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Recently a T = 1 resonance in the Λ-π system called Y_1^* has been observed with a mass of 1385 Mev.[1-6] Two types of resonances have been predicted that might relate this observation to other elementary-particle interactions: (1) P 3/2 resonances in the Λ-π and Σ-π systems predicted by global symmetry,[7,8] corresponding to the (3/2, 3/2) resonance of the π-N system, (2) a spin-1/2 Y-π resonance resulting from a bound state in the $\bar{K}$-N system.[9,10] The position and the width of the observed Y_1^* resonance agree with both theories, but since the spin and parity have not yet been determined, we cannot distinguish between the two theoretical interpretations.

Global symmetry[11] (including a phase-space factor) predicts a branching ratio $R = (Y_1^{*\pm} \rightarrow \Sigma^0 + \pi^\pm)/(Y_1^{*\pm} \rightarrow \Lambda^0 + \pi^\pm) = (Y_1^{*\pm} \rightarrow \Sigma^\pm + \pi^0)/(Y_1^{*\pm} \rightarrow \Lambda^0 + \pi^\pm) = (1/4)(0.225) \approx 5\%$. The $\bar{K}$-N bound-state model suggests values of R considerably larger than 5%. However, when nonzero effective ranges are taken into account,[12] R can become quite small, especially if the Σ-Λ parity should be odd.

To investigate these possibilities, we have continued our study of K^--p interactions at 1.15 Bev/c in the Lawrence Radiation Laboratory 15-in. Hydrogen bubble chamber by studying events in which a Σ is observed. The total cross sections for these interactions are shown in Table I; only statistical errors are indicated. The separation of $\Sigma^\pm + \pi^\mp + \pi^0$ and $\Sigma^\pm + \pi^\mp + 2\pi^0$ events was difficult because many of the latter events will also fit the first hypothesis. The numbers given in Table I and in the mass plots below were corrected to account for this ambiguity. The correction factor was estimated by using our $\Sigma^{\pm} + \pi^{\mp} + \pi^{+} + \pi^{-}$ events.

To obtain an upper limit for the branching ratio, R, we combined the Σ-2π events into different charge states of the Σ-π system. All charged Σ hyperons were observed; however, in the Σ^0 cases only two-thirds of the events were observable because of the neutral decays of the Λ^0. Furthermore, we had estimated that about one-third of the $\Sigma^0\pi^+\pi^-$ events also fitted a $\Lambda\pi^+\pi^-$ interpretation and had been included in already published data.[1] Consequently each $\Sigma^0\pi^+\pi^-$ event was given a weight of 2.25. The resultant mass spectra are shown in Fig. 1. In the cases of $(\Sigma$-$\pi)^+$ and $(\Sigma$-$\pi)^-$ there appears to be no excess of events in the region of M = 1385 Mev. Using the number of $(\Lambda$-$\pi^+)$ and $(\Lambda$-$\pi^-)$ events with 1355 Mev < $M_{\Lambda-\pi}$ < 1415 Mev from reference 1, and assuming that all charged Σ-π systems in the same mass regions of Fig. 1 are Y_1^*, we obtain $R_{max} \lesssim 8\%$. This treatment yields an unrealistic upper limit, since there is no evidence of any peaking above background. The $\Sigma^{\pm} + \pi^{\mp} + 2\pi^0$ events possibly misidentified as $\Sigma^{\pm} + \pi^{\mp} + \pi^0$ (or vice versa) do not fall into the mass band used in this analysis.

We conclude that the Σ/Λ branching ratio R for the strong decay of the T = 1 Y_1^* is at most a few percent and is consistent with zero. This result agrees with the value of R obtained by Bastien et al.[13] As indicated above, this value of R does not rule out either the global symmetry or the $\bar{K}$-N bound-state model of the Y_1^* resonance.

