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Some Rare Decay Modes of the ω Meson*

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Summary

We present in this paper the following measurements on ω decay:

1. Decay modes:

 a. $\Gamma(\omega \to \text{neutral})/\Gamma(\omega \to \pi^+\pi^-\pi^0) = (9.7 \pm 1.6) \times 10^{-2}$

 b. $\Gamma(\omega \to \eta(\text{all modes}) + \text{neut.})/\Gamma(\omega \to \pi^+\pi^-\pi^0) \leq 1.7 \times 10^{-2}$

 c. $\Gamma(\omega \to \pi^+\pi^-\gamma)/\Gamma(\omega \to \pi^+\pi^-\pi^0) < 0.05$

 d. $\Gamma(\omega \to \pi^+\pi^-)/\Gamma(\omega \to \pi^+\pi^-\pi^0) = (0.17 \pm 0.03)^2 = 2.9 \times 10^{-2}$ ("complete coherence")
 $= (8.2 \pm 2.0) \times 10^{-2}$ ("complete incoherence")

Glashow[1] points out that $\omega \to \eta + \pi^0$ violates C conservation. The branching ratio b sets an upper limit of 0.14 MeV for $\Gamma(\omega \to \eta\pi^0)$.

2. The $\omega \to \pi^+\pi^-\pi^0$ decay has been tested for nonconservation of C as suggested by Lee[2] and found to be consistent with C conservation.

Experimental Details

Following is a resume of experimental methods we used to determine these numbers. Details will be presented in a forthcoming article to be submitted to the Physical Review.[3]

Measurements have been completed on approximately 43 620 V 2-prong events in an exposure of the 72-inch hydrogen chamber to K^- mesons with momenta between 1.2 and 1.8 BeV/c. Among these events we have identified 28 850 as $K^- + p \to \Lambda + 2$ prongs, and of these, 10 242 are identified as

$$K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0. \qquad (1)$$

By plotting the $M(\pi^+\pi^-\pi^0)$ histogram, we identify 4 208 events as

$$K^- + p \rightarrow \Lambda + (\omega \rightarrow \pi^+\pi^-\pi^0). \tag{2}$$

There are 1 450 background events that lie in the ω-peak region, 750 MeV $\leq M(\pi^+\pi^-\pi^0)$ $\leq$ 815 MeV. In the control regions on either side of the peak region we find 1202 events in the interval 685 MeV $\leq M(\pi^+\pi^-\pi^0) \leq$ 750 MeV and 1276 events in the interval 815 MeV $\leq M(\pi^+\pi^-\pi^0) \leq$ 880 MeV. We use these control-region events to estimate the behavior of the background events in the peak region.

Neutral Decay Mode

All the measurements of 27 660 V 0-prong events have been completed for the momentum settings 1.42, 1.51, 1.60, and 1.70 BeV/c. From these events, 12 351 have been identified as $K^- + p \rightarrow \Lambda +$ neutrals. Figure 1 is the histogram of the invariant mass squared of the neutral system that recoils against the Λ; we refer to this as the square of the missing mass. Peaks for the π^0, η, and ω mesons are clearly visible . Few of the K^-'s in this experiment had momenta above the threshold for production of the η(960) meson. The smooth curve drawn above the background curve in the ω region contains 359 events. Several independent estimates were made by drawing similar curves; the average of these estimates is 348±55. By determining the number of events of reaction (2) in the same sample and making corrections for different fiducial volumes, Λ path-length cutoffs, and scanning efficiencies, we find $\Gamma(\omega \rightarrow \text{neutrals})/\Gamma(\omega \rightarrow \pi^+\pi^-\pi^0) = (9.7\pm1.6)\times10^{-2}$. Barmin et al[4] report evidence for $\omega \rightarrow \pi^0 + \gamma$. In our experiment we cannot say much about the composition of the neutral decay mode except that the contribution of $\omega \rightarrow \eta$+neutrals is small (see the next section).

