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Recently, Bastien et al. reported the results of an extensive analysis of $K^- + p$ interactions below 1 BeV/c.[1] They found that both the $\Sigma^-\pi^+/\Sigma^+\pi^-$ ratio and the cross sections for production of $\Lambda\pi(\pi)$ and $\Sigma\pi(\pi)$ final states varied rapidly in the region $p_K = 760$ MeV/c ($E_{c.m.} = 1681$-MeV). In addition, Alexander et al. examined the two-body effective-mass distributions for $Y\pi K$ states produced in $\pi^- + p$ interactions at 2.1 to 2.3 BeV/c.[2] They observed an enhancement in the region $M(Y\pi) \approx 1685$ MeV, and tentatively ascribed the effect to a resonance in the $I=1$ $Y\pi$ system.

To obtain additional evidence regarding the existence and properties of such a state, we have studied the three- and four-body final states produced in $K^- + p$ interactions at $p_K = 1.51$ BeV/c ($E_{c.m.} = 2025$ MeV). The effective-mass distribution for these events establish the existence of an $I=1$ resonant state, Y_1^*, with mean energy $M^* \approx 1660 \pm 10$ MeV and full width at half maximum $\Gamma \approx 40 \pm 10$ MeV. Enhancements in the mass spectra associated with the positive component of Y_1^*(1660 MeV) are particularly strong and have been used to estimate 7:6:4:4: < 1 as the relative rates for decay into $\Lambda\pi : \Sigma\pi : \Lambda\pi\pi : \Sigma\pi\pi : \bar{K}N$. Because of interference with the large background of competing mechanisms in each channel, neither the spin nor parity of the resonant state could be inferred. The possible relevance of Y_1^* (1660 MeV) to the recently proposed SU(3) symmetry scheme[3,4] is discussed.

The data were obtained during an extensive exposure of the Lawrence Radiation Laboratory's 72-in. hydrogenbubble chamber to a K^- beam. At the momentum setting of 1.51 BeV/c the observed path length provided 5000 events per millibarn of cross section.[5]

After scanning and measurement, events were fitted kinematically by using an IBM program "PACKAGE".

We have studied the effective-mass distributions for the reactions

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- \qquad (1a)$$

$$\rightarrow \Lambda + \pi^+ + \pi^- + \pi^0 \qquad (1b)$$

$$\rightarrow \Sigma^0 + \pi^+ + \pi^- \qquad (1c)$$

$$\rightarrow \Sigma^\pm + \pi^\mp + \pi^0 \qquad (1d)$$

$$\rightarrow \Sigma^\pm + \pi^\mp + \pi^+ + \pi^- \qquad (1e)$$

$$\rightarrow \overline{K}^0 + \pi^- + p. \qquad (1f)$$

The final states 1a, b, c, and f appear topologically in the bubble chamber as interactions leading to two prongs plus an associated V. For approximately 98% of the events, reaction 1f could be unambiguously separated from the Λ/Σ^0 final states by kinematic fits to both the decay and the production vertices. The more difficult task of apportioning the two-prong-plus-Λ events among reactions 1a, b, and c was performed by using the χ^2 criteria enumerated in Table I.

Events arising from reactions 1d and 1e were obtained by measurement of two- and four-prong interactions having a kink in any track at a distance greater than 0.3 cm from the production vertex. Kinematic fitting resulted in almost unambiguous identification of the $\Sigma^\pm \pi^\mp \pi^0$ and $\Sigma^\pm \pi^\mp \pi^+ \pi^-$ final states. The number of events assigned to reactions 1a to 1f is given in the first column of Table II.

Several of the final states studied arise predominantly through production of low-mass resonances in association with one or two additional particles. Therefore it is difficult to establish the existence of more weakly produced higher-lying resonances, which must appear as superpositions on this large background. The effect is illustrated in Fig. 1, which shows the Dalitz plot for the 1852 events idendified as $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$. This final state is clearly dominated by the sequence $K^- + p \rightarrow Y_1^*(1385\,\text{MeV}) + \pi \rightarrow \Lambda + \pi^+ + \pi^-$. Nevertheless, an enhancement of $\approx$ 130 events may be observed both on the Dalitz plot and in the projected effective-mass distribution given in Fig. 2a. No significant effect occurs in the distribution for $M(\Lambda\pi^-)$.

