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Abstract. The present state of the experimental evidence for elementary particle resonances, other than the pion-nucleon resonances, is presented. The properties of the four pion-hyperon resonances, as well as those of the k^*, ρ, ω, and η mesons, are discussed. Emphasis is placed on the experimental determination of the spin, parity and G parity of the ω and η particles.

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1. Introduction

If I had been asked a year and a half ago to name the elementary particles known at that time, I would have presented a list that had not changed for many years. In addition to the photon, there were three leptons, the electron, the muon and neutrino; two mesons, the pion and kaon; and four baryons, the nucleon, the lambda, the sigma, and the xi. Since that time the number of leptons has not changed. However, the number of objects listed with the strongly interacting particles has increased greatly, as can be seen in figure 1, and it will undoubtedly continue to grow.

Actually, most of the objects labeled N^*, the pion-nucleon resonances, and especially the $J = 3/2$, $I = 3/2$ resonance, were well known eighteen months ago. The fact that they appear here along with the longer-lived particles reflects more a change in outlook by high-energy physicists than an increase in experimental knowledge. I remember that many years ago R. R. Wilson referred to the 3/2-3/2 resonance as a particle, but for a number of reasons this was not fashionable at the time. In the first place, theorists didn't want to consider a particle that has a spin of 3/2 because a field theory of a spin 3/2 particle is not re-normalizable. Second, to admit that the 3/2-3/2 resonance is a particle would allow the existence of doubly charged elementary particles, a development strongly resisted by physicists, who always hope for simplicity in nature. Finally, the 3/2-3/2 resonance was not thought of as a particle because of its very short lifetime, which is evidenced by its broad width of about 90 MeV. Lifetime alone cannot be the criterion upon which we decide whether or not a particle is elementary, for we certainly cannot say that because the π^+ lives 10^8 times as long as the π^0 it is more elementary. Nevertheless, one would hesitate to call one of these objects an elementary particle if the distance that it travels before it breaks up is small compared with the range of nuclear forces. In this respect it is useful to express $\hbar c$ as 197 MeV fermi, which implies, by the uncertainty principle, that if there is a "particle" having a width of 200 MeV, and traveling with a momentum equal to its mass (i.e., pc = m), it decays in a distance of about one fermi. Thus a resonance that has a width of much less than 200 MeV can be thought of as a free particle, in the sense that its breakup (or decay) is independent of its production process. For a resonance with a width of the order of 200 MeV one can expect interference effects between the decay particles and other particles involved in the production process. Partly because field theory has failed to describe strong interaction physics, and partly because of the discovery of many new resonances with lifetimes spanning the gap between the broad resonances and the previously known particles, the prejudice against grouping all of these objects together has largely disappeared. I therefore use the words resonance and particle interchangeably to suit my fancy, taking the position that without a successful theory of strong interactions, we cannot distinguish one from the other.

Resonances have been discovered in two distinct experimental situations. In the first case, the two particles in the initial state of a reaction are at the resonant energy. With one notable exception the resonances of this type, which includes all the pion-nucleon resonances, were found by using counter techniques. The pion-nucleon resonances—S(strangeness) = 0, B(baryon number) = 1–form a topic unto themselves and I shall not discuss them here. In the second case, two or more of the particles in a many-body final state are at the resonant energy. These resonances were found primarily in experiments using bubble chambers, and it is upon these that this discussion is concentrated.

In the bubble chamber experiments the procedure in looking for resonances is generally as follows. From measurements made on stereoscopic pairs of bubble chamber photographs a computer calculates the momentum, azimuth, and dip for each track associated with an interaction. A subsequent kinematic analysis identifies the interaction and finally, a phenomenological analysis is made of all the events that have been identified as being a particular interaction. In looking for resonances between N particles, one calculates the invariant mass

$$M_N = \left[\left(\sum_{i=1}^{N} E_i\right)^2 - \left(\sum_{i=1}^{N} \vec{P}_i\right)^2\right]^{1/2} ,$$

and investigates the frequency of occurrence of these mass values.

Let us consider the evidence for these resonances. An excellent discussion of this topic was presented in a lecture series by Dalitz (1961).

First I shall discuss the only ~~meson~~ resonance having S = 1 and B = 0; namely, the K^*. This was found by Alston et al. (1961a) in an experiment using a K^- beam of 1.15 BeV/c in the Berkeley 15-inch hydrogen bubble chamber. The reactions

$$K^- + p \rightarrow p + \pi^0 + K^-$$
$$\rightarrow p + \pi^- + \overline{K}^0$$

were found to be frequently

$$K^- + p \rightarrow p + K^{*-} ,$$

with the K^* decaying into $\overline{K}^0 + \pi^-$, or $K^- + \pi^0$, in the ratio

$$\frac{K^{*-} \rightarrow \overline{K}^0 + \pi^-}{K^{*-} \rightarrow K^- + \pi^0} = 1.4 \pm 0.4$$

The K^* has a mass of 885 MeV. This and other values that are quoted here are not reliable to an accuracy of greater than ±5 MeV. Experimental reproducibility is often better than this. However, unknown systematic errors can very well exist, producing errors of 5 MeV or more in some bubble chamber determinations of resonance masses. The K^* has been observed and reported (Walker, Rogozinski 1961) in the reaction

$$\pi^- + p \to \Sigma^- + \overset{0}{K^{+}} + \overset{+}{\pi^{0}} ,$$

and in antiproton annihilations (Morrison, Kalbfleisch 1962). The branching ratio of 1.4±0.4 for the K^{*-} is more consistent with the value of 2 predicted for $I = 1/2$ than it is with the $I = 3/2$ prediction of 0.5. Because of this, and also because no K^* with charge 2 has been observed, the K^* quite probably has an isotopic spin of 1/2. The most impressive evidence so far for the K^* is to be seen in data from the recent 1.22-BeV/c K^- run in the 72 inch hydrogen chamber (Alston et al. 1962, private communication) as shown in figure 2. These data indicate that the width of the K^* is about 45 MeV, a value considerably larger than the 16 MeV reported earlier on the basis of limited statistics by Alston et al. (1961a). When I speak of a width of a resonance I always mean its full width at half-maximum. The angular distribution of the decay of the K^* in this experiment is nearly isotropic, but it has a small amount of a $\cos^2\theta$ term in it, such as one would expect from a spin 1 particle. However, the evidence for spin 1 is not strong, the probability being about 0.1 that the data would look this much like spin 1, even if the spin were in fact zero.

2. The Y^*'s

The pion-hyperon resonances (B = 1, S = -1) have all been labelled Y^* with a subscript indicating their isotopic spin. The first of these to be discovered was the Y_1^*, mass 1385 MeV. It too was found in the 1.15-BeV/c K^- data reported by Alston et al. (1960) in the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$. These events were found to be almost entirely either $K^- + p \rightarrow Y^{*-} + \pi^-$ or $\rightarrow Y^{*-} + \pi^+$, with $Y^{*\pm} \rightarrow \Lambda + \pi^\pm$. The Y^{*-} has since been observed in other experiments (Berge et al., Block et al. 1961).

A large number of Y_1^* have been observed in an experiment with 1.11-BeV/c K^- in the Berkeley 30-inch propane chamber. Figure 3 shows the effective mass distribution for these events reported by Ely et al. (1961). Their analysis of the up-down distribution of the Λ from the decay of the Y_1^* relative to the plane of production of the Y_1^* indicates strongly that the Y_1^* has a spin of 3/2. In the data from the newer 1.22-BeV/c K^- run there are more than 1000 Y_1^* (Berge et al. 1962a). The Y_1^* width determined from these data is 55 MeV. Whereas the data from the propane chamber experiment suggested that the widths of the Y^{*+} and the Y^{*-} may be different, no such effect is observed in the 1.22-BeV/c data. The Y_1^* decays rarely, if at all, ($< 4\%$ of the time) into $\Sigma^\pm \pi^0$ (Bastien, Ferro-Luzzi, and Rosenfeld 1962).

Evidence for a Y_0^* at 1405 MeV has also been reported by Alston et al. (1961b). It decays into $\Sigma^\pm \pi^\mp$ and possibly into $\Lambda \pi^+ \pi^-$ ~~and $\Sigma\pi\pi$~~ states. Until very recently the evidence for this has been rather weak. However, it has shown up in the 1.22-BeV/c K^- interactions in the $\Sigma^\pm \pi^\mp$ decay modes (Berge et al. 1962, private communication). It has a width of about 50 MeV.

Another Y_0^* with a mass of 1520 MeV has been reported by Ferro-Luzzi, Tripp, and Watson (1962), who have investigated $K^- p$ cross sections for K^- with momenta around 400 MeV/c. This is the only resonance between particles in the initial state of a reaction which has been discovered in a bubble chamber experiment. The data are from the 15-inch hydrogen chamber. Figure 4 shows the behavior of the charge-exchange and $\Lambda\pi^+\pi^-$ cross sections in this energy range. The resonance shows up also in all three of the $\Sigma\pi$ channels, including the $\Sigma^0\pi^0$ state, a configuration that must have zero isotopic spin. It is not seen in the $\Lambda^0\pi^0$ state, which has unit isotopic spin. Therefore this resonance is assigned a zero isotopic spin.

The low-energy K^-p scattering has been studied and shown to be dominated by s wave up to the region of this resonance (Humphrey, Ross 1961). Figure 5 shows that in the energy region just below the resonance the elastic scattering is very nearly isotropic, in agreement with s-wave scattering. In the resonance region it has a strong $\cos^2\theta$ term that largely goes away at higher energies. The only angular-momentum state that can be added to the s-wave scattering to produce a strong $\cos^2\theta$ term, and not producing large contributions from other powers of $\cos\theta$, is the D 3/2 state. By adding the s-wave scattering amplitude extrapolation from the lower-energy data to a d-wave amplitude of the Breit-Wigner form with a central value (395 MeV/c) and a width (8 MeV) determined by the total cross section data, Ferro-Luzzi, Tripp, and Watson (1962) predict the angular distribution of the elastic and charge-exchange interactions. Figure 6 shows that this prediction is in good agreement with the data. The agreement is poorest at the high energies, presumably because one cannot neglect the p-wave amplitude at these energies. Thus at 1520 MeV there is a resonance with a spin of 3/2 and an even parity with respect to the KN system. By analyzing the $\Sigma\pi$ states in these data, Tripp, Watson, and Ferro-Luzzi (1962) demonstrate that the $Kp\Sigma$ relative parity is odd, indicating that the $\Sigma\Lambda$ relative parity is even.