Search for $\omega \rightarrow (\eta \rightarrow \pi^+\pi^-\pi^0)$ + Neutrals

Events of this type are kinematically underdetermined but in general fail to fit the overdetermined reactions:

$$K^- + p \to \Lambda + \pi^+ + \pi^- \qquad (3)$$

$$K^- + p \to \Sigma^0 + \pi^+ + \pi^- \qquad (4)$$

$$K^- + p \to \Lambda + \pi^+ + \pi^- + \pi^0. \qquad (1)$$

Figure 2(a) is a histogram of the invariant mass squared of the system that recoils against the Λ for those events that fail to fit reactions (1), (3), and (4). The events are further required to have a missing mass greater than a π^0 mass. Fewer than 30 events occur above the background in the ω mass region of Fig. 2(a), as indicated by the arrow. Figure 2(b) is a similar plot for events with $\delta(\text{mm})^2 \leq 6\,000\ \text{MeV}^2$ (that is, well-measured events). Some events of reaction (2) are expected to have pions that scatter or decay in flight in an unobservable fashion and consequently will fail to fit reaction (2). We estimate that 10 events of this type are in the ω region of Fig. 2(a). Hence, in our data there are fewer than 20 events of the type $\omega \to \pi^+\pi^-x^0$, where x^0 is a neutral system with effective mass greater than the mass of the π^0. The decay $\omega \to (\eta \to \pi^+\pi^-\pi^0)$ + neutrals is included in this type. Using the known branching ratio[5] $\Gamma(\eta \to \pi^+\pi^-\pi^0)/\Gamma(\eta \to \text{all modes}) = 0.274$, we determine that there are fewer than 73 events of the type $\omega \to (\eta \to \text{all modes})$ + neutrals. Consequently,

$$\Gamma(\omega \to \eta(\text{all modes}) + \text{neutrals})/\Gamma(\omega \to \pi^+\pi^-\pi^0) \leq [(73/4208) = 1.7 \times 10^{-2}].$$

This number is important because it forms the upper limit of (a) the C-violating decay mode $\omega \to \eta + \pi^0$, and (b) the electromagnetic decay mode $\omega \to \eta + \gamma$.

The branching ratio[6] $\Gamma(\eta \to \text{neutrals})/\Gamma(\eta \to \text{all modes}) = 0.67$ allows us to set an upper limit on one of the contributions to the neutral decay mode of the ω:

$$\Gamma[\omega \to (\eta \to \text{neutrals}) + \text{neutrals}]/\Gamma(\omega \to \pi^+\pi^-\pi^0) \leq 1.1 \times 10^{-2}.$$

Glashow[1] shows that if the C-violating $\omega\eta\pi$ coupling constant were the same as the $\rho\pi\pi$ coupling constant, then $\Gamma(\omega \to \eta\pi^0) = 9.3$ MeV. Our experiment places an upper limit of (0.017)(8.5 MeV) = 0.14 MeV. See reference 7 for width of ω meson.

Hence the C-violating $\omega\eta\pi$ coupling can be compared to the C-conserving $\rho\pi\pi$ coupling:

$$G^2(\omega\eta\pi)/G^2(\rho\pi\pi) < 1.5\times10^{-2}$$

In his Varenna lectures (1964) Glashow[8] points out that measurements of $\omega\to\eta+\gamma$, $\phi\to\pi^0+\gamma$, and $\phi\to\eta+\gamma$ can provide tests of the ϕ - ω mixing theory. His predictions are $\Gamma(\omega\to\eta\gamma)\approx 0.002(1-5\epsilon)^2$ MeV, $\Gamma(\phi\to\pi^0\gamma)\approx 2.1\epsilon^2$ MeV, and $\Gamma(\phi\to\eta\gamma)\approx 0.26(1+0.2\epsilon)^2$ MeV, where ϵ is the ratio of the $\phi\rho\pi$ coupling constant, $G(\phi\rho\pi)$, to the $\omega\rho\pi$ coupling constant, $G(\omega\rho\pi)$. The quantity $|\epsilon|\equiv|G(\phi\rho\pi)/G(\omega\rho\pi)|$ is known to be less than 0.2 from the observed rates $\Gamma(\phi\to3\pi)\leq(1/15)\Gamma(\omega\to3\pi)$. Thus $\Gamma(\omega\to\eta\gamma)$ could be zero if $\epsilon=+0.2$ and could be 0.008 MeV if $\epsilon=-0.2$. Both are consistent with our result of $\leq$ 0.14 MeV.