Effective-mass distributions for the positively charge combinations $\Lambda\pi^+\pi^0$, $\Sigma^0\pi^+$, $\Sigma^+\pi^0$, $\Sigma^{\mp}\pi^{\pm}\pi^+$, and $\bar{K}^0p$ are given in Fig. 2b, c, d, and Fig. 3a and b. With the exception of the $K^0p\pi^-$ mass spectrum, each distribution shows a significant enhancement in the $M \approx 1660$ MeV region. An examination of the corresponding negatively charged and neutral combinations indicates that enhancement at $M \approx 1660$ MeV is weak or absent. Accordingly, we are led to conclude that the positively charged component of an $I=1$ (since $\Lambda\pi^+$ is pure I-spin1)resonant state with mass 1660 MeV is produced at this energy.[6]

The relative rates for Y_1^*(1660 MeV) decay into various channels were obtained from suitably corrected estimates for the number of resonance events in each final state. To estimate these numbers in a systematic manner, we fitted the data in the region of the peak with a smooth background curve plus the Breit-Wigner resonance distribution $N(M) = \frac{n_0\Gamma}{2\pi}[(M-M^*)^2 + (\Gamma/2)^2]^{-1}$. Since the final states (1a through f) are dominated by production of low-mass resonances, interference effects may modify significantly the shapes of the distributions observed for Y_1^*(1660 MeV). Figures 2 and 3 suggest that the apparent mean energy and width may vary by as much as ± 10 MeV. Nevertheless, because of the large uncertainties in background and statistical limitations in some channels, a single mass and width have been used. An adequate fit is obtained with $M^* = 1660$ MeV and $\Gamma = 40$ MeV.

The data on the branching ratios of Y_1^*(1660 MeV) are summarized in Table II. It is of interest to note that, within statistics, no enhancement whatever is observed in the $\bar{K}^0p\,(\pi^-)$ final state.[7] In addition, an examination of the Dalitz plot (not shown) for the $\Sigma^0\pi^+\pi^-$ events indicates that the asymmetric resonance distribution results from a constructive interference between the overlapping bands for $Y_1^{*\pm}$(1660 MeV)$\to \Sigma^0\pi^{\pm}$. It should be emphasized that purely experimental uncertainties associated with estimating the number of resonant events make the relative branching ratios reliable to only about 25%.

Furthermore, any strong interference effects, either with three- or four-body background or other resonant states could alter these numbers even further.

The numbers quoted in Table II yield a cross section of approximately 0.4 mb for the process $K^- + p \rightarrow Y_1^{*+}(1660 \text{ MeV}) + \pi^-$. The best estimate for the production ratios $Y_1^{*+} : Y_1^{*0} : Y_1^{*-}$ is $5 : < 1 : < 1$.

One may attempt to relate $Y_1^*(1660 \text{ MeV})$ and other baryon resonances to the approximate symmetry model proposed by Gell-Mann[3] and Ne'eman[4] and discussed further by Glashow and Sakurai.[8] It has been suggested that the stable baryons plus the low-lying resonant states may be accomodated in unitary supermultiplets of dimensionality 1, 8, 8, and 10.[9] Approximate sum rules for masses result from the additional assumption that violations of unitary symmetry occur in a particular and simple manner. The suggested assignments for low-lying baryon resonances are summarized in Table III. Because of uncertainty in quantum numbers, several assignments are speculative. However, if the 1385-MeV Y_1^* is called Σ_δ[10] in accordance with recent evidence for $J = 3/2^+$ from the $\Lambda\pi$ decay mode,[11] then the only remaining vacancy for the 1660-MeV Y_1^* is Σ_γ with spin $J = 3/2^-$. Furthermore, this assignment gives excellent agreement with the equal-mass spacing rule of the δ decuplet if the presently known Ξ^* is a $J = 3/2^+$ resonance.

It has already been pointed out that SU(3) requires an $S = -3$ singlet, Ω^-, of mass 1676 MeV, to complete the 10-fold δ multiplet.[12, 13] We further observe, that if the assignment of Σ_γ for the 1660-MeV Y_1^* is correct, then the predicted mass of the remaining member of the γ octet, an $S = -2$ doublet, Ξ_γ, is approximately 1600 MeV (see Table III). Moreover, Ξ_γ should be very narrow, and hence easy to detect.[14] Accordingly, the theory now predicts the existence and masses of two new particles, both of which can be produced relatively easily using presently available experimental techniques.[15]

The authors are indebted to the operators of the 72-in. bubble chamber and the Bevatron for their skill and patience. Furthermore, this work would have been impossible without the enormous effort of our scanning and measuring staffs.