Finally, there is a bump with a width of about 120 MeV/c in the total K^-p cross section at a K^- momentum of 1050 MeV/c reported by Chamberlain et al. (1962). The properties of this region are being investigated.

3. Nonstrange Mesons

The last system to be discussed here is that having S = 0, B = 0. The first of these resonances to be observed was the ρ meson, which had been sought for some time in order to explain the observed charge distribution of the nucleon.[1] The first convincing evidence for the ρ was reported by Erwin et al. (1961), who analyzed 1.9-BeV/c π^- interaction in the Adair 14-inch hydrogen bubble chamber, and also by Stonehill et al. (1961), who analyzed 1090-MeV and 1260-MeV π^+ interactions in the 20-inch Shutt hydrogen bubble chamber. Strong evidence that a pion-pion resonance exists had been presented earlier by Anderson et al. (1961) who analyzed 1.05-BeV/c π^- interactions in the 72-inch chamber. The ρ has been observed to decay into $\pi^{\pm}\pi^0$ and $\pi^+\pi^-$ but not $\pi^{\pm}\pi^{\pm}$, and therefore has I = 1.

The ρ has since been observed in other experiments, as by Pickup, Robertson, and Salant (1961), Alliti et al., Button et al., Carmony and Van de Walle, and M. Derrick (1962). The central value of the resonance, as well as its width, seems to vary from one experiment to another, the central value ranging from 720 through 770 MeV. A central value of 750 MeV and a width of 110 MeV seem to describe the data best.

If one looks at the reactions

$$\pi^{\pm} + p \rightarrow \pi^{\pm} + p + \pi^0$$

in which the proton has a very small momentum in the laboratory system, one obtains a sample enriched in ρ mesons. One can visualize this process as one in which the incident pion interacts with a π^0 in the pion cloud of the proton and the proton is essentially a spectator particle. Figure 7 shows the data of Alliti et al. (1961), who looked at events of very low momentum transfer from 1.6-BeV/c π^- interactions in the Saclay 50-cm hydrogen bubble chamber. It can be seen that these data are dominated by the ρ meson. From them one can calculate by means of the Chew and Low (1959) method a pion-pion cross section. Figure 8 shows data represented in this way. The resonance is nearly as high as $12\pi\lambda^2$, which is the value expected for a $J = 1$ resonance. Stronger evidence for the $J = 1$ assignment of the ρ comes from the distribution of the breakup angle of the products of the ρ. Figure 9 shows these angular distributions from the data of Carmony and Van de Walle (1962), demonstrating how the $\cos^2\theta$ term predicted by the $J = 1$ assignment dominates the resonance region.

In the data of Button et al. (1962), in which the ρ was observed among 4-prong annihilations of 1.61-BeV/c antiprotons, there was a suggestion that the ρ resonance does have structure and is double peaked. This effect has not been reported in other experiments. In particular, the groups at Oxford and Padua (Derrick 1962) who are analyzing annihilations of stopping antiprotons in the Saclay 80-cm hydrogen bubble chamber, find that all three charge states of the ρ show up very prominently in the three-body annihilations,

$$\bar{p} + p \rightarrow \pi^+ + \pi^- + \pi^0$$

and that no evidence for any double peak is observed. It therefore seems likely that this apparent structure was a statistical fluctuation.

The next meson to be discovered was the ω meson having a mass of about 780 MeV. It was first seen and reported by Maglić et al. (1961), in the 1.61-BeV/c antiproton annihilation in the Berkeley 72-inch hydrogen chamber, in the reaction

$$\bar{p} + p \rightarrow \pi^+ + \pi^- + \pi^+ + \pi^- + \pi^0,$$

as a particle that decays into $\pi^+\pi^-\pi^0$. These data are shown in Figure 10. It was also seen in the 6-prong annihilations, by Xuong and Lynch (1961). Probably the purest sample of ω mesons yet found is the sample of Pevsner et al. (1961), who looked at the reaction $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$ for incident pions of 1.23 BeV/c. These data are shown in figure 11. The ω has been seen only in the neutral charge state and therefore is assigned an I = 0. Masses of the ω ranging from 765 through 787 MeV have been reported (Maglić et al., Xuong and Lynch, Pevsner et al. 1961, and Hart et al. 1962). In these experiments the width of the ω resonance was about equal to the experimental resolution of the experiment. Thus all we can say about the width of the ω is that it is less than 25 MeV.

Information about the spin and parity of the ω is obtained by making a Dalitz plot for the three pions from the ω decay. Such a Dalitz plot for the data of Pevsner et al. (1961) is shown in figure 12. A particle which has I = 0 and decays into $\pi^+\pi^-\pi^0$ by strong interactions can have three spin parity assignments 1^-, 0^+, or 1^+. As was pointed out by Stevenson et al. (1962), the distribution of events in the Dalitz plot predicted by the 0^+ and the 1^+ assignments is very different from the observed distribution. Both assignments predict a depopulation at the center of the Dalitz plot and also predict that the most densely populated regions are near the edges. The simplest matrix element, corresponding to 1^-, predicts a maximum density at the center of the plot and a vanishing density all around the edges, in agreement with the data. Thus if the ω decays by strong interactions, it is a 1^- particle.

The data of Pevsner et al. (1961) shown on figure 12 is now also the first evidence for the η meson. The first detailed study of this $\pi^+\pi^-\pi^0$ resonance at 550 MeV came from the data of Bastien et al. (1962), who analyzed the reactions

$$K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$$

for 750-MeV K^- in the Berkeley 15-inch chamber. They also looked at the events $K^- + p \rightarrow \Lambda$ + (other neutrals), and observed that in the effective-mass spectrum of the neutrals there was also a peak, and that the η decays more copiously into some all-neutral decay mode than into the $\pi^+\pi^-\pi^0$ mode. Figure 13 shows these data. Figure 14 shows the evidence for the η in the 1.22-BeV/c K^- run (Berge et al. 1962). The η has also been seen at Brookhaven by Pickup, Robinson, and Salant (1962), in the reaction $p + p \rightarrow p + p + \pi^+ + \pi^- + \pi^0$, and at Berkeley by Carmony et al. (1962) in the reaction $\pi^- + p \rightarrow \pi^- + p + \pi^+ + \pi^- + \pi^0$. Searches have been made in vain to find a charged η. Carmony, Rosenfeld and Van de Walle (1962) looked for, and did not detect, the reaction $\pi^+ + p \rightarrow p + \eta^+$, for η^+ of the same momentum as had been used in the experiment of Pevsner et al. (1961). These authors used triangular inequalities to prove that the isotopic spin of the η is zero. Just as in the case with the ω, the η has a narrow width and experimentally only an upper limit of 10 MeV for the width is known.

Figure 15 shows the Dalitz plot for the $\pi^+\pi^-\pi^0$ decays of the η. It is a compilation of the data from five experiments.[2] In none of these experiments is the background negligible. However, there doesn't seem to be any evidence that the background shows the effect observed in the resonance region; namely, that the Dalitz plot is more densely populated at the bottom (i.e., for π^0's with low energy) than at the top. It seems very unlikely, though not out of the question, that this effect is due to systematic errors. Any wave function for an $I = 0$, 3-pion system has the property that the Dalitz plot associated with it must have what A. H. Rosenfeld calls "sextant symmetry," that is, all six sectors should be populated identically. Thus the indication is that the decay of the η violates isotopic spin conservation, and the decay is presumably electromagnetic.

Before I discuss these electromagnetic decays some other possible meson resonances should be mentioned.

A peak was observed by Abashian, Booth, and Crowe (1960) in the momentum spectrum of the He^3 in the reaction $p + d \rightarrow He^3$ + other particles presumably pions. The peak could be due to a particle with a mass of about 300 MeV. This so-called ABC particle occurs in the I = 0 state and seems to have zero spin. It has not been observed to be produced in other experiments. Therefore it is yet to be determined whether or not this phenomenon represents a resonance.

Recently evidence was found for an I = 1 dipion resonance at about 575 MeV by Barloutaud et al. (1962), who called it a ζ meson. Other experimentors (Peck, Jones, and Perl 1962) have reported supporting evidence for this particle. This evidence is as yet unconvincing, particularly since the Yale group (Stonehill and Kraybill 1962) does not see this resonance in an experiment almost identical to the one in which Barloutaud et al. (1962) see their largest effect.

Shortly after discovery of the ω meson and the assignment of 1^{--} to it, Duerr and Heisenberg (1962) pointed out that since the width of the ω is small, and could be very small, possibly the ω may decay electromagnetically, in which case other spin parity assignments must be considered. If we confine ourselves to spins less than 2, there are eight possible states to consider. These states, as well as the selection rules for the modes of decay of an isoscalar particle with these assignments are shown in table I. The second superscript on the spin stands for the G parity. The G-parity operator is defined in terms of the charge-conjugation operator C and the isotopic spin I by

$$G = Ce^{i\pi I_y}.$$

It has the convenient property that pion systems are eigenfunctions of G parity, an odd number of pions having G = -1, and an even number of pions having G = +1. In this notation the pion is 0^{--}, the ρ is 1^{-+} and the ω is 1^{--}.

G parity is conserved in strong interactions but not in electromagnetic interactions. For neutral particles, $G = C(-1)^I$. One of the positive G-parity states (0^{++}) is strictly forbidden to decay into three pions. A second one (1^{-+}), can be ruled out because for this assignment the density of events at the center of the Dalitz plot should go to zero. The other two assignments (0^{-+} and 1^{++}) predict Dalitz plot distribution which could be uniform and cannot be ruled out by the data (Stevenson et al. 1962).

An ω with these G^+ assignments would decay strongly into four pions and would also have all-neutral decay modes. It is therefore important to look for all possible decay modes of the ω as well as for the η and the ρ mesons. Tables II and III shows some experimental values and upper limits for various decay modes of these mesons. This type of information is difficult to accumulate because much of it has not yet been published, and for this reason I am sure that in some cases better values already exist in preliminary form. The table shows that the ω does not decay very often into four pions. This eliminates the 1^{-+} assignment and argues strongly against the 1^{++} assignment for the ω. Also the ω decays infrequently to an all-neutral decay mode, which argues strongly against the 0^{-+} assignment. Therefore the original assignment of 1^{--} for the ω is very probably the correct one.

