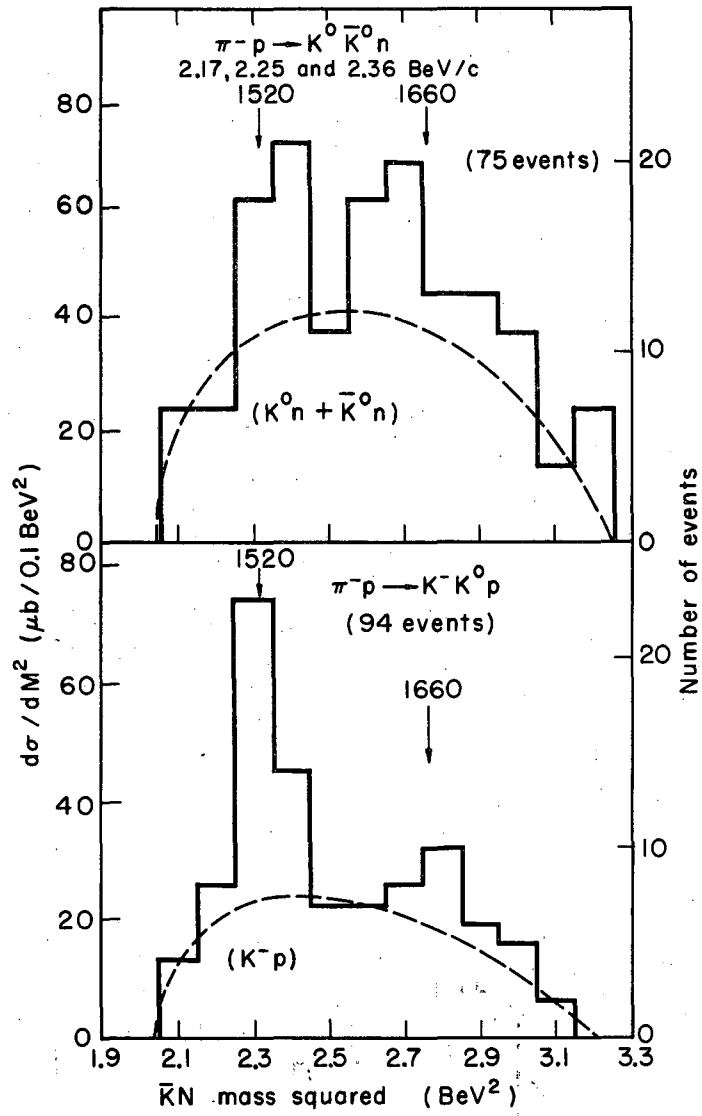
MUB-1708

Fig. 4

MU-30073

Fig. 5

MUB-1711

Fig. 6

MUB-1712

Fig. 7

MUB-1709

Decay of Kπ system with respect to line
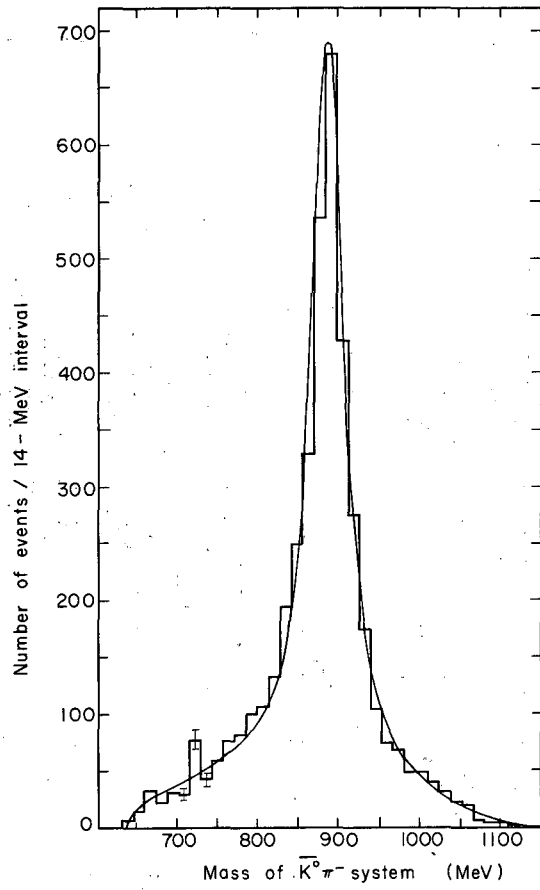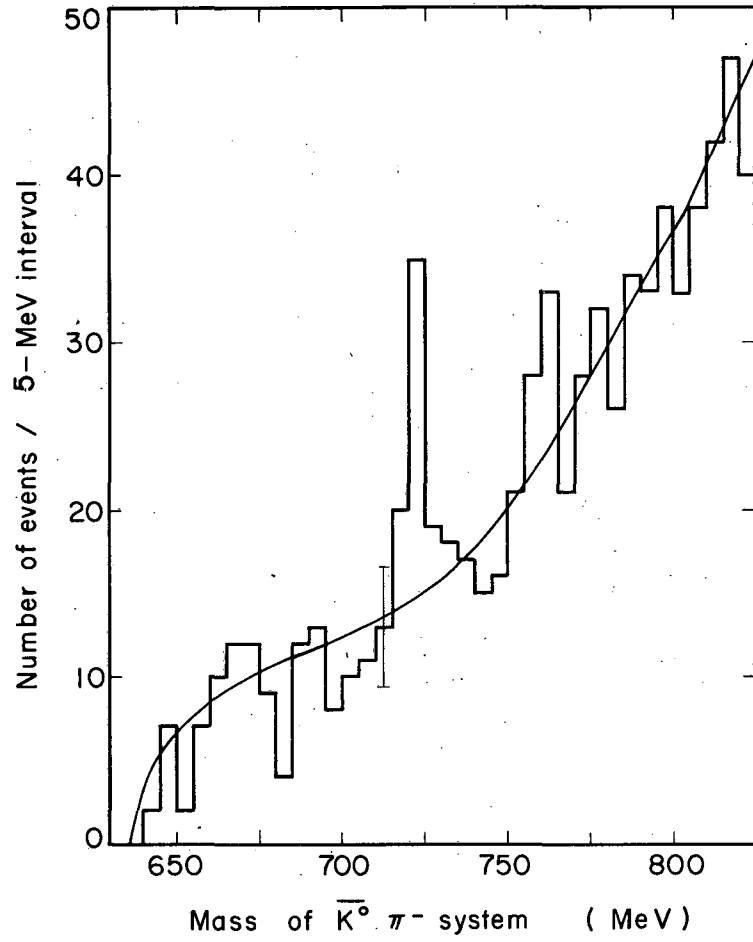of flight in production center-of-mass

$643 \leq M(K\pi) \leq 706$

Fig. 8

MUB-1707

Fig. 9

Fig. 10

MU-30082