FOOTNOTES AND REFERENCES

*Work done under the auspices of the U. S. Atomic Energy Commission.

1. P. L. Bastien, J. P. Berge, O. I. Dahl, M. Ferro-Luzzi, J. Kirz, D. H. Miller, J. J. Murray, A. H. Rosenfeld, R. D. Tripp, and M. B. Watson, in Proceedings of the 1962 International Conference on High Energy Physics at CERN(CERN, Geneva, 1962), p. 373. See also P. L. Bastien and J. P. Berge, Phys. Rev. Letters, this issue.

2. G. Alexander, L. Jacobs, G. R. Kalbfleisch, D. H. Miller, G. A. Smith, and J. Schwartz, in Proceedings of the 1962 International Conference on High Energy Physics at CERN, (CERN, Geneva, 1962) p. 322.

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

4. Y. Ne'eman, Nuclear Phys. 26, 222 (1961).

5. All of the path length was utilized for the $\Sigma 3\pi$ events, whereas other topologies studied in this experiment have been analyzed only in about 40% of the film.

6. San-Fu Tuan, Phys. Rev. 125, 1761 (1962) has suggested that Peierls's mechanism [See Ronald F. Peierls, Phys. Rev. Letters 6, 641 (1961)] applied to the $\Lambda\pi^+\pi^-$ final state might provide the dynamical basis for Y^* in the 1645-MeV region.

7. Michael Nauenberg (Theory of Final-State Interactions, submitted to Nuovo Cimento) has pointed out that, in general, the observed branching ratios for a resonant state strongly coupled to several channels may depend sensitively upon whether the resonant state is produced in association with other particles or is formed directly from the interaction of two specific particles. In the former case, the final state may be considered to be the result of a set of three-body production processes, (e. g. $\Lambda\pi\pi$, $\Sigma\pi\pi$, $\bar{K}p\pi$) followed by coherent rescattering of some groups of particles formed. Since only one of the possible intermediate states will be analogous to formation in the two-body situation, the observed final states may have markedly

different properties.

8. S. Glashow and J. J. Sakurai, Nuovo Cimento 25, 337 (1962).

9. M. Gell-Mann, California Institute of Technology, Pasadena, and S. Glashow, University of California, Berkeley, private communication.

10. For the explanation of this notation see A. H. Rosenfeld, in Proceedings of the 1962 International Conference on High Energy Physics at CERN, (CERN, Geneva, 1962) p. 325.

11. J. J. Murray, J. B. Shafer, and D. O. Huwe, Spin and Parity of the 1385-MeV Y_1^* Resonance, UCRL-10534 Abstract, November 1962, submitted to the A. P. S. Meeting in New York City, January 1963; see also D. Colley, N. Gelfand, U. Nauenberg, J. Steinberger, S. Wolf, H. R. Brugger, P. R. Kramer, and R. J. Plano, Proceedings of the 1962 International Conference on High Energy Physics at CERN, (CERN, Geneva, 1962) p.315.

12. M. Gell-Mann, Proceedings of the 1962 International Conference on High Energy Physics at CERN, (CERN, Geneva, 1962) p. 805.

13. S. Glashow and J. J. Sakurai, Nuovo Cimento 26, 662 (1962).

14. S. Glashow and A. H. Rosenfeld, submitted to Physical Review Letters.

15. The threshold for the reaction $K^- + p \rightarrow \Omega^- + K^+ + K^0$ is about 3.2 BeV/c. The threshold for the production of Ξ_γ is only about 1.7 BeV/c, so it is slightly disconcerting that it has not yet been observed.