The arguments of Duerr and Heisenberg (1962) are even more applicable to the η meson, for we have evidence from the Dalitz plot that the η decays electromagnetically, and also there is a frequently occurring all-neutral decay mode. Furthermore if the η has negative G parity one would expect the decay $\rho \to \eta + \pi$ to occur frequently, which it does not. Therefore it seems most likely that the η has positive G parity. However, the 1^{--} assignment cannot be ruled out completely by this argument, which is merely a phase-space argument. The η has a mass of just four pion masses and is therefore nearly, if not exactly, forbidden to decay into four pions[2]. Therefore, if the η has 0^{-+}, 1^{++} or 1^{-+} it is effectively forbidden to decay at all by strong interactions and must decay electromagnetically. The fact that the η decays frequently into an all-neutral decay mode is a strong argument against 1^{++} and 1^{-+}. An I = 0 particle with these states is forbidden to decay into $\gamma\gamma$ or $(\pi^0)\gamma$, leaving $\pi^0\pi^0\pi^0$ as the only reasonable decay mode. From isotopic spin considerations we can say that the ratio

$$\frac{\eta \to \pi^0\pi^0\pi^0}{\eta \to \pi^+\pi^-\pi^0}$$

must be less than 3/2, whereas experimentally it is more than 2.[2] This leaves the 0^{-+} assignment as the one most consistent with the experimental data. The difficulty one encounters in trying to assign 0^{-+}, or any positive G-parity assignment, to the η is the difficulty in explaining why the $\pi^+\pi^-\pi^0$ decay mode is so much larger than the $\pi^+\pi^-\gamma$ mode. One would expect the $\pi^+\pi^-\pi^0$ rate to be on the order of a smaller than the $\pi^+\pi^-\gamma$ rate because one needs to emit and re-absorb a virtual γ ray to get $\pi^+\pi^-\pi^0$, whereas only a single γ-ray emission is involved in the $\pi^+\pi^-\gamma$ decay. One possible explanation for this is that there is a 0^{++}, I = 0 dipion final-state interaction or resonance with an energy of at least 400 MeV. This would enhance the decay rate of the $\pi^+\pi^-\pi^0$ and $\pi^0\pi^0\pi^0$ modes as well as enhance the population of the lower part of the Dalitz plot.

So far very little evidence is available about what neutral decay modes are present. This information is important because if the 2γ decay mode of the η were found, it would prove that it is 0^{-+}, and if the $\pi^0\gamma$ decay mode were found, it would disprove 0^{-+} and indicate 1^{--}.

It is interesting to note that all three of the mesons for which spin and parity assignments have been made are those having odd parity and also ones which can dissociate into the nucleon-antinucleon system. If the η is either 1^{--} or 0^{-+}, it too falls into this category.

The question arises, why had these resonances not been discovered earlier? Though part of the answer is that up until recently most of the interest in high-energy physics was with the weak interactions, the answer is mostly a technological one. Of course high-energy accelerators are needed for these experiments. But such accelerators have been available for five years. More importantly, the discovery of resonances had to await the development of bubble chambers, particularly hydrogen bubble chambers. However, the technological development that precipitated this breakthrough was the development of data-analysis systems with high-speed computer programs with which to do the stereoscopic reconstruction and kinematic analysis of bubble chamber events. Without these programs it is virtually impossible to do an adequate analysis of the large numbers of multiparticle bubble chamber events which had to be analyzed in order to discover most of these resonances. With the now available data-analysis systems these discoveries are relatively easy, and I expect that before this paper has been published, the list of new resonances will have grown.

ACKNOWLEDGMENTS

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I am likewise indebted to David Stonehill and Dr. Jack Sandweiss at Yale for showing me their pion-pion resonance data, and to Professor A. Rogozinski at Saclay and Professor Aihud Pevsner at Johns Hopkins for providing me with graphs of their ρ and η data.

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FOOTNOTES

† A lecture delivered at a Symposium on High-Energy Nuclear Physics, at Imperial College of Science and Technology, March 26, 1962, London.

1. For a comprehensive bibliography of both the theoretical and experimental papers on this subject, see Stevenson, M. L., 1961, Bibliography on Pion-Pion Interaction, Lawrence Radiation Laboratory Report UCRL-9999, Nov. 1961 (unpublished).

2. The sources of these data are:

Authors	Reaction	Momentum (BeV/c)	Number of events	Estimated No. of background events
Pevsner et al. (1961)	$\pi^+ + d \rightarrow p + p + \eta$	1.23	18	4
Bastien et al. (1962)	$K^- + p \rightarrow \Lambda + \eta$	0.76	19	3
Pickup et al. (1962)	$p + p \rightarrow p + p + \eta$	2.81	42	8
Berge et al. (1962)	$K^- + p \rightarrow \Lambda + \eta$	1.22	47	13
Carmony et al. (1962)	$\pi^- - p \rightarrow \pi^- + p + \eta$	2.04	13	3

<u>Table 1</u>

Selection Rules for the Decay of I = 0 Particles

	$\bar{p}p$	$\pi^+\pi^-$	$\pi^0\pi^0$	$\pi^+\pi^-\pi^0$	$\pi^0\pi^0\pi^0$	$\pi^+\pi^-\pi^0\pi^0$ $\pi^+\pi^-\pi^+\pi^-$	$\pi^0\pi^0\pi^0\pi^0$	K^+K^- $\bar{K}^0K^0$	$\pi^+\pi^-\gamma$	$\pi^0\pi^0\pi^0\gamma$ $\pi^0\pi^0\gamma$	$\gamma\gamma$	$\pi^0\gamma$
0^{++}				JP	JP					C		J, C
0^{+-}	CJP	B	B, C	JP	JP, C	G	C				C	J
0^{-+}		JP, B	JP, B	G	G			JP		C		J, C
0^{--}	CJP	JP	JP, C		C	G	C	JP			C	J
1^{++}		JP	JP	G	G			JP		C	J	C
1^{+-}		JP, B	JP, B, C		C	G	C	JP			C	
1^{-+}	CJP	B	B	G	G					C	J	C
1^{--}		G	C		C	G	C				C	

B = Bose statistics. C = charge conjugation. G = G parity. J = angular momentum. P = parity. C, for instance, means that the decay in question is forbidden by charge-conjugation invariance.

Multiple symbols such as CJP indicate that the simultaneous invocation of these three conservation rules forbids the decay in question. More than one criterion for ruling out a decay mode may be given, although no systematic attempt has been made to do this. The redundant ones are separated by commas. It should be remembered that whereas B, C, J, and P give as far as we know, absolute selection rules, G conservation is only as good as isotopic spin conservation, and is not conserved for electromagnetic decays.

Table 2

Measured Branching Fractions and Upper Limits for Several Possible Decay Modes of Neutral Meson Resonances

Decay modes	η %	ω %	ρ^0 %
All-neutral	68 E	< 10 P	< 20 P
$\pi^+\pi^-$	<100 B	< 10 BU	100
$\pi^+\pi^-\pi^0$	27 E	100	--
$\pi^+\pi^-\gamma$	5	<3 M	--
$\pi^+\pi^-\pi^+\pi^-$	--	< 5 X	< 2 X
$\pi^+\pi^-\pi^0\pi^0$	--	< 12 X	--

For the ρ^0 and ω, the only known decay modes are listed as 100%; all upper limits are listed relative to this. To differentiate, we have assumed a 100-MeV width for the ρ, whereas the ω width is much narrower. An entry of 100 % means that that decay mode is less frequent than the sum of the known decay modes.

For the $\pi^+\pi^-\gamma$ decay of η, Bastien et al. (1962) quote an upper limit of 5%, and Berge et al. (1962) a tentative lower limit of approx 5%.

B = Berge et al. (1962, private communication). BU = Button et al. (1962). E = numbers obtained from the list of authors (Pevsner, etc., in the footnoted table. M = Maglic, Rosenfeld, and Stevenson (1962, private communication). P = Pevsner (1962, private communication). X = Xuong and Lynch (1962).

Upper Limits of the Branching Fraction for the Charged ρ Decay

Decay modes	%
$\pi^{\pm}\pi^{0}$	100
$\pi^{\pm}\eta$	<0.6 R
$\pi^{\pm}\pi^{+}\pi^{-}$	--
$\pi^{\pm}\pi^{0}\pi^{0}$	<4 A
$\pi^{\pm}\gamma$	--
$\pi^{\pm}\pi^{0}\pi^{+}\pi^{-}$	<5 X
$\pi^{\pm}\pi^{0}\pi^{0}\pi^{0}$	<4 A

R = Rosenfeld, Carmony, and Van de Walle (1962). A = Alliti et al. (1962). X = Xuong and Lynch (1962).

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FIGURE CAPTIONS

Fig. 1. A list of the known particles and possible resonances. Broad resonances have been given flags to denote their width. Antiparticles of bosons are shown, but antifermions are not, They would be plotted on the left side of the figure and be mirror images of the fermions.

Fig. 2. Mass spectrum of the $\bar{K}^0\pi^-$ system from the reactions $K^- + p \rightarrow \bar{K}^0 + \pi^- + p$ for K^- of 1.22 BeV/c (Berge et al. 1962). The solid curve is a phase-space curve normalized to the events having mass <850 MeV.

Fig. 3. Weighted histograms of the distribution in the invariant mass for (a) $M(\Lambda, \pi^-)$ and (b) $M(\Lambda, \pi^+)$, from interactions of 1.11-BeV/c K^- (Ely et al. 1961). The solid lines are fits to a curve of the form $[(M - M_0)^2 + (\Gamma/2)^2]^{-1}$ of the data near the resonance energy. The dashed curves represent the expected distribution of $M(\Lambda, \pi)$ when the other pion resonates with the Λ.

Fig. 4. Momentum dependence of the cross section for the reactions (a) $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$, and (b) $K^- + p \rightarrow \bar{K}^0 + n$ (Ferro-Luzzi, Tripp, and Watson 1962). The lower curves in (a) and (b) represent the presumed nonresonant background; the upper curves contain in addition the superposed resonance.