Next, we wish to report the results of our study of the three reactions:

$$K^- + p \rightarrow \Sigma^+ + \pi^- + \pi^- + \pi^+ \quad (1)$$

$$K^- + p \rightarrow \Sigma^- + \pi^+ + \pi^+ + \pi^- \quad (2)$$

$$K^- + p \rightarrow \Sigma^0 + \pi^0 + \pi^+ + \pi^-. \quad (3)$$

Reactions (1) and (2) are readily identified and measured, but reaction (3) cannot be identified unambiguously. Accordingly, we discuss first the results pertaining to reactions (1) and (2). In a search for possible Σ-π resonances, we have plotted in Fig. 2 histograms of the invariant masses of the Σ and each of the three pions in reactions (1) and (2). Figure 2b refers to the Σ and pion of like charge; Fig. 2a to the Σ and each of the pions of unlike charge. For this reason twice as many events appear in Fig. 2a as in Fig. 2b. The plotted curves are mass distributions expected on the basis of a uniform phase-space population. The histogram of Fig. 2b agrees with the phase-space curve, but the Σ and unlike-charged pion distribution appears to exhibit an anomaly, indicating a concentration of events with a Σ-π mass of about 1405 Mev. A more detailed investigation of the distribution of our events in the four-particle phase space suggests that it is quite unlikely that we are dealing with a statistical accident. In fact, in practically every event one of the neutral Σ-π systems has a mass which lies in the resonance region. If one interprets the observed distribution as a resonance, its peak corresponds to a mass of 1405 Mev, and its full width at half maximum is about 20 Mev after unfolding experimental errors.

To investigate further the possibility of a Σ-π resonance, we studied the 39 two-prong events associated with a Λ that did not fit the $K^- + P \rightarrow \Lambda + \pi^+ + \pi^-$ or $K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^-$ interpretations. These events could be:

$$K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^- + \pi^0 \qquad (3)$$

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0 \qquad (4)$$

$$K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^- + \pi^0 + \pi^0 \qquad (5)$$

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0 + \pi^0. \qquad (6)$$

Identification is very difficult because only reaction (4) is sufficiently over-constrained to permit a kinematical fit. Furthermore, most of the events that are actually examples of reaction (3) fit hypothesis (4), but generally with a larger χ^2 value.

Of the 39 events, 16 had $\chi^2 \geq 2$ when kinematically fitted to the one-constraint hypothesis (4). Most of these events are probably due to reaction (3), since a priori only 17% of the events due to reaction (4) should have $\chi^2 \geq 2$. Also, only one example of the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^+ + \pi^-$ and no examples of $K^- + p \rightarrow \Sigma^{\pm} + \pi^{\mp} + \pi^+ + \pi^- + \pi^0$ were observed; thus reactions (5) and (6) are probably rare. Even though a kinematical fit to hypothesis (3) is impossible, one can obtain the invariant mass of the Σ^0-π^0 system from the incident K^- momentum and the measured momenta of the two charged pions. However, since no kinematic constraints can be imposed on such events, the experimental errors will, in general, be larger than for fitted events and fluctuate more widely. Therefore, the data are better represented by ideograms.

Figure 3a shows the ideogram of the mass distribution of the 16 events with $\chi^2 \geq 2$. The three events with $M < 1320$ Mev can be interpreted as the tail of the χ^2 distribution of reaction (4); the four events with $M > 1450$ Mev are probably due to reactions (5) and (6). The remaining nine events fall into a narrow band centered at about 1386 Mev and are most probably due to reaction (3). The plotted curve is the mass distribution of Σ^0-π^0 systems based on phase space and normalized to nine events. It is worth emphasizing that due to our experimental errors of ~20 Mev, the actual peak is expected to be somewhat sharper than shown.