Search for $\omega\to\pi^+\pi^-\gamma$

This mode of decay is harder to identify because events of the type (1), (3), and (4) with large measurement errors can simulate it. Therefore we select "good events," that is, those with error in missing mass $\delta(\mathrm{mm})^2$ less than 6 000 MeV^2. The missing-mass squared histograms of those events that are (a) poor fits to (3), presumably of the type $K^-+p\to\Lambda+\pi^++\pi^-+x^0$, and (b) have an invariant mass $M(\Lambda x^0)$ greater than 1250 MeV (a value sufficient to exclude most Σ^0 events) are plotted in Fig. 3(a), (b), (c). Events with $M(\pi^+\pi^-x^0$ in the ω mass region (750 to 810 MeV) are shown in Fig. 3(c). Figure 3(a) and (b) are corresponding histograms for events in the η region (510 to 580 MeV) and for events in between the η and ω regions (580 to 750 MeV). We find evidence for $\eta\to\pi^+\pi^-(x^0=\gamma)$ and for $\eta\to\pi^+\pi^-(x^0=\pi^0)$ in Fig. 3(a). We see evidence also of Σ^0 events [see Fig. 3(b)] not excluded by our criteria. In Fig. 3(c) we find no evidence for $\omega\to\pi^+\pi^-(x^0=\gamma)$. Fewer than 24 $\omega\to\pi^+\pi^-\gamma$ events are in the vicinity of zero $(\mathrm{mm})^2$. From this number we determine that $\Gamma(\omega\to\pi^+\pi^-\gamma)/\Gamma(\omega\to\pi^+\pi^-\pi^0)<0.05$. This result supersedes the value 0.032 ± 0.013 reported previously (Shafer et al.[9]) on a partial sample of the present data. They observed a small narrow peak at $(\mathrm{mm})^2=0$, which they interpreted as $\omega\to\pi^+\pi^-\gamma$. Subsequently, the addition of more data showed a larger peak which was anomalously narrow; it vanished when the events in the peak were remeasured. How this peak, many times narrower than the resolution function (that vanishes upon remeasurement), came about remains a mystery. Singer's predictions[10] of this ratio are much smaller than the present limit.

$\omega \rightarrow \pi^+ + \pi^-$ Decay Mode

The reaction

$$K^- + p \rightarrow [Y_1^*(1385) \rightarrow \Lambda + \pi] + \pi \qquad (5)$$

dominates the topology of reaction (3) and makes the identification of the reaction $K^- + p \rightarrow \Lambda + (\omega \rightarrow \pi^+\pi^-)$ difficult. Consequently we discard type (5) events from the sample of $\Lambda\pi^+\pi^-$ events. The $M^2(\pi^+\pi^-)$ histogram of Fig. 4(a) displays 3 887 such events for momenta between 1.0 and 1.8 BeV/c. We first examine the possibility that the narrow peak near the ω mass might be a statistical fluctuation. The curve of Fig. 4(a) is the "least-square" solution to a single $\rho \rightarrow \pi^+\pi^-$ resonance superimposed upon a smooth background. The ρ amplitude has the form

$$A_\rho = \frac{m_\rho^{3/2}\Gamma_\rho^{1/2}}{(m_\rho^2 - M^2) - i m_\rho \Gamma_\rho}$$

$$\Gamma_\rho = \Gamma_{\rho 0} \frac{m_\rho}{M} \left(\frac{M^2 - 4m_\pi^2}{m_\rho^2 - 4m_\pi^2}\right)^{3/2},$$

where M is the invariant mass of the $\pi^+\pi^-$ system. The mass m_ρ and width $\Gamma_{\rho 0}$ of the ρ were allowed to vary along with three parameters representing the parabolic background. The fit, with $m_\rho = 762 \pm 4$ MeV and $\Gamma_{\rho 0} = 105 \pm 13$ MeV, is very poor. Chi-squared is 103.4 when 60 is expected. The confidence level (the probability of our getting a fit worse than this) is 0.04%. We reject the possibility that this is a statistical fluctuation. We have explored and ruled out the possibility that the $Y^*(1660)$ could have produced a peak in the ω region [by its projection on the $M^2(\pi^+\pi^-)$ axis.] Nor could coherent interference between ρ and background improve the fit appreciably.

The next possibility is that we are observing the decay $\omega \to \pi^+ + \pi^-$, a mode that many authors[11] have commented on. Here we are faced with the problem of ρ - ω interference. We consider two extreme possibilities: complete coherence and complete incoherence. The curve in Fig. 4(b) shows the best fit solution to the hypothesis of complete coherence, where m_ρ, $\Gamma_{\rho 0}$, m_ω, and $\Gamma_{\omega 0}$ have been fixed at 750, 100, 782, and 9 MeV, respectively. The branching ratio corresponding to this fit is $\Gamma(\omega \to \pi^+\pi^-)/\Gamma(\omega \to \pi^+\pi^-\pi^0) = (0.17 \pm 0.03)^2 = 2.9 \times 10^{-2}$; the relative ρ -ω phase angle, well below either resonance, is equal to 0.81 ± 0.26 radians. Chi-squared for this fit is 81.1 when 60 is expected. The confidence level is 3.7%. We quote the error in branching ratio in this strange way because we find the amplitude and not the intensity to be Gaussianly distributed.