Fig. 5. Angular distributions for the reaction $K^- + p \rightarrow K^- + p$ for three momentum intervals, one below the 1520-MeV resonance, one in the resonance region, and one above the resonance. The points at zero-deg scattering angle represent the optical-theorem lower limit obtained from the total cross section. The dashed curves are least-squares fits to the data.

Fig. 6. Experimental points and calculated curves showing the momentum dependence of the coefficients of the angular distributions for the reactions (a) $K^- + p \rightarrow K^- + p$, and (b) $K^- + p \rightarrow \bar{K}^0 + n$ (Ferro-Luzzi, Tripp, and Watson 1962). The coefficients are dimensionless constants defined by $d\sigma/d\Omega = (A + B \cos\theta + C \cos^2\theta)\ (\pi \lambda\!\!\!^{-}/4\pi)$ mb/sr.

Fig. 7. Histogram of the distribution in the square of the effective mass of the $\pi^-\pi^0$ pair from the reaction $\pi^- + p \rightarrow \pi^- + p + \pi^0$ for 1.6 BeV/c (Alliti et al. 1962) incident pions. The effective mass is measured in units of μ, the charged pion mass. The solid curve is the phase-space distribution normalized to the total number of events.

Fig. 8. The $\pi^-\pi^0$ elastic scattering cross section, calculated by using the Chew-Low method with the data from the reaction $\pi^- + p \rightarrow \pi^- + p + \pi^0$ for 1.6 BeV/c (Alliti et al. 1962) incident pions.

Fig. 9. Histograms showing the differential $\pi^{\pm}\pi^0$ cross sections (a) below the resonance, (b) in the resonance region, and (c) above the resonance, taken from interactions of 1.23-BeV/c π^+ (Carmony and Van de Walle 1962). The smooth curves are least-squares fits to the data.

Fig. 10. Histograms of the number of pion triplets vs the effective mass of the triplets for the reaction $\bar{p} + p \rightarrow 2\pi^+ + 2\pi^- + \pi^0$ with 1.61-BeV/c antiprotons (Maglić et al. 1961). (A) is the distribution for the $|Q| = 1$ combinations, (B) is for the $|Q| = 2$ combinations, and (C) for the $Q = 0$ combination. Full width of one interval is 20 MeV. In (D), the combined distribution (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

Fig. 11. Histogram of the effective mass of the three-pion system for 233 events of the reaction $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$ for incident pions of 1.23 BeV/c (Pevsner et al. 1961).

Fig. 12. Dalitz plot of the $(\pi^+\pi^-\pi^0)$ triplets with effective masses between 740 and 800 MeV in the reaction $\pi^+ + d \rightarrow p + p + \pi^+ + \pi^- + \pi^0$, for the data shown on figure 11.

Fig. 13. Histograms at (top) the invariant mass distribution of the $\pi^+\pi^-\pi^0$ from the reaction $K^- + p \rightarrow \Lambda\,\pi^+\pi^-\pi^0$ for K^- for incident K^- of 760 MeV/c, and (bottom) the upper part of the distribution of the invariant mass of the unseen neutrals in the reaction $K^- + p \rightarrow \Lambda$ + neutrals at the same energy. The solid curve on top is Lorentz-invariant phase-space calculations normalized to the 27 $\Lambda\,\pi^+\pi^-\pi^0$ events. The dashed curve is phase space normalized to the 4 events to the left of 530 MeV.

Fig. 14. A histogram of the distribution of the effective mass of the $(\pi^+\pi^-\pi^0)$ from the reaction $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$ with 1.22-BeV/c incident K^- (Berge et al. 1962). The solid curve represents the phase space normalized to the total number of events.

Fig. 15. A composite Dalitz plot of 139 $\pi^+\pi^-\pi^0$ triplets from five experiments. The histograms at top left show the reflections of their distribution onto the y and x axes. The solid curves associated with these histograms represent the phase space normalized to the data.

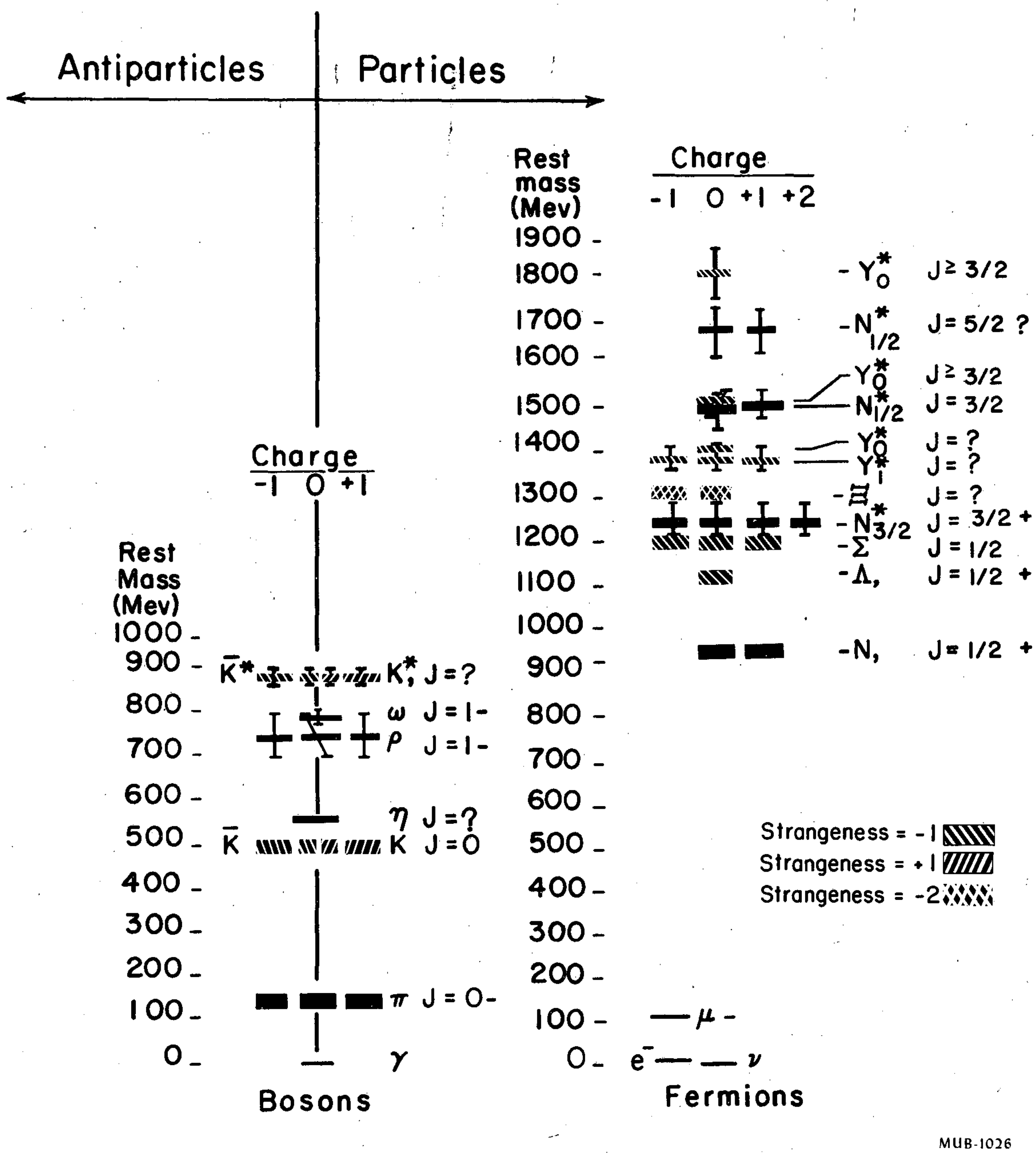
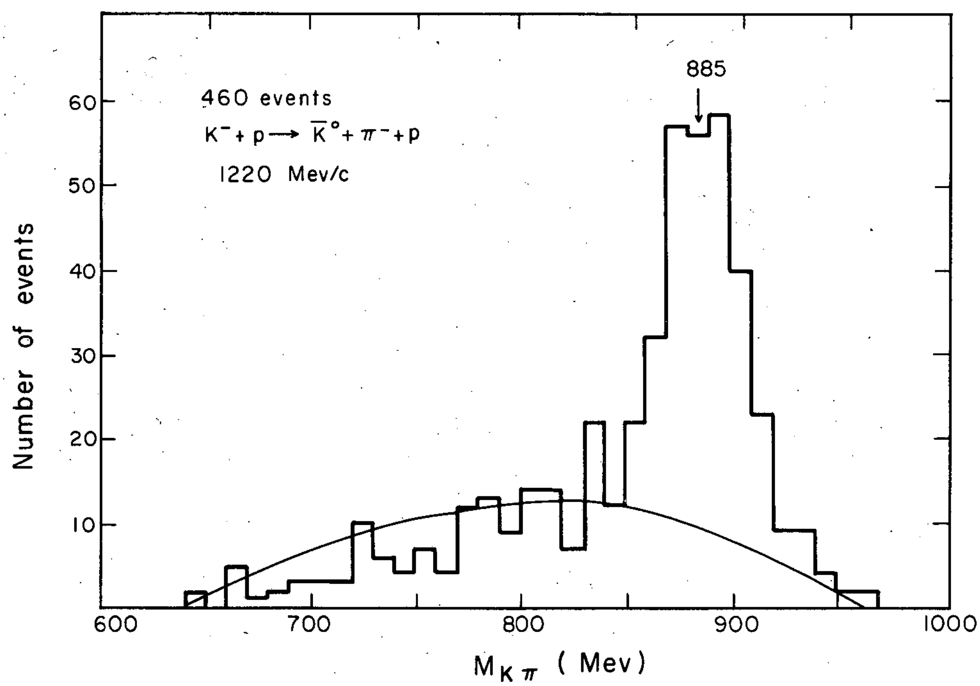

Antiparticles
Particles
Charge
-1 0 +1
Rest Mass (Mev)
1000
900
800
700
600
500
400
300
200
100
0
K̄*
K*
J = ?
ω J = 1-
ρ J = 1-
η J = ?
K̄
K J = 0
π J = 0-
γ
Bosons
Rest mass (Mev)
Charge
-1 0 +1 +2
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Y*0 J ≥ 3/2
N*1/2 J = 5/2 ?
Y*0 J ≥ 3/2
N*1/2 J = 3/2
Y*0 J = ?
Y*1 J = ?
Ξ J = ?
N*3/2 J = 3/2 +
Σ J = 1/2
Λ, J = 1/2 +
N, J = 1/2 +
μ
e⁻
ν
Fermions
Strangeness = -1
Strangeness = +1
Strangeness = -2
MUB-1026