Figure 3b shows the corresponding distribution for the events with $\chi^2 < 2$. In order to permit a direct comparison with Figure 3a, again only the measured momenta of the charged pions were used to obtain the mass ideogram. The measured distribution appears to agree with that expected from phase space for $\Lambda\pi^0\pi^+\pi^-$ events. No anomaly at $M \sim 1390$ Mev is observed. Thus there does not appear to be any evidence of the $T = 1$ Y_1^{*0} resonance in the $\Lambda\pi^0\pi^+\pi^-$ data. Furthermore, if one fits all 39 events to the $\Lambda\pi^0\pi^+\pi^-$ hypothesis and then calculates the

Λ-π^0, Λ-π^+, and Λ-π^- masses from the fitted values, there is still no evidence for the Y_1^* resonance. In particular, the peak of Fig. 3a vanishes. Thus we cannot attribute the observed peaks in the mass distribution shown in Figs. 2a or 3a to the Y_1^* resonance, especially in view of the low Σ/Λ branching ratio discussed above. Because of this and the selection criterion used in isolating the events of Fig. 3a, the nine events probably represent a Σ^0-π^0 resonance linked by charge independence to the Σ^+-π^- and Σ^--π^+ resonance already discussed.

It is easy to show that the branching ratio $\beta = N_{\Sigma^0\pi^0}/(N_{\Sigma^+\pi^-} + N_{\Sigma^-\pi^+})$ uniquely determines the isotopic spin of the resonance. For T = 2, 1, or 0, we have β = 2, 0, or 1/2, respectively. Neglecting possible backgrounds, and correcting for neutral decays and escape of the Λ hyperons in the Σ^0-π^0 case, we have $\beta = 0.6 \pm 0.2$. Hence, the isotopic spin of the indicated resonance is zero, and we will call it Y_0^*.

One difficulty of our interpretation of the data is the difference in mass of 19 Mev ± 6 Mev between the two peaks of Figs. 2a and 3a. However, since there are two identical pions in the charged Σ cases and not in the Σ^0 cases, it is possible that the effect of Bose statistics could cause a shift of the peaks. Also, from the fact that the charged Σ can resonate with either of the two unlike charged pions, one would expect interference effects between the two resonant amplitudes. Another possibility is interference between the resonance and non-resonant backgrounds. Both these interferences might alter the observed positions of the peaks. Electromagnetic mass differences in the Σ^+-π^-, Σ^--π^+, and Σ^0-π^0 have a negligible effect on the position of the peaks if one assumes transition probabilities that are proportional to the decay momentum.

The Y_0^* could also be produced in the events in which the final state consists of a Σ and two pions. If it is produced, it should appear in the $(\Sigma$-$\pi)^0$ mass plot given in Fig. 1c. No significant peak is observed; however, the number of events in this region of the mass plot is uncertain because of the difficulty of correcting for $\Sigma^{\pm}\pi^{\mp}\pi^0\pi^0$ production. The absence of the Y_0^* in this final state ($Y_0^* + \pi$) could be easily understood if the interaction took place mainly through the T = 0 initial channel. The equality of the cross sections for Σ-2π reactions producing Σ of all charges (Table I) is consistent with this possibility. A stronger test of this possibility is provided by the interaction $\bar{K}^0 + p$ (a pure T = 1 state) currently being studied by Adair.[4]

We believe that our data for Σ and three pions are most naturally interpreted by invoking a T = 0 Σ-π resonance. However, both because of the small number of events involved and the complexity of the final state, we cannot regard the evidence as conclusive. Evidence for a ($\Sigma^{\pm}$ - $\pi^{\mp}$) resonance has been obtained by Eisenberg et al., who have studied K^--meson interactions in emulsion and find a peaking in the $(\Sigma$-$\pi)^0$ mass spectrum at 1405 Mev.[14] This peaking could be attributed to a Y_0^*. In addition, Schult and Capps have recently invoked a T = 0 resonance at a mass of about 1410 Mev to explain the hyperon branching ratio in low-energy K^--d interactions.[15]