The second of the two extreme possibilities is that the ρ and ω are incoherent. This is perhaps a more reasonable possibility because the data come from all incident momenta, from all momentum transfers, and from all decay angles. The best fit solution, shown in Fig. 4(c), gives $\Gamma(\omega \to \pi^+\pi^-)/\Gamma(\omega \to \pi^+\pi^-\pi^0) = (8.2 \pm 2.0) \times 10^{-2}$. Chi-squared is 79.5 when 60 is expected. The confidence level is 4.7%. In this latter solution we allowed the ρ mass to vary rather than fixing it at 750 MeV. The best fit value is $m_\rho = 740 \pm 7$ MeV. The mass of the ω has been fixed at 782 MeV with a width $\Gamma_{\omega 0} = 9$ MeV. The resolution function, of 10-MeV width, has been folded into all curves.

The latest prediction* comes from Coleman et al.[12] $[\Gamma(\omega \to \pi^+\pi^-) = 0.09 \text{ MeV}]/\Gamma(\omega \to \pi^+\pi^-\pi^0) = 1.1 \times 10^{-2}$. The main contribution to this calculated rate comes from the diagrams that are possible if an octet of scalar mesons exists. This latter postulate is made in order to provide a specific mechanism for octet dominance in the eightfold way. If such terms are not included in their calculation, a negligible rate of $\Gamma(\omega \to \pi^+ + \pi^-) = 0.0002$ MeV is predicted.

Finally, we note the compilation that Lütjens and Steinberger[13] made at a time when less than a quarter of our data was published.[14] They place an upper limit of

*A more recent estimate by Picasso et al.[16] is 1.6×10^{-2}.

$[\Gamma(\omega \to \pi^+\pi^-) < 0.07 \text{ MeV}]/\Gamma(\omega \to \pi^+\pi^-\pi^0) = 0.8 \times 10^{-2}$ with 90% confidence. The number of $\omega \to \pi^+\pi^-\pi^0$ events that they compared with their $\pi^+\pi^-$ mass spectrum was 3541, of which 234 were from our data. (This number should properly have been 342.) The number of $\omega \to \pi^+\pi^-\pi^0$ in our experiment that should be compared with our $\pi^+\pi^-$ spectrum is 2330. [We have 4208 $\omega \to \pi^+\pi^-\pi^0$ events. The correction for elimination of $Y^*(1385)$ from our $\pi^+\pi^-$ spectrum gives 4208/1.81 = 2330.] Perhaps it would be prudent to keep an open mind to other hypotheses that might explain our data. We feel that the enhancement in the ω region is not a statistical fluctuation. If it is a phenomenon that is unrelated to ω decay and if it does not interfere with the ρ meson, it would have its mass centered at about 780 MeV with a width of $\Gamma \approx 20$ MeV. We have examined the production angular distribution of the events in the ω peak region and found it to resemble approximately the $\Lambda + (\omega \to \pi^+\pi^-\pi^0)$ production angular distribution.

Is the $\omega \to \pi^+\pi^-\pi^0$ Decay Consistent with C-Conservation?

Lee and Wolfenstein[15] have suggested that the apparent CP violation of $K_2 \to \pi^+\pi^-$ decay, a $|\Delta S| = 1$ transition, might be explained by introduction into the Hamiltonian of a specific form of CP-violating interaction. For $|\Delta S| = 0$ transitions, as in ω and η decay, this interaction could become large enough to be observed along with strong or electromagnetic interactions. Lee[2] proposes that the matrix element for ω decay might be of the form $\mathcal{M} = (\underset{\sim}{p_1} \times \underset{\sim}{p_2})(A + B e^{i\phi_B} r \sin\theta)$, where r is the distance from the center of the Dalitz plot and θ is the angle, measured clockwise, starting at the point of maximum momentum for the π_0. The term ϕ_B is a measure of final-state interactions and A and B are positive real numbers, whose ratio B/A could be of the order of 10^{-2}. This is a very small effect to be observed even with 4200 ω decays. Nevertheless, we fitted our data to this form of matrix element. The fit, which was excellent, gave $B/A = 0.11 \pm 0.09$, and $B/A = 3 \pm 6$ radians. The confidence level is 66 percent (chi-squared is 171 when 179 is expected). As we suspected, with our data we are unable to detect such a small effect as $B/A \sim 10^{-2}$.