Fig. 1



MU-26417

Fig. 2

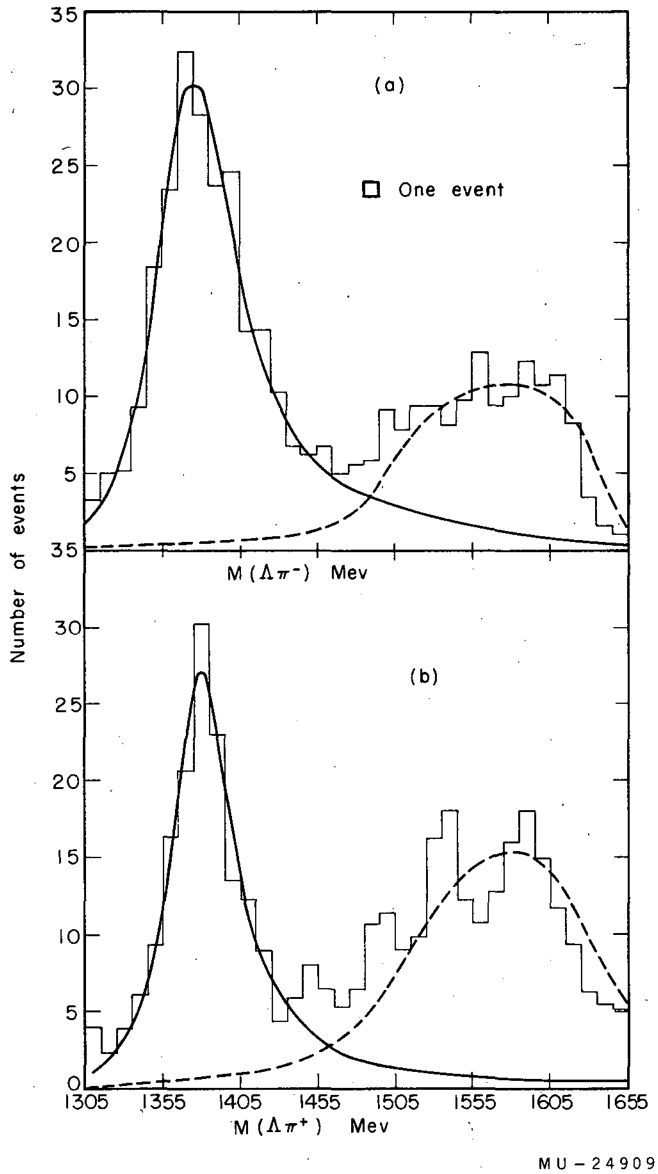
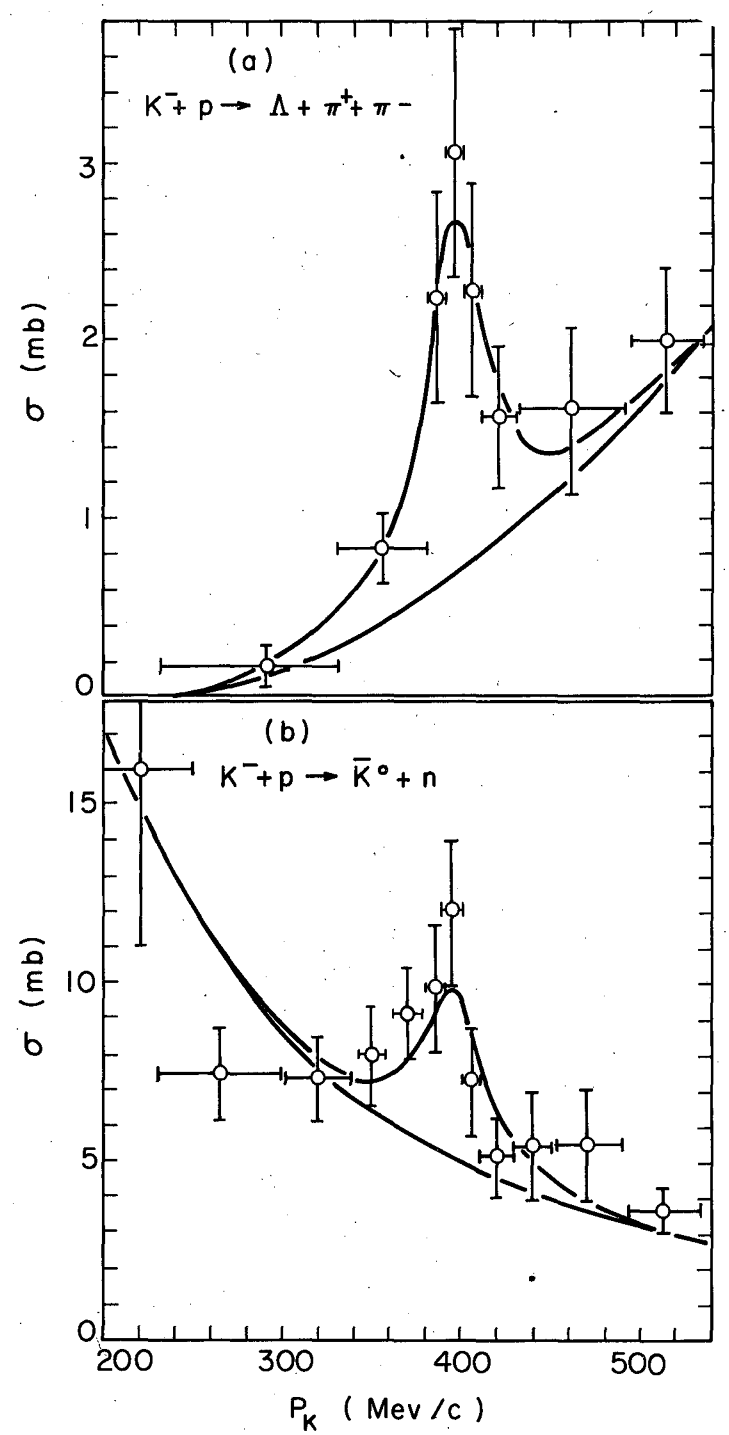
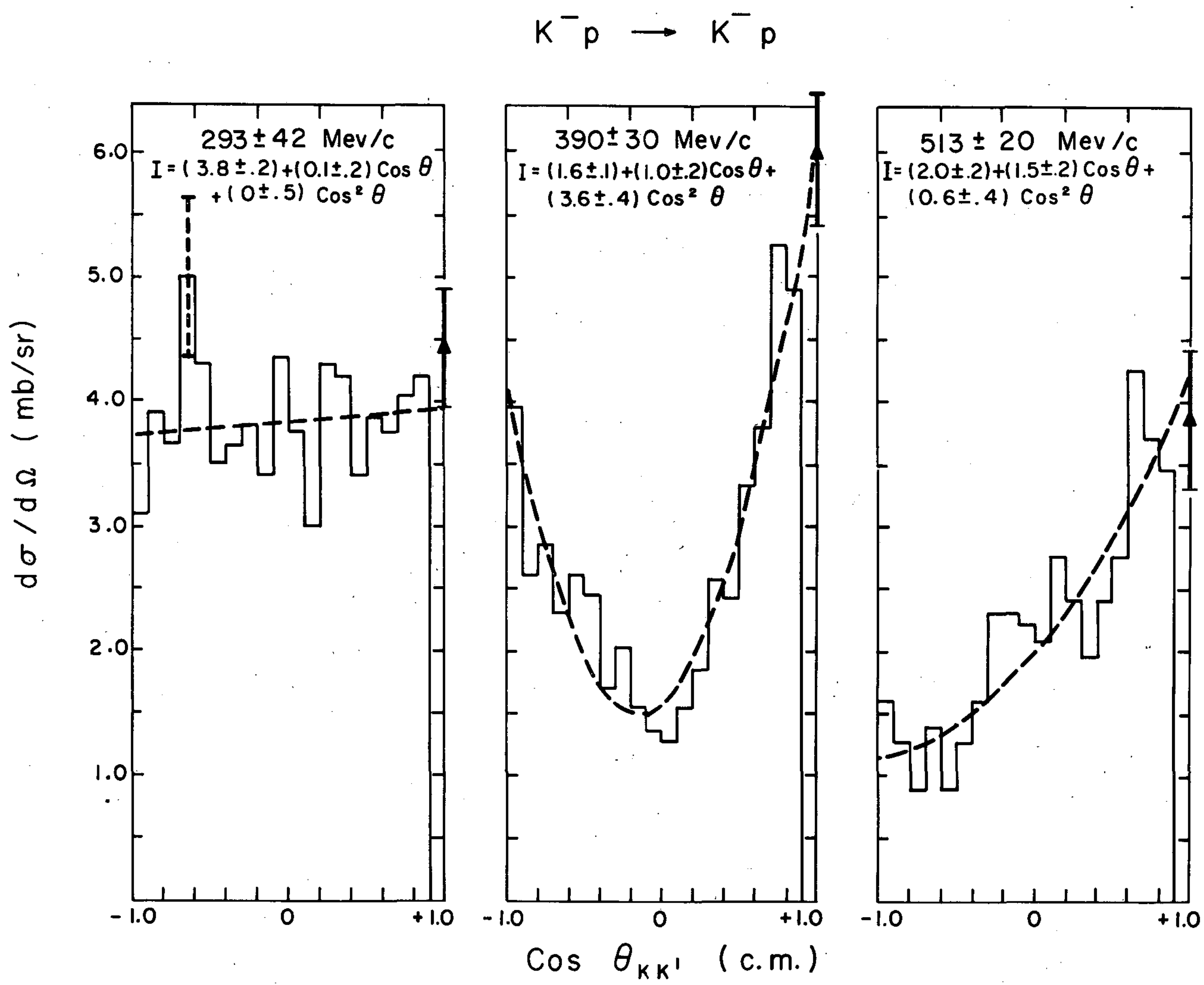