Table I. Selection criteria for apportioning V^0 plus 2-prong events.*

Final state	Constraints	a.	b.	c.
a. $\Lambda\pi^+\pi^-$	4	$\chi_a^2 < 40$	$\chi_b^2 > 10$	$\frac{\chi_a^2}{\chi_c^2} < \frac{4}{2}$
b. $\Lambda\pi^+\pi^-\pi^0$	1	$\frac{\chi_b^2}{\chi_a^2} < \frac{1}{4}$	$\chi_b^2 < 10$	$\frac{\chi_b^2}{\chi_c^2} < \frac{1}{2}$
c. $\Sigma^0\pi^+\pi^-$	2	$\chi_a^2 > 40$	$\frac{\chi_c^2}{\chi_b^2} < \frac{2}{1}$	$\chi_c^2 < 20$

*The average expected value of χ^2 is proportional to the number of constraints. For an event to be assigned to a given hypothesis it must satisfy all three χ^2 tests listed in the row associated with that interpretation. Note that the χ^2 criteria are chosen in a manner such that no event can be assigned to more than one interpretation. Furthermore, the highly ambiguous events are not accepted anywhere in this table. This results in rejecting approximately 9% of the data.

Table II. Summary of data used in determination of Y_1^* (1660-MeV) decay branching ratios.

Final state[a]	Number of events	Estimated number of Y_1^* events: Observed	Estimated number of Y_1^* events: Corrected[b]	Relative decay rate
$\Lambda\pi^+$	1852	130	700	7
$\Sigma^0\pi^+$	504	60	320	6 (with $\Sigma^+\pi^0$)
$\Sigma^+\pi^0$	752	70	280	
$\Lambda\pi^+\pi^0$	1736	90	440	4
$(\Sigma\pi\pi)^+$ visible[c]	1058	180	270	
$(\Sigma\pi\pi)^+$ total			400	4
$\bar{K}^0 p$	1223	0	0	< 1

a. We have also examined about 400 events of the type $K^- + p \rightarrow \bar{K}N2\pi$, corresponding to slightly more than half of the entire film sample. No statistically significant enhancement is observed in the region of 1660 MeV in the mass spectra of the $\bar{K}N\pi$ system.

b. The numbers in this column have been obtained by applying corrections for detection efficiency, neutral decay modes, and amount of path length analyzed for each topology.

c. Of the four charge states that make up the $(\Sigma\pi\pi)^+$ combination, both $\Sigma^0\pi^0\pi^+$ and $\Sigma^+\pi^0\pi^0$ involve two missing neutrals and thus are inaccessible to us. Because of the three possible $\Sigma\pi$ amplitudes (I=0, 1, or 2) which can make up an I=1 $\Sigma\pi\pi$ state, the ratio of the two visible modes $\Sigma^+\pi^+\pi^-$ and $\Sigma^-\pi^+\pi^+$ to the other two can vary anywhere from 1:1 to 4:1. As a compromise we have arbitrarily taken this ratio to be 2:1 in estimating the total rate into $\Sigma\pi\pi$.

Table III. The SU(3) representation of low-mass baryons. Not shown is the β singlet, whose sole member Λ_β could well be Y^{*0} (1405 MeV). In its $\Sigma\pi$ channel, Λ_β would represent a resonance; in its $\bar{K}N$ channel, it would represent an s-wave bound state. We have used the symbol Λ for the metastable 1115-MeV Λ particle as well as the two Y^{*0} resonances which have the same values for baryon number, strangeness, and isotopic spin. We treat Σ, N, and Ξ similarly and invent Δ to stand for $N_{3/2}^{*}$. This notation is further explained in reference 7.

$$\frac{m_N + m_\Xi}{2} \approx \frac{m_\Sigma + 3m_\Lambda}{4}$$ Equal-mass spacing rule[a]

α octed $J^P = 1/2^+$			γ octed $J^P = 3/2^-$			δ decuplet $J^P = 3/2^+$			
Baryon	m (MeV)	2I+1	Baryon	m (MeV)	2I+1	Baryon	m (MeV)	Δm	2I+1
Ξ[b]	1320	2	Ξ (?)	1600	2	Ω (?)	1676		1
								146	
Σ	1190	3	Σ[c]$=Y_1^*$	1660	3	Ξ[b]$=\Xi_{1/2}^*$	1530		2
								145	
Λ	1115	1	$\Lambda = Y_0^*$	1520	1	$\Sigma = Y_1^*$	1385		3
								147	
N	939	2	$N=N_{1/2}^*$	1512	2	$\Delta = N_{3/2}^*$	1238		4
Total:		8	Total:		8			Total:	10

[a]The two mass formulas are special cases of Okubo's generalization of Gell-Mann's mass formula [S. Okubo, Progr. Theoret. Phys. 27, 949 (1962)].

[b]This assignment is speculative; neither the spin nor parity is determined.