Dalitz and Tuan have shown that the (b^-) solution for the scattering lengths in $\bar{K}$-N low-energy interactions will result in a Σ-π resonance in the T = 0 state.[9] Recent values for the zero-energy $\bar{K}$-N scattering lengths obtained by Dalitz[16] using the data presented by Alvarez at the Kiev Conference,[17] indicate that this resonance will be at 1415 ± 3 Mev, with a half-width ($\Gamma/2$) of about 20 Mev. If this explanation of the T = 0 resonance is correct, it should have J = 1/2; the observed T = 1 resonance could be the resonance predicted by global symmetry with J = 3/2.[18] Dalitz has pointed out that the values of the (a^-) solution given in reference 9 are consistent with both a T = 1 and a T = 0 $Y\pi$ resonance;[19] both of these resonances should then have J = 1/2.

The authors wish to thank the many members of the Bevatron and bubble chamber crews and the scanners who made this experiment possible. We also thank Professors R.H. Dalitz, A. Pais, B. Sakita, and S. Treiman for several helpful discussions. One of us (PE) wishes to thank the Philippe's Foundation, Inc. and the Commisariat a l'Energie Atomique of France for a fellowship.

Table I. Cross sections for the Σ producing interactions at 1.15 Bev/c

Reaction	No. of events (uncorrected)	Cross sections (mb)
$K^- + p \rightarrow \Sigma^- + \pi^+$	87	1.40 ± 0.16
$\rightarrow \Sigma^+ + \pi^-$	84	1.34 ± 0.18
$\rightarrow \Sigma^+ + \pi^- + \pi^0$	57	0.97 ± 0.16
$\rightarrow \Sigma^- + \pi^+ + \pi^0$	54	0.83 ± 0.20
$\rightarrow \Sigma^0 + \pi^+ + \pi^-$	27	0.97 ± 0.20
$\rightarrow \Sigma^+ + \pi^- + \pi^0 + \pi^0$	13	0.18 ± 0.06
$\rightarrow \Sigma^- + \pi^+ + \pi^0 + \pi^0$	9	0.12 ± 0.05
$\rightarrow \Sigma^+ + \pi^+ + \pi^- + \pi^-$	19	0.19 ± 0.06
$\rightarrow \Sigma^- + \pi^- + \pi^+ + \pi^+$	13	0.12 ± 0.05

FOOTNOTES

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16. R.H. Dalitz, On the Strong Interactions of the Strange Particles, Lawrence Radiation Laboratory Report UCRL-9580, January 27, 1961 (unpublished)

17. L.W. Alvarez, paper presented at the 1959 International Conference on Physics of High Energy Particles, Kiev, July 1959 (unpublished): The Interactions of Strange Particles, Lawrence Radiation Laboratory Report UCRL-9354, August 11, 1960 (unpublished).

18. A. Pais has pointed out to us that if the Y_1^* should turn out to be the resonance predicted by global symmetry, the question arises whether the existence of Y_0^* could have anything to do with global symmetry as well. This is certainly not the case because, if the Y_0^* is related to the global symmetry hypothesis, then there should be a corresponding $T = 1/2$ π-N resonance with $Q \sim 160$ Mev. Thus the existence of a Y_0^* may indicate that the assumption of global symmetry is wrong. However, another possibility is that this symmetry could be valid in the P-wave but not the S-wave pion-baryon interaction.

19. R.H. Dalitz, Enrico Fermi Institute for Nuclear Studies, University of Chicago, private communication.

FIGURE LEGENDS

Fig. 1. Mass plots of the charged and neutral Σ-π systems, including curves representing phase-space distributions.

(a) Mass of $(\Sigma\text{-}\pi)^-$, from the reactions: $K^- + p \rightarrow \Sigma^0 + \pi^- + \pi^+$

$\rightarrow \Sigma^- + \pi^0 + \pi^+$

(b) Mass of $(\Sigma\text{-}\pi)^+$, from the reactions: $K^- + p \rightarrow \Sigma^0 + \pi^+ + \pi^-$

$\rightarrow \Sigma^+ + \pi^0 + \pi^-$

(c) Mass of $(\Sigma\text{-}\pi)^0$, from the reactions: $K^- + p \rightarrow \Sigma^+ + \pi^- + \pi^0$

$\rightarrow \Sigma^- + \pi^+ + \pi^0$

Fig. 2. Mass plots of the neutral and doubly charged Σ-π systems.