35
30
25
20
15
10
5
(a)
One event
M (Λπ⁻) Mev
Number of events
(b)
0
1305
1355
1405
1455
1505
1555
1605
1655
M (Λπ⁺) Mev
MU-24909

Fig. 3



MUB-870

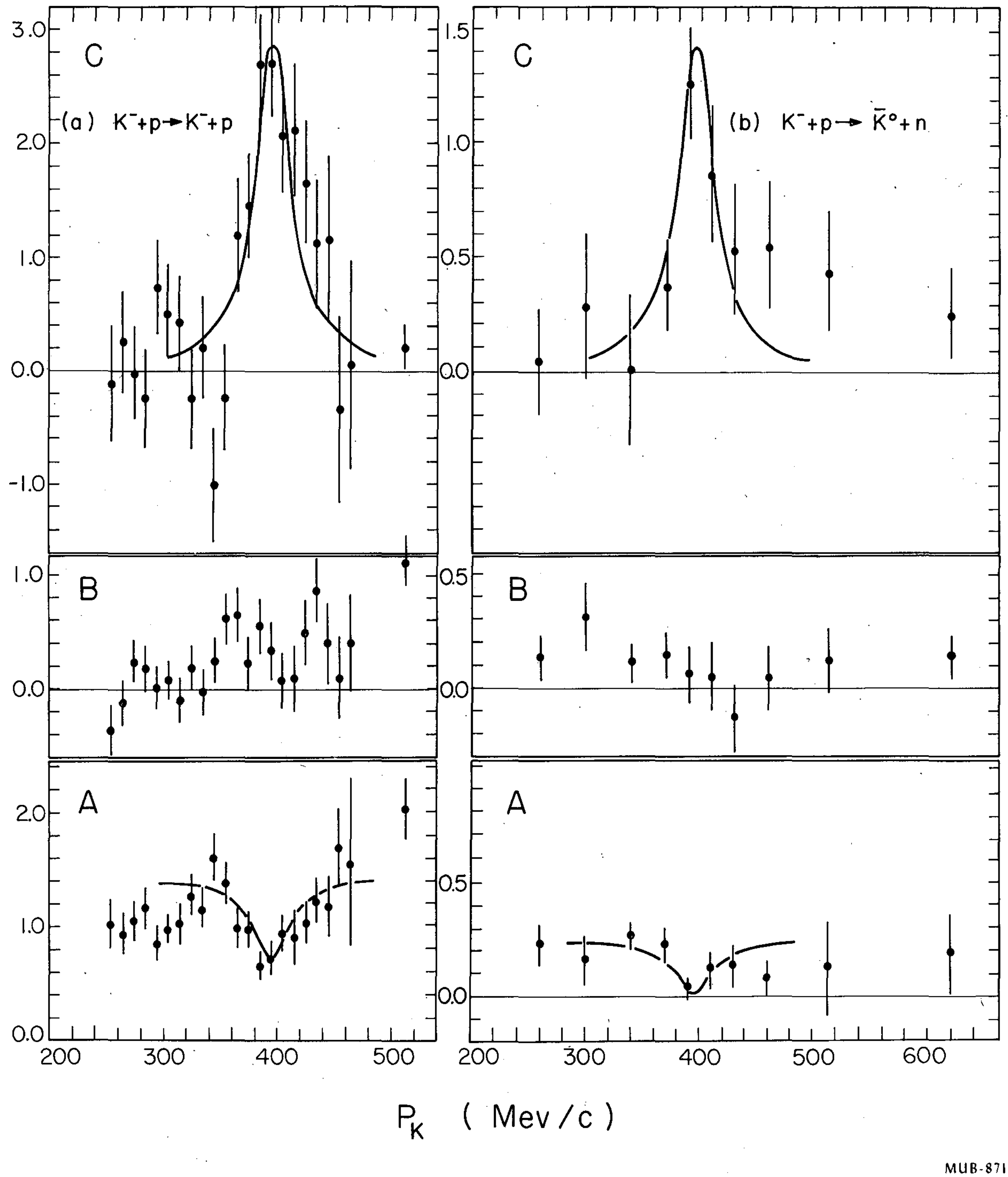
Fig. 4



K⁻p ⟶ K⁻p
293 ± 42 Mev/c
I = (3.8 ±.2)+(0.1±.2) Cos θ + (0±.5) Cos² θ
390 ± 30 Mev/c
I = (1.6±.1)+(1.0±.2)Cos θ+ (3.6±.4) Cos² θ
513 ± 20 Mev/c
I = (2.0±.2)+(1.5±.2) Cos θ+ (0.6±.4) Cos² θ
dσ / dΩ (mb/sr)
Cos θ_KK' (c.m.)

MUB-913

Fig. 5



3.0
2.0
1.0
0.0
-1.0
C
(a) K⁻+p → K⁻+p
1.5
1.0
0.5
0.0
C
(b) K⁻+p → K̄°+n
1.0
0.0
B
0.5
0.0
B
2.0
1.0
0.0
A
0.5
0.0
A
200
300
400
500
200
300
400
500
600
P_K (Mev/c)
MUB-871

Fig. 6

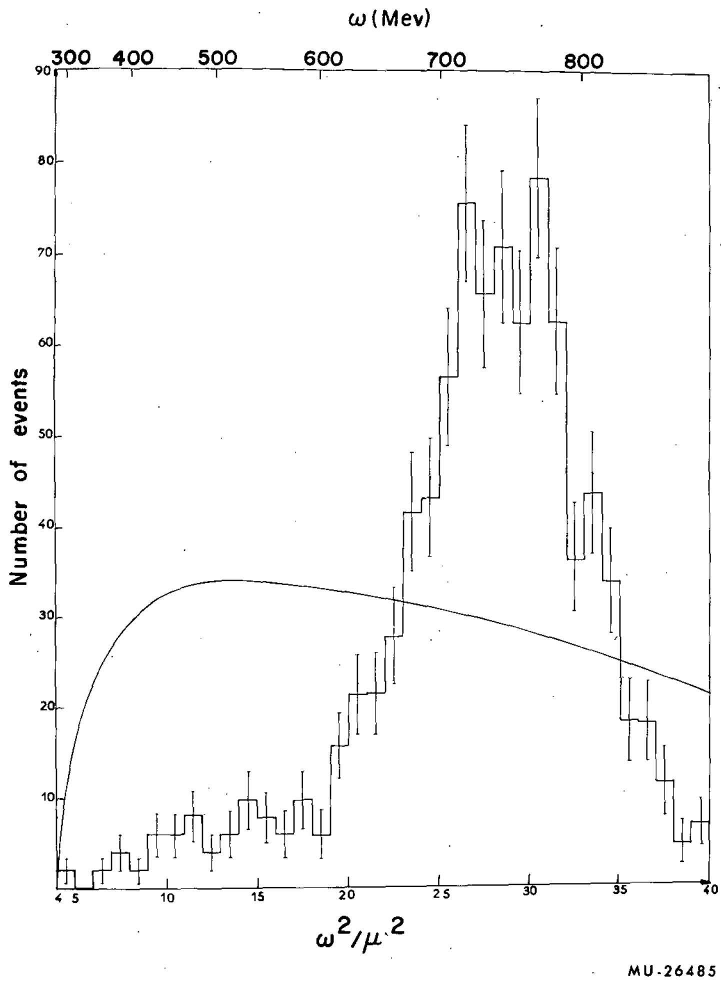

ω (Mev)
300
400
500
600
700
800
Number of events
90
80
70
60
50
40
30
20
10
4
5
10
15
20
25
30
35
40
ω²/μ²
MU-26485

Fig. 7

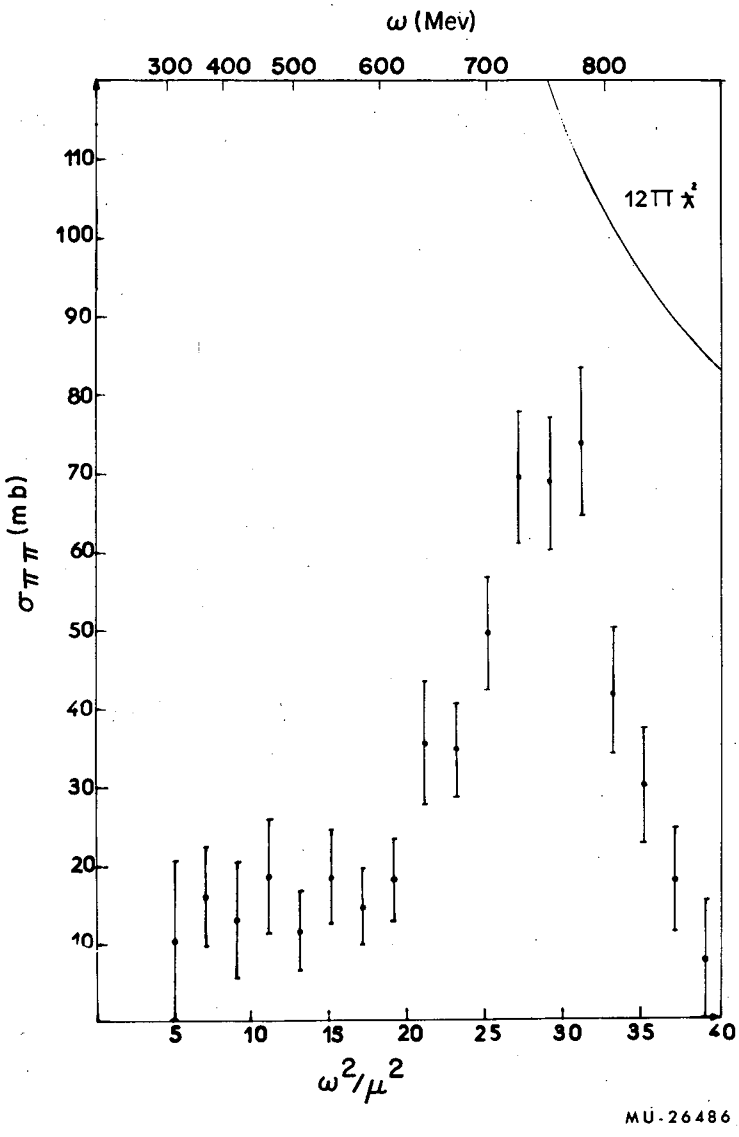

ω (Mev)
300 400 500 600 700 800
12π ƛ²
110
100
90
80
70
60
50
40
30
20
10
σππ (mb)
5 10 15 20 25 30 35 40
ω²/μ²
MU-26486