[c]This assignment is speculative; the parity is yet undetermined; the spin assignment is suggested by the work of Bastien and Berge.[1]

FIGURE LEGENDS

Fig. 1. Dalitz plot of 1352 examples of the reaction $K^- + p \rightarrow \Lambda\pi^+\pi^-$.

Fig. 2. Two-body decay modes of the 1660 MeV Y_1^{*+}. The dashed portion of the Fig. 2d includes only non-K^* events (events satisfying the criterion 850 MeV < $M(K\pi)$ < 940 MeV have been removed). The curves represent the best fits of the data to a smooth background curve plus a Breit-Wigner distribution. Here Γ_r indicates the experimental resolution in the 1660-MeV region.

Fig. 3. Three-body decay modes of the 1660-MeV Y_1^{*+}. The curves represent the best fit of the data to a smooth background curve plus a Breit-Wigner distribution. Here Γ_r indicates the experimental resolution in the 1660-MeV region.

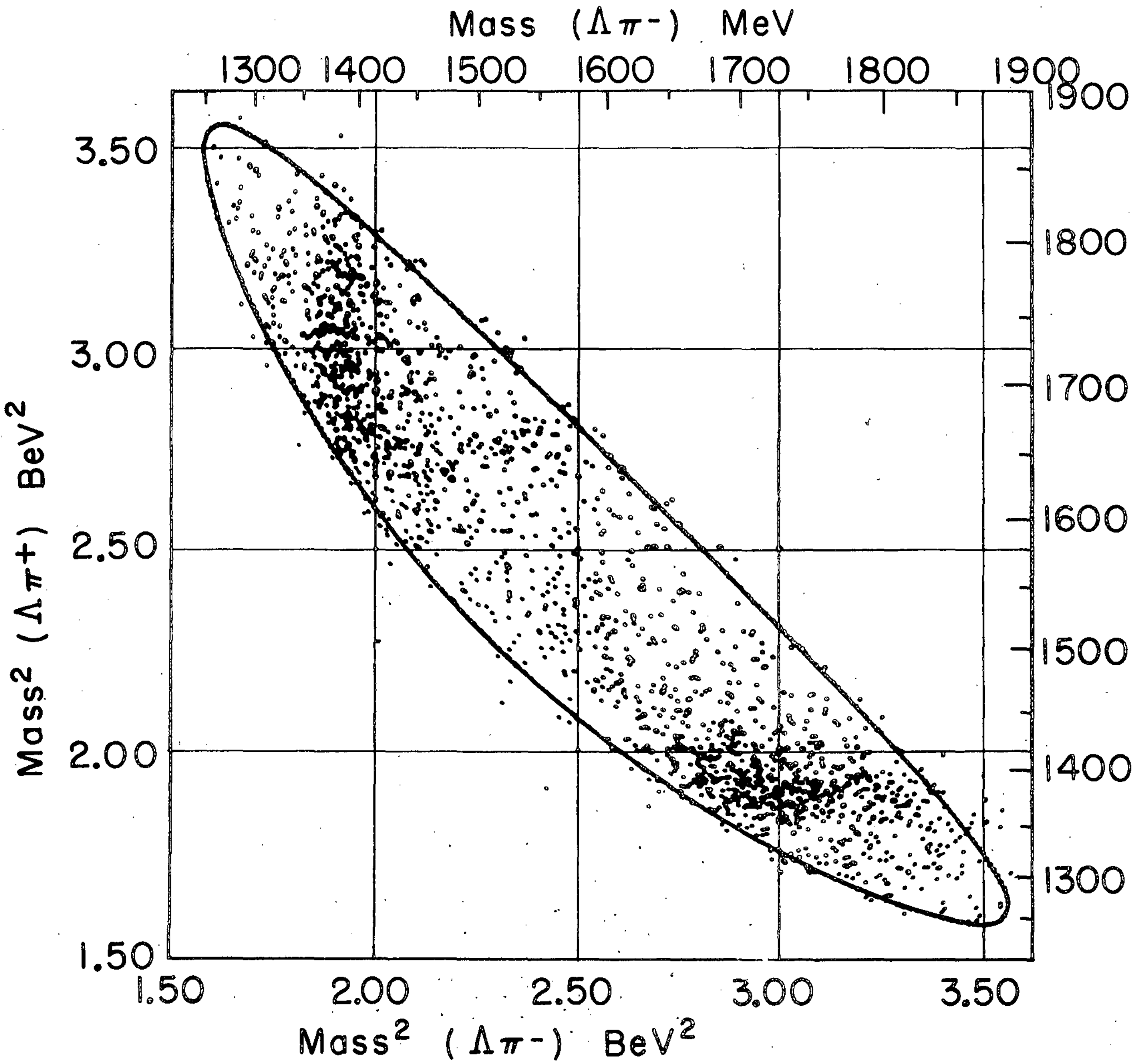

Fig. 1

MU-28877

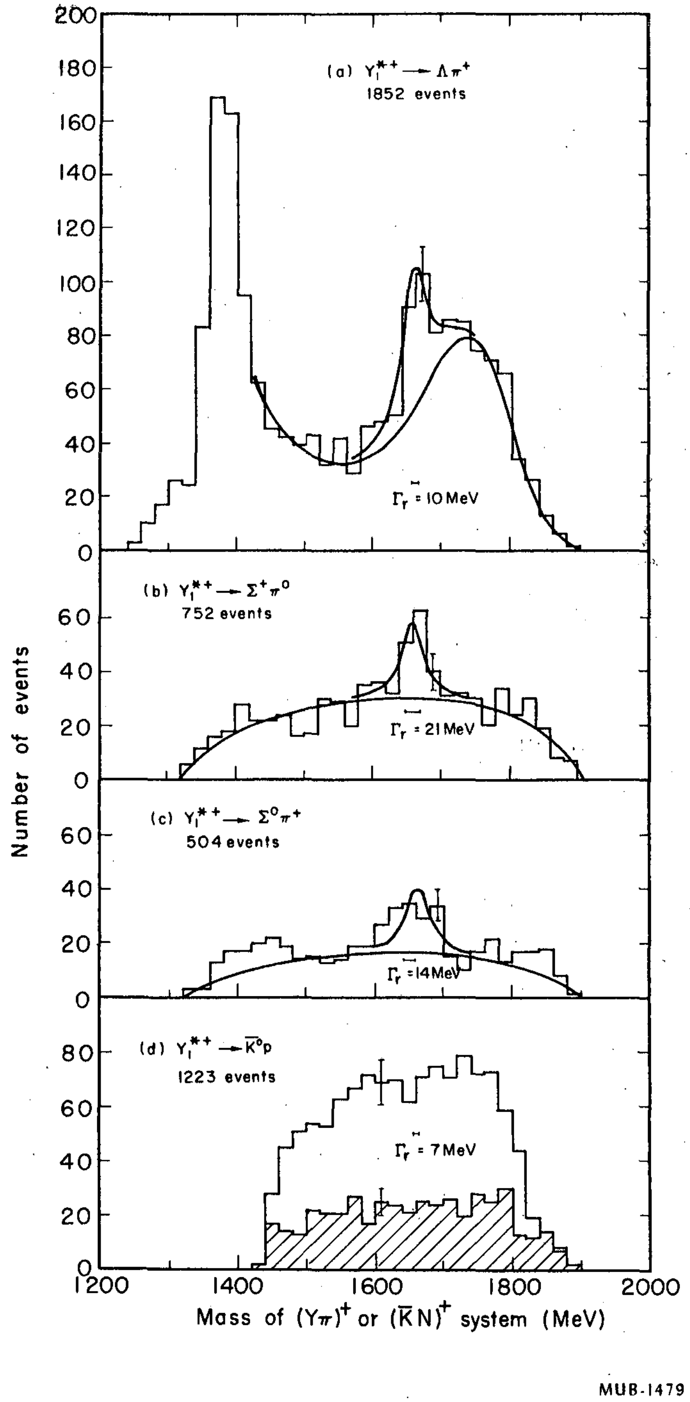
(a) $Y_1^{*+} \rightarrow \Lambda\pi^+$
1852 events
Γ_r = 10 MeV
(b) $Y_1^{*+} \rightarrow \Sigma^+\pi^0$
752 events
Γ_r = 21 MeV
(c) $Y_1^{*+} \rightarrow \Sigma^0\pi^+$
504 events
Γ_r = 14 MeV
(d) $Y_1^{*+} \rightarrow \bar{K}^0 p$
1223 events
Γ_r = 7 MeV
Number of events
Mass of $(Y\pi)^+$ or $(\bar{K}N)^+$ system (MeV)
1200
1400
1600
1800
2000
MUB-1479