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FOOTNOTES AND REFERENCES

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Figure Captions

Fig. 1. Missing-mass squared distribution for 12 351 events of $K^- + p \rightarrow \Lambda +$ neutrals at 1.4, 1.5, 1.6, and 1.7 BeV/c.

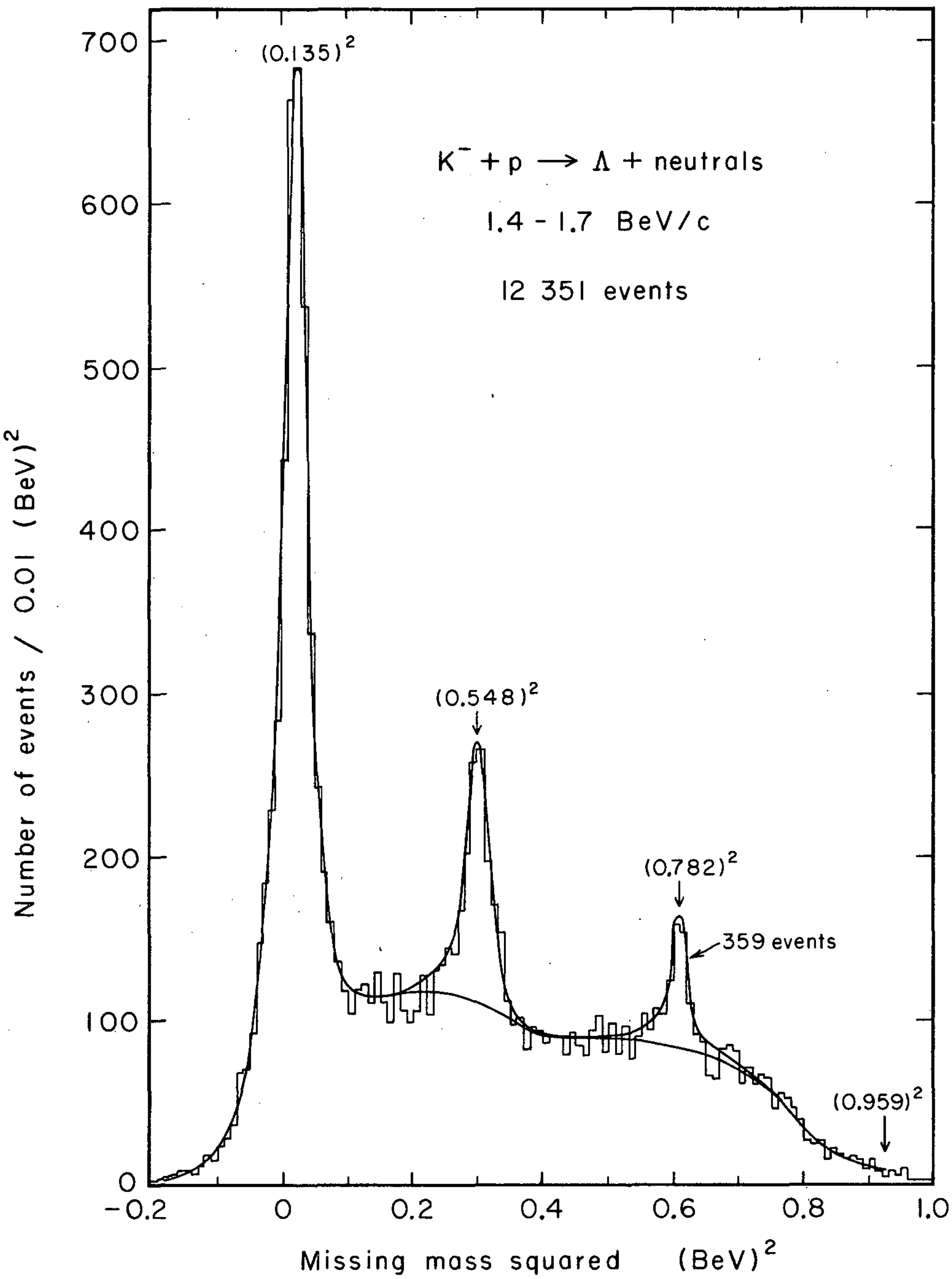
Fig. 2(a). Histogram of the invariant mass of the system that recoils against the Λ for 1461 events that fail to fit the final states $\Lambda\pi^+\pi^-$, $\Lambda\pi^+\pi^-\pi^0$, and $\Sigma^0\pi^+\pi^-$. 2(b). Only those events are plotted whose error in (missing mass)^2 is less than 6 000 MeV^2.