Fig. 3. Ideograms of the missing mass for the 39 events in which a Λ and two charged pions were observed and neutral pions were also produced. (a) Events with $\chi^2 \geq 2$ for the $\Lambda\pi^0\pi^+\pi^-$ hypothesis. The superimposed curve is the phase-space distribution for the $\Sigma^0\pi^0\pi^+\pi^-$ reaction normalized to nine events. (b) Events with $\chi^2 < 2$ for the $\Lambda\pi^0\pi^+\pi^-$ hypothesis. The superimposed curvesis the expected $\Lambda\pi^0\pi^+\pi^-$ phase-space distribution.

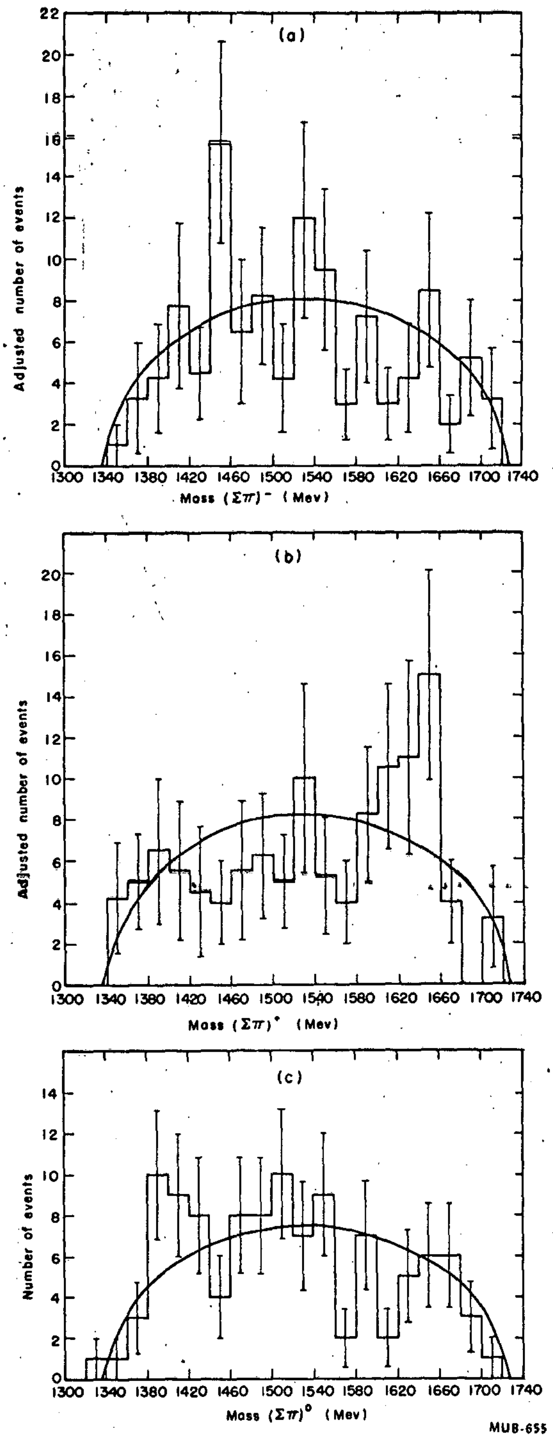
(a)
Adjusted number of events
Mass (Σπ)⁻ (Mev)
(b)
Adjusted number of events
Mass (Σπ)⁺ (Mev)
(c)
Number of events
Mass (Σπ)⁰ (Mev)
MUB-655

Fig. 1.