Fig. 8

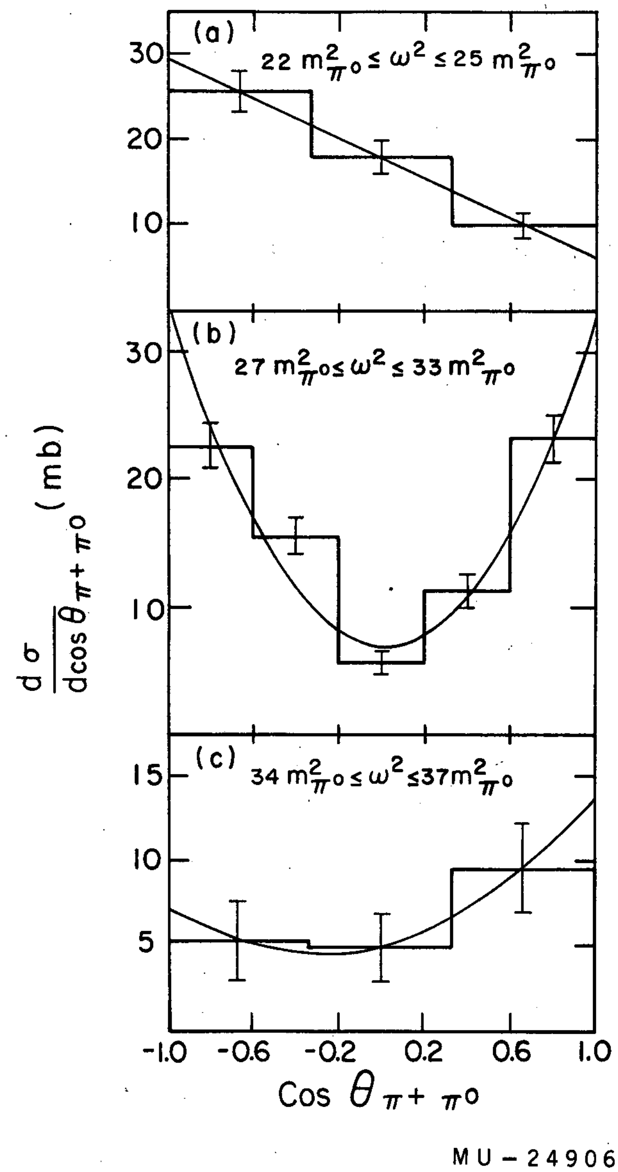

(a)
22 $m^2_{\pi^0} \le \omega^2 \le 25\ m^2_{\pi^0}$
(b)
27 $m^2_{\pi^0} \le \omega^2 \le 33\ m^2_{\pi^0}$
(c)
34 $m^2_{\pi^0} \le \omega^2 \le 37 m^2_{\pi^0}$
$\frac{d\sigma}{d\cos\theta_{\pi^+\pi^0}}$ (mb)
Cos $\theta_{\pi^+\pi^0}$
30
20
10
15
5
-1.0
-0.6
-0.2
0.2
0.6
1.0
MU-24906

Fig. 9

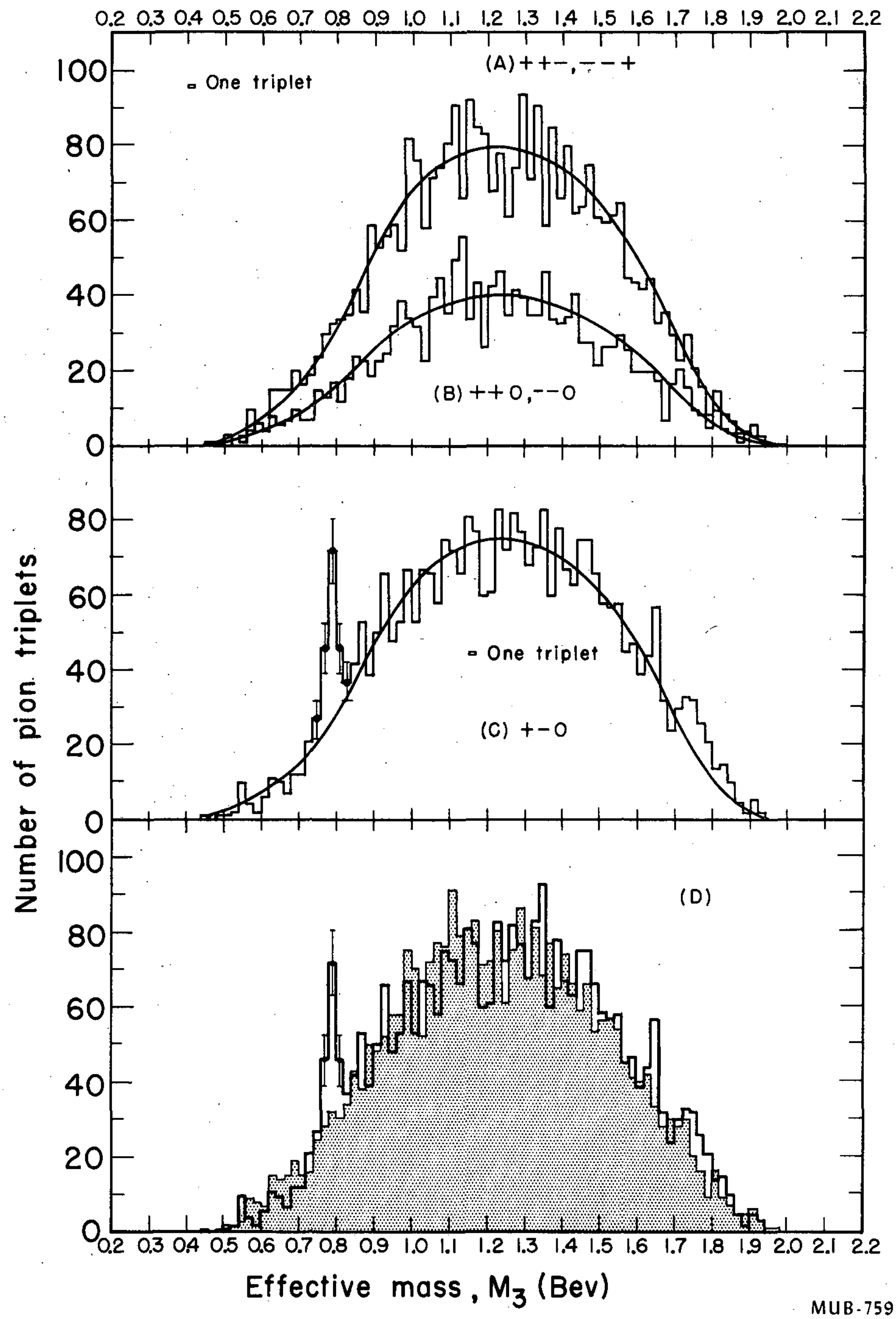
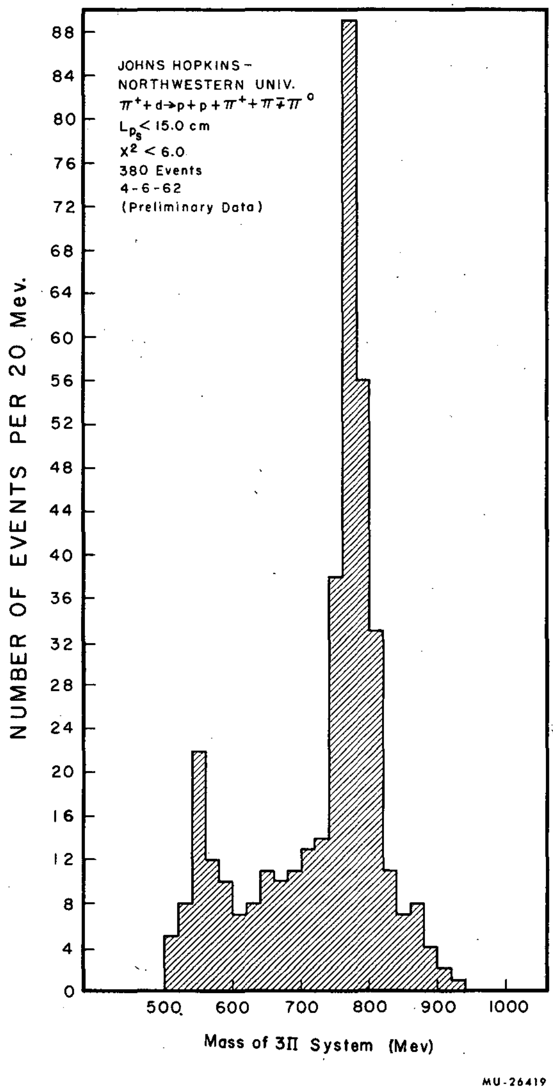
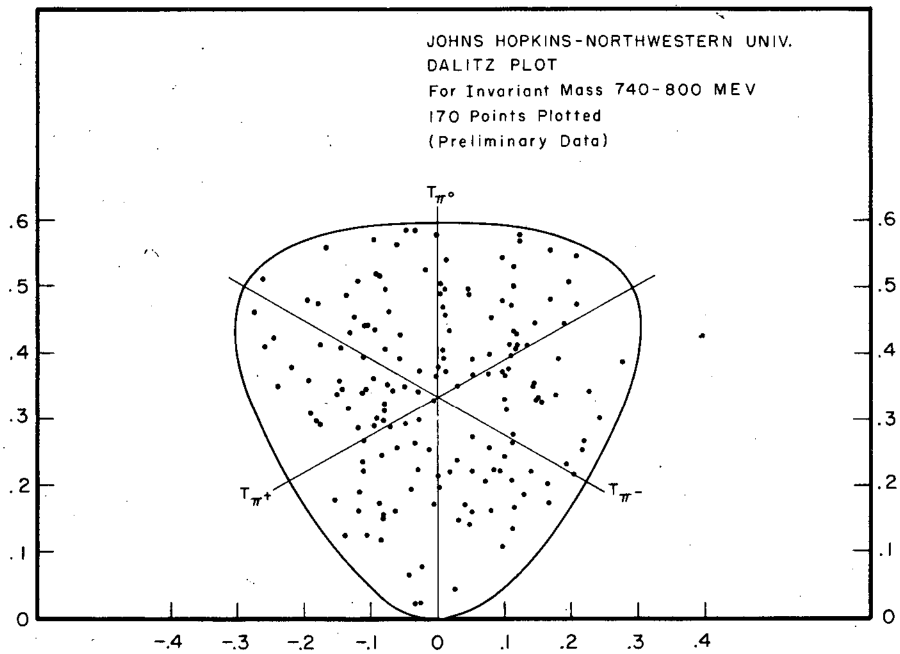