Fig. 2

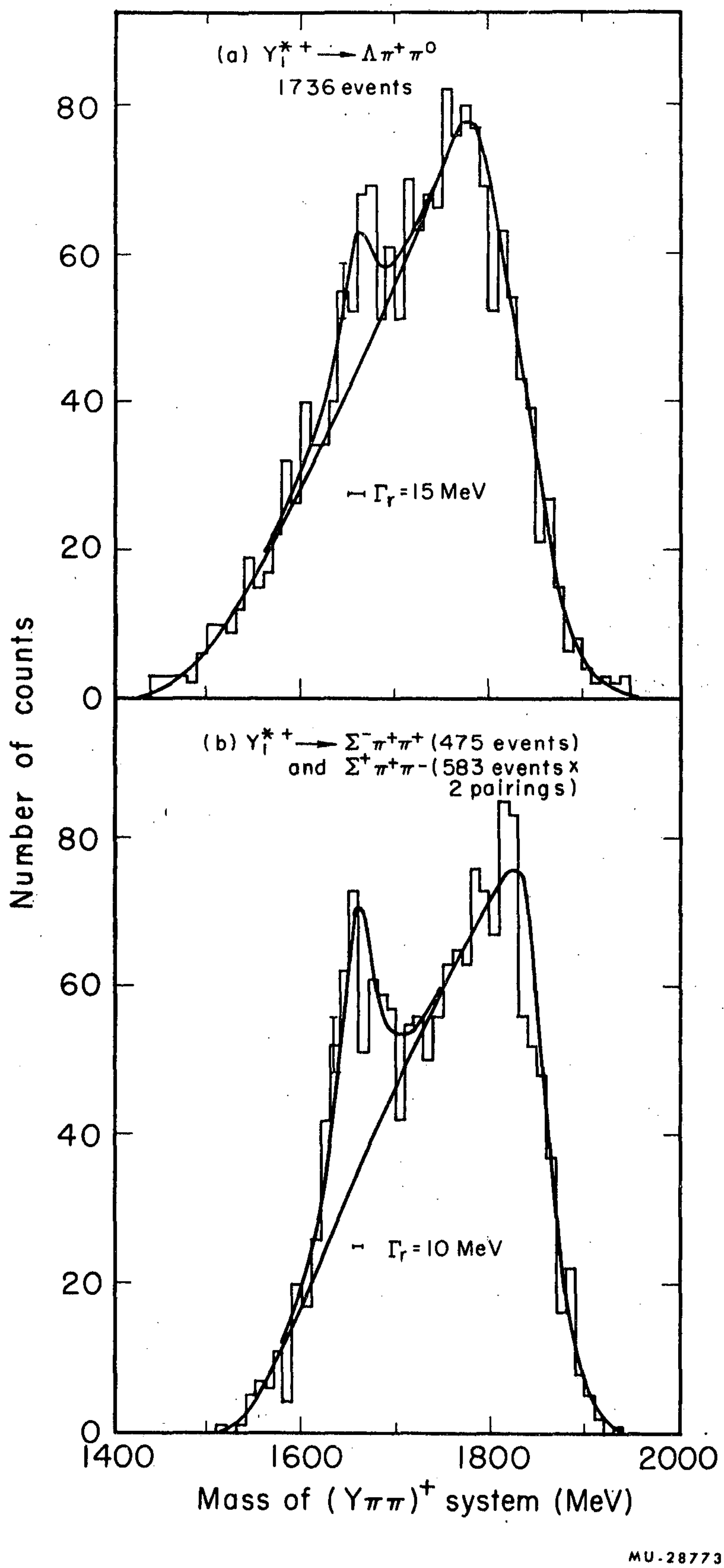
(a) $Y_1^{*+} \rightarrow \Lambda\pi^+\pi^0$
1736 events
Γ_r = 15 MeV
(b) $Y_1^{*+} \rightarrow \Sigma^-\pi^+\pi^+$ (475 events)
and $\Sigma^+\pi^+\pi^-$ (583 events x 2 pairings)
Γ_r = 10 MeV
Number of counts
80
60
40
20
0
1400
1600
1800
2000
Mass of $(Y\pi\pi)^+$ system (MeV)
MU-28773

Fig. 3