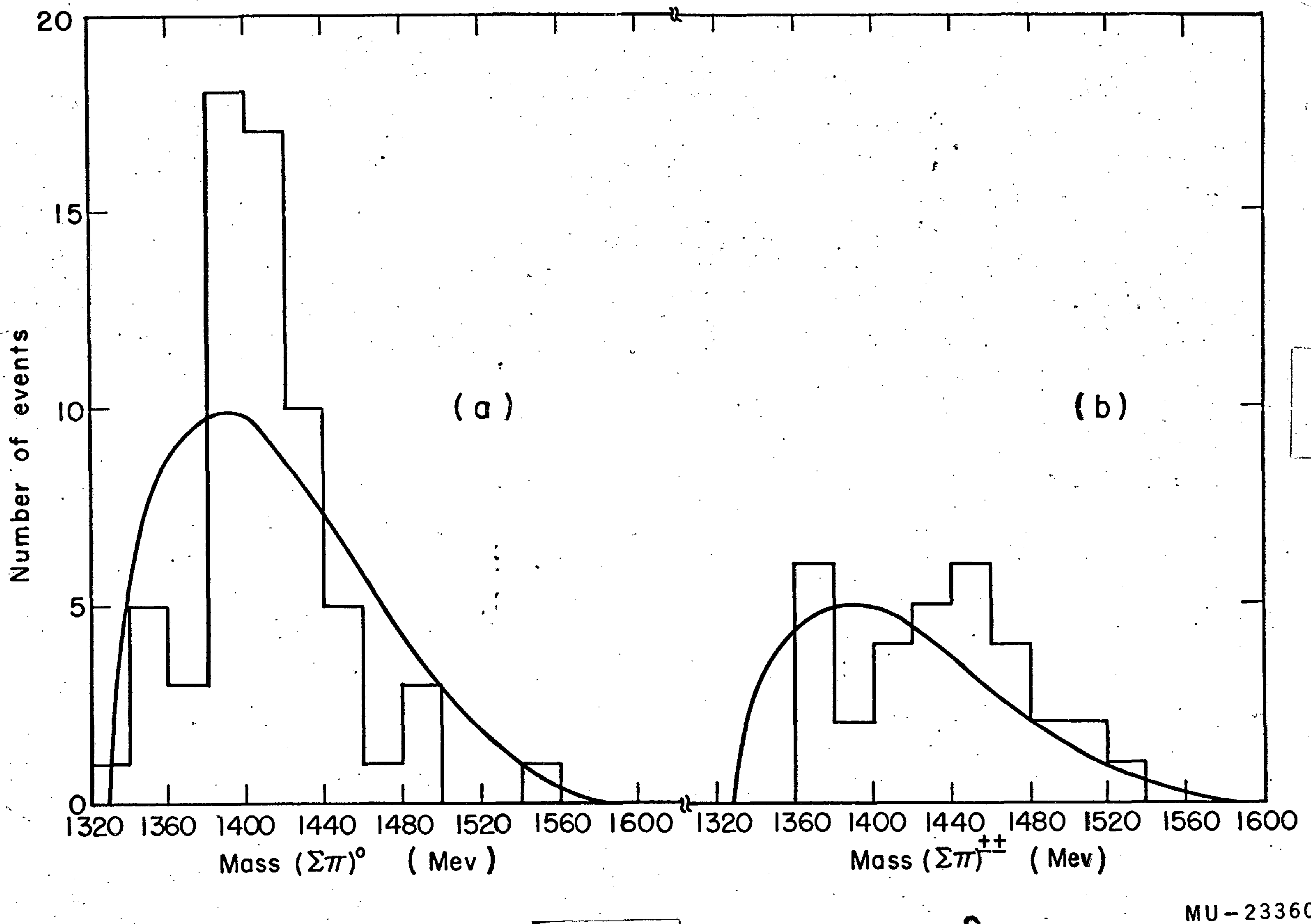
20
15
10
5
0
Number of events
(a)
(b)
1320 1360 1400 1440 1480 1520 1560 1600
1320 1360 1400 1440 1480 1520 1560 1600
Mass $(\Sigma\pi)^0$ (Mev)
Mass $(\Sigma\pi)^{\pm\pm}$ (Mev)
MU-23360