Fig. 3. Histograms of the (missing mass)^2 for "good events" (δ mm^2 < 6 000 MeV) that fail $\Lambda\pi^+\pi^-$ and $\Sigma^0\pi^+\pi^-$. (a) Events with an invariant mass ($\pi^+ + \pi^- +$ neutral) in the η region, 510 to 580 MeV; (b) events in between the η and ω regions, namely, 580 to 750 MeV; (c) events in the ω mass region, 750 to 810 MeV.

Fig. 4(a). Histogram of $M^2(\pi^+\pi^-)$ for $K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$ events that are not $K^- + p \rightarrow Y_1^*(1385) + \pi$; 1.0 to 1.8 BeV/c. (a) The solid curve is the fit to ρ alone; the phase-space (dashed) curve is normalized to the total number of background events. The other dashed curve is the background curve. (assumed to be parabolic).

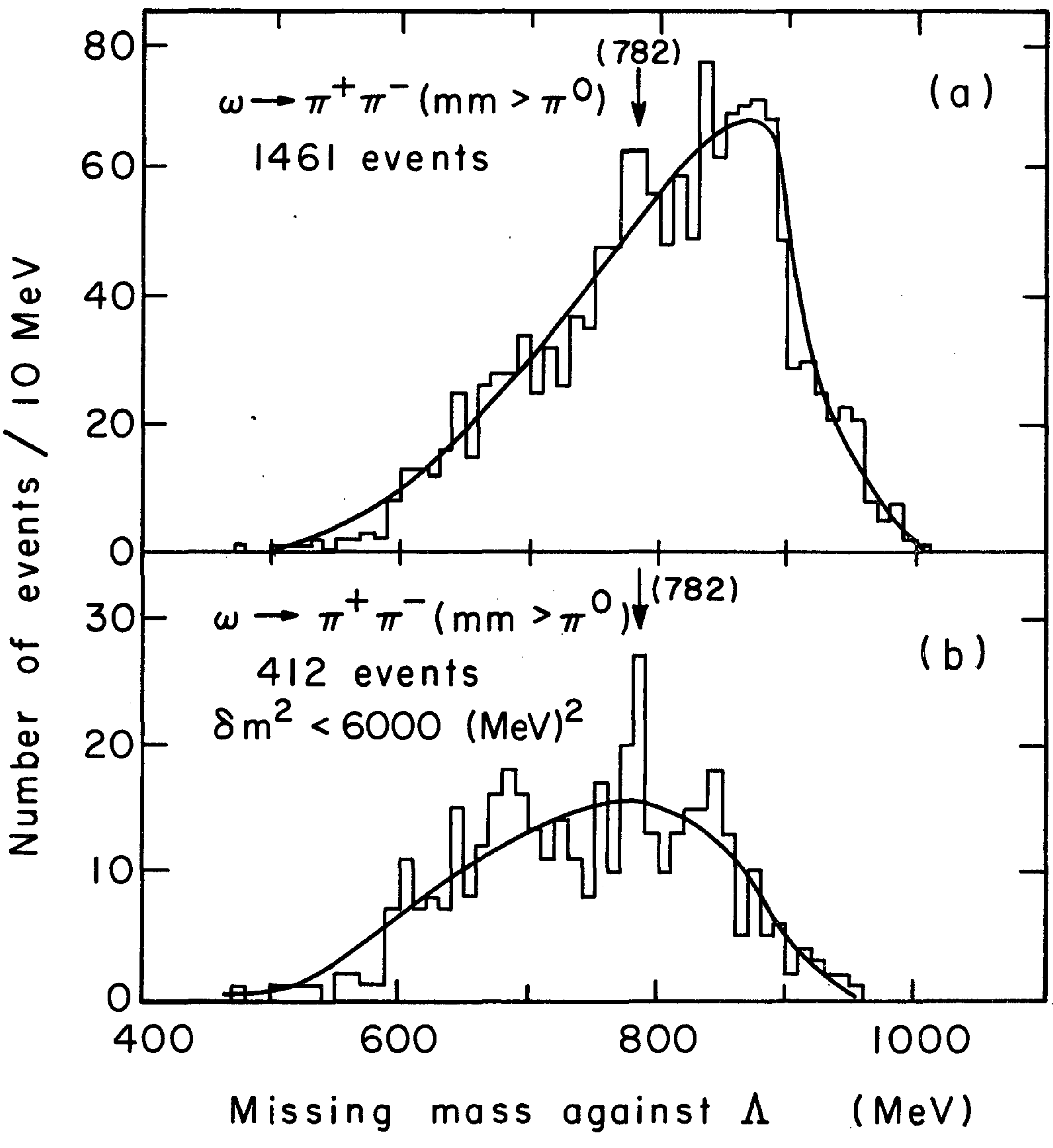
4(b). The solid curve is the fit to ρ and ω with completely coherent amplitudes. The dashed curve is background.