0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4 1.5 1.6 1.7 1.8 1.9 2.0 2.1 2.2
One triplet
(A) ++−, −−+
(B) ++0, −−0
(C) +−0
(D)
Number of pion triplets
0 20 40 60 80 100
Effective mass, M3 (Bev)
MUB-759

Fig. 10



JOHNS HOPKINS -
NORTHWESTERN UNIV.
$\pi^+ + d \rightarrow p + p + \pi^+ + \pi^{\mp} \pi^0$
$L_{p_s} < 15.0$ cm
$X^2 < 6.0$
380 Events
4-6-62
(Preliminary Data)
NUMBER OF EVENTS PER 20 Mev.
0
4
8
12
16
20
24
28
32
36
40
44
48
52
56
60
64
68
72
76
80
84
88
500
600
700
800
900
1000
Mass of 3Π System (Mev)
MU-26419

Fig. 11



MU-26420

Fig. 12

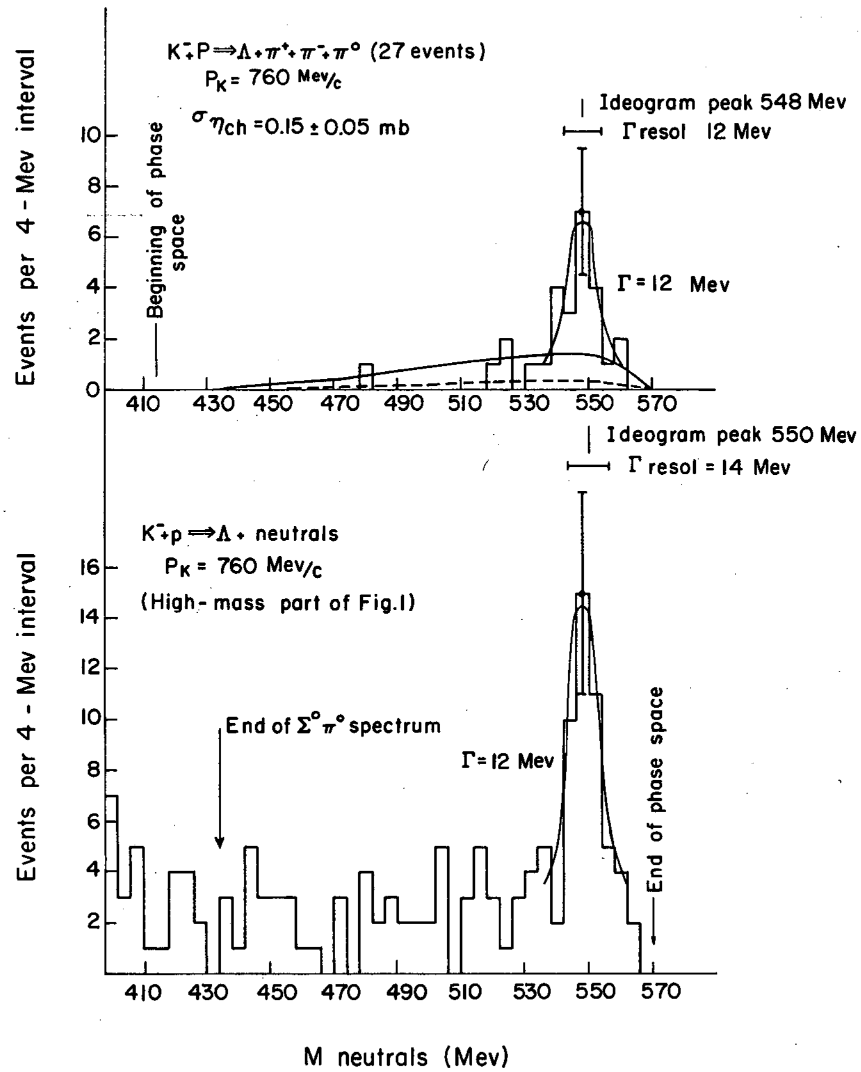
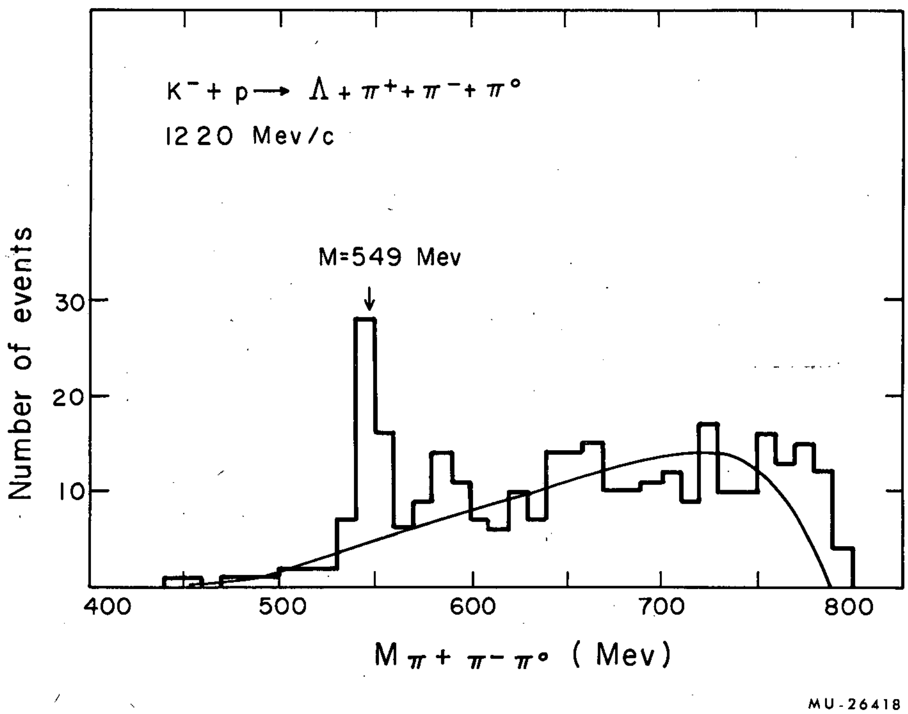

K⁻+P ⟹ Λ+π⁺+π⁻+π° (27 events)
P_K = 760 Mev/c
σ η_ch = 0.15 ± 0.05 mb
Ideogram peak 548 Mev
Γ resol 12 Mev
Γ = 12 Mev
Beginning of phase space
Events per 4 - Mev interval
Ideogram peak 550 Mev
Γ resol = 14 Mev
K⁻+p ⟹ Λ + neutrals
P_K = 760 Mev/c
(High- mass part of Fig.1)
End of Σ°π° spectrum
Γ = 12 Mev
End of phase space
M neutrals (Mev)
MU-25344

Fig. 13



K⁻ + p ⟶ Λ + π⁺ + π⁻ + π°
1220 Mev/c
M=549 Mev
Number of events
10
20
30
400
500
600
700
800
M π+ π- π° (Mev)
MU-26418

Fig. 14.

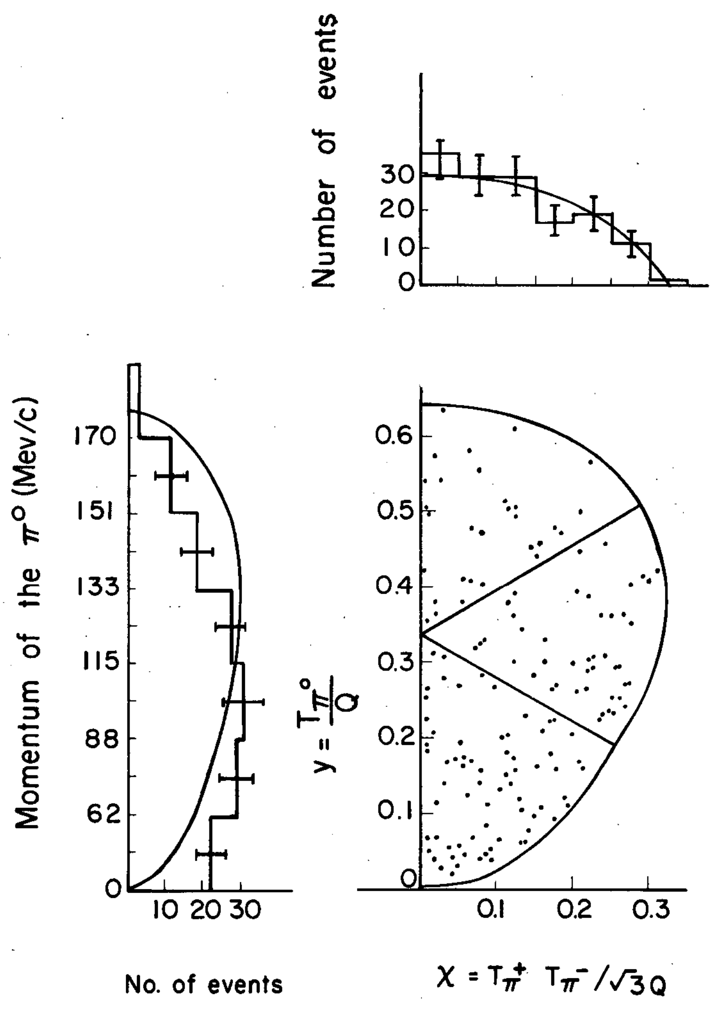

Number of events
30
20
10
0
Momentum of the π^0 (Mev/c)
170
151
133
115
88
62
0
10 20 30
No. of events
$y = \frac{T_{\pi^0}}{Q}$
0.6
0.5
0.4
0.3
0.2
0.1
0
0.1
0.2
0.3
$X = T_{\pi^+}\ T_{\pi^-}/\sqrt{3}Q$
MU-26484

Fig. 15.