Fig. 2

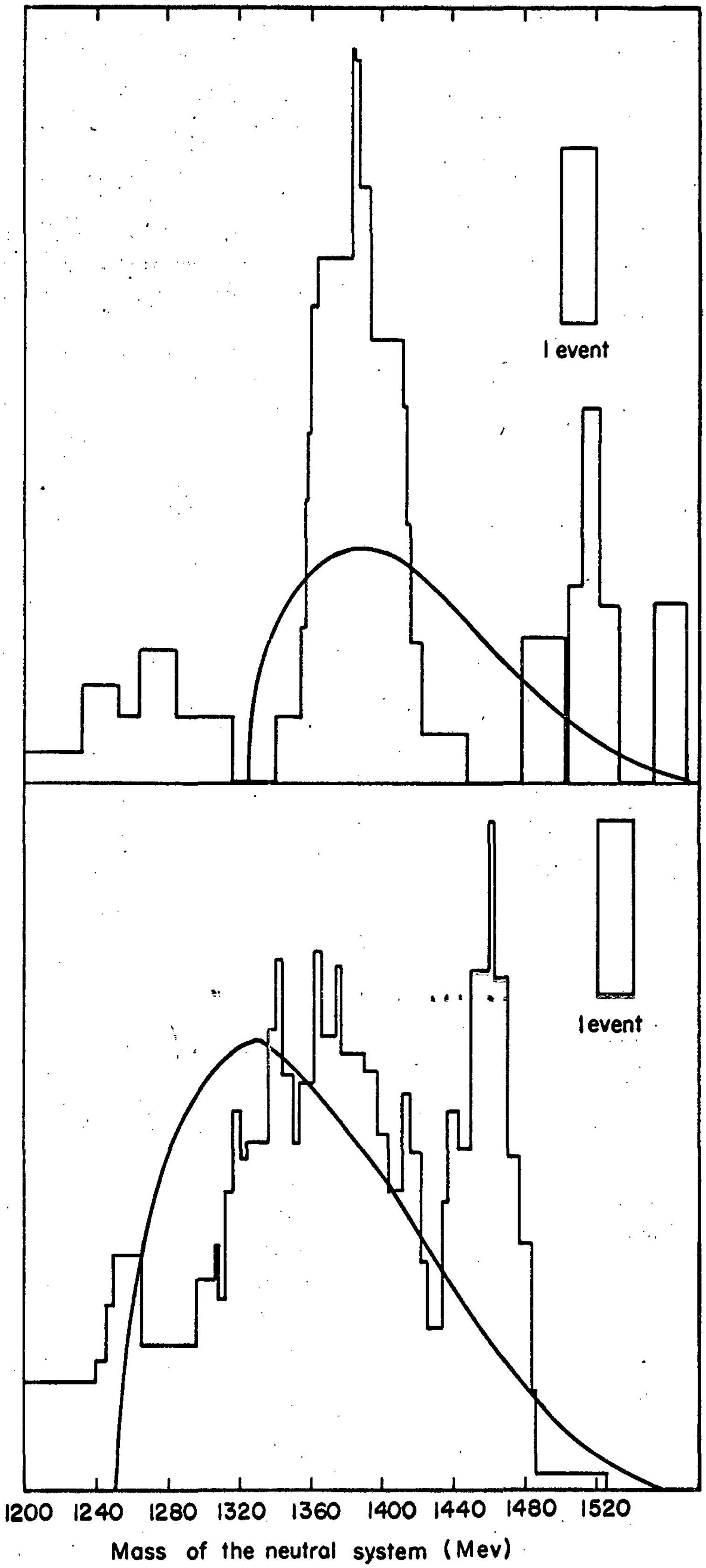

Fig. 3.

MU-23462