4(c). The solid curve is the fit to ρ and ω with completely incoherent amplitudes. The dashed curve is background.



MUB-5814

Fig. 1



MUB-5805

Fig. 2

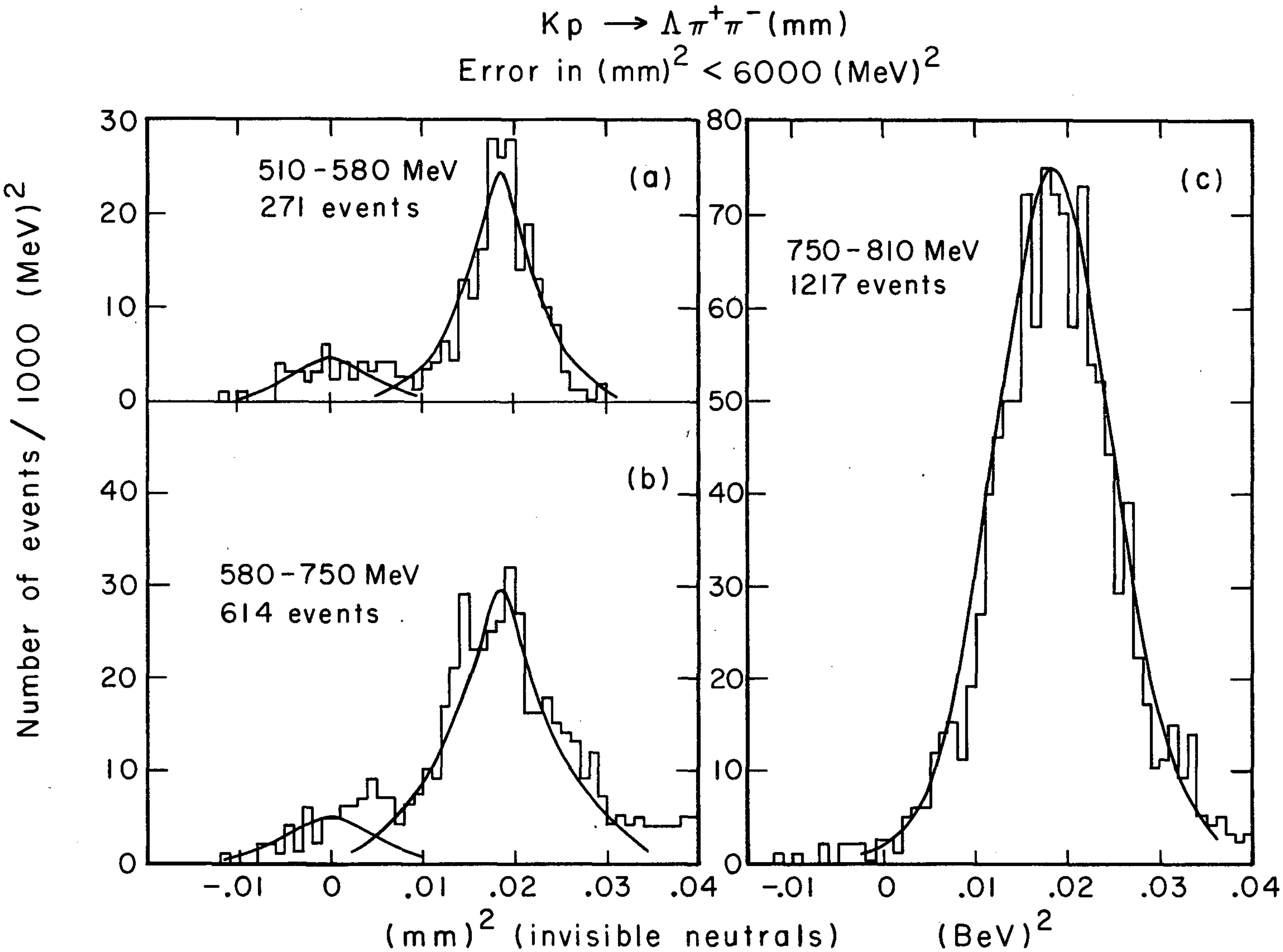


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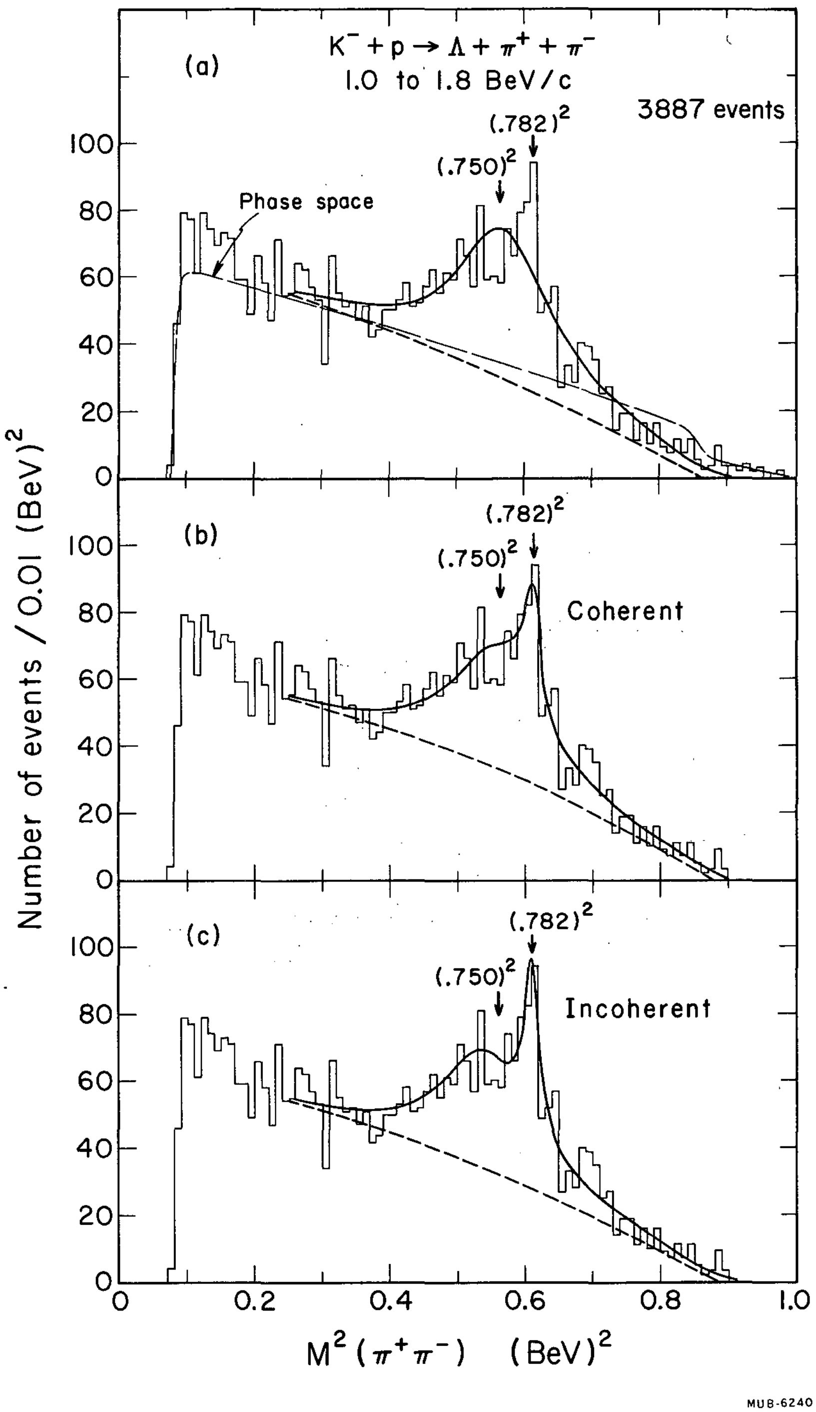
Fig. 3



(a)
$K^- + p \rightarrow \Lambda + \pi^+ + \pi^-$
1.0 to 1.8 BeV/c
3887 events
$(.782)^2$
$(.750)^2$
Phase space
(b)
Coherent
(c)
Incoherent
Number of events / 0.01 (BeV)^2
$M^2(\pi^+\pi^-)$ (BeV)^2
MUB-6240

Fig. 4