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We present here additional data on the $\eta 2\pi$ meson.[1,2] We find that this meson decays via all-neutral, $\pi^+\pi^-\eta$, and $\pi^+\pi^-\gamma$[3] modes, and most probably has the quantum numbers $TJ^{PG} = 00^{-+}$. This result follows from the analysis of the decay correlations in the $\pi^+\pi^-\gamma$ mode. The all neutral decay mode is observed to yield ~8 photons on the average, from the direct observation of the gamma rays associated with these events. Branching ratios for the various decay modes have been determined.

In the current 72-inch hydrogen bubble-chamber experiment, the chamber has been exposed to 2.45-, 2.55-, 2.63-, and 2.70-BeV/c K^- mesons from the Bevatron. Approximately 525 000 pictures have been taken to date. The reactions of interest in this paper are

$$K^- + p \rightarrow \Lambda + n(\pi^+ + \pi^-) \qquad \text{for } n \geq 1 \qquad (1)$$

$$\rightarrow \Lambda + n(\pi^+ + \pi^-) + (\pi^0 \text{ or } \gamma) \qquad \text{for } n \geq 1 \qquad (2)$$

and

$$\rightarrow \Lambda + m(\pi^+ + \pi^-) + MM \qquad \text{for } m \geq 0, \qquad (3)$$

where "MM" denotes missing mass in those channels which are kinematically underdetermined, i.e., where two or more neutrals are missing. We have selected a subset of the events from reactions (1) through (3) in which the mass of the system recoiling against the Λ is in a wide band about 958 MeV $[0.80 \leq M^2 \leq 1.04\ (\text{BeV})^2]$, and fitted these events to the final states $\Lambda\pi^+\pi^-\gamma$ and $\Lambda\pi^+\pi^-\eta$ [including subsequent decay of the η for reaction (2) with $n = 2$] in addition to the usual hypotheses.[1] We can separate out the

$\Lambda\pi^+\pi^-\gamma$ and $\Lambda\pi^+\pi^-\eta$ final states without a momentum-transfer selection in this way. However, for the analyses of this paper, we use only those events with low momentum transfer $[\Delta^2_{p,\Lambda} \leq 0.5\ (\mathrm{BeV})^2]$ in order to substantially reduce the background.

We summarize here the conclusions found for the possible J^P assignments from an analysis of the $\pi^+\pi^-\eta$ decay mode, as done by ourselves[1] and by the Syracuse-BNL collaboration.[3] Our data (not shown) for the 124 $\pi^+\pi^-\eta$ events, containing less than 5% background are very similar to the first 61 events shown in Fig. 3 of our preceding paper.[1] The $\pi^\pm\eta$ systems show no apparent structure, whereas the $\pi^+\pi^-$ system indicates a possible peaking around 350 MeV. All J^P states except 0^+ are allowed. We consider all $J \leq 2$. The angular distribution of the decay as viewed in the dipion rest frame is essentially isotropic.[4] This rules out $J^P = 1^-$ and 2^+ for charge conjugation $C = \pm 1$, and 0^- for $C = -1$. The momentum dependencies of the decay are not favorable to the assignments $J^P = 1^+$ for $C = +1$, and 2^- for $C = -1$.[5] We conclude that $J^P = 0^-$ and 2^- for $C = +1$, and 1^+ for $C = -1$ are all compatible with the $\pi^+\pi^-\eta$ decay of this meson.[6]

We now turn our attention to the evidence for the $\pi^+\pi^-\gamma$ mode in our data.[3] The $M^2(\pi^+\pi^-\gamma$ or $\pi^+\pi^-\pi^0)$ distribution for all $\Lambda\pi^+\pi^-\gamma$ or $\Lambda\pi^+\pi^-\pi^0$ events that do not fit $\Lambda\pi^+\pi^-$ and (or) $\Sigma^0\pi^+\pi^-$ are shown in Fig. 1a. These events fit both the γ and π^0 hypotheses. The better fit is chosen as correct, however. We see that the $M(\pi^+\pi^-\gamma)$ peaks at a mass of 958 MeV $[0.92\ (\mathrm{BeV})^2]$, whereas the $M(\pi^+\pi^-\pi^0)$ does not. In addition, we have searched for gammas that are "visible" due to pair conversion or Compton scattering in the liquid hydrogen of the chamber, or make Dalitz conversions, associated with all passing and failing events in our selected sample (see above) for reactions (1) through (3). The search has yielded four events that fit the

4-constraint $\Lambda\pi^+\pi^-\gamma$ hypothesis, but do not fit either $\Sigma^0\pi^+\pi^-$ or $\Lambda\pi^+\pi^-\pi^0$, where the π^0 decay yields a nonzero energy for the second "invisible" gamma. These four events all have $M^2(\pi^+\pi^-\gamma)$ in the range 0.88 to 0.94 $(\text{BeV})^2$, with two also having $\Delta^2_{p,\Lambda} \leq 0.5\ (\text{BeV})^2$. (These last two events are shown in Figs. 1, 2, and 3 as $\pi^+\pi^-\gamma_V$.) The 40 $\pi^+\pi^-\gamma$ and 32 $\pi^+\pi^-\pi^0$ events in the interval $0.90 \leq M^2(\pi^+\pi^-\gamma$ or $\pi^+\pi^-\pi^0) \leq 0.94\ (\text{BeV})^2$ along with the 2 $\pi^+\pi^-\gamma_V$ events are shown in Figs. 1b and 2. The MM^2 distribution (Fig. 1b) shows two barely-resolved peaks at the γ and π^0 masses. We conclude that the $\pi^+\pi^-\gamma$ mode exists, and is fairly separable from 3π events. The background in the accepted $\pi^+\pi^-\gamma$ events is less than ~30% (see Fig. 1).

The Dalitz plot of the $\pi^+\pi^-\gamma$ system is shown, along with the 3π events, in Fig. 2 (we use the events selected for Fig. 1b in the remaining discussion). The data show a striking deviation from uniformity, which is not attributable to biases involving the $\pi^+\pi^-\gamma/3\pi$ separation, as the 3π events attest. The simplest matrix elements and angular dependencies for electric-(E. D.) and magnetic-dipole (M. D.) transitions into $\pi^+\pi^-\gamma$ for $J \leq 2$ are given in Table I (ℓ denotes the "spin" angular momentum of the dipion system).[7] We have ignored $J^P = 0^+$ since it is not allowed for the $\pi^+\pi^-\eta$ decay mode. Only $J^{PC} = 0^{-+}$ vanishes all around the boundary of the Dalitz plot as do the data. However, the observed depopulated area at high gamma energy also requires a strong $\pi^+\pi^-$ interaction, which can only be the ρ for the $(\pi^+\pi^-)$ masses available in the decay.[8] Thus $C = -1$ is ruled out by the Dalitz plot. With a strong ρ final-state interaction, the vanishing of the density on the boundaries can only be checked along the $\pi^\pm\gamma$ axes, and the data are not convincing without a subtraction of the estimated background. The $M^2(\pi^+\pi^-)$ and $\cos\theta_{\pi^+\gamma}$ distributions are shown in Fig. 3, along with the estimated background subtraction. The 0^- (with ρ) and $\sin^2\theta$ curves

agree well with the data (the angular distribution is not changed by the ρ enhancement's inclusion in the matrix element). Comparing Table I and Fig. 3b, we see that $J^P = 1^{\pm}$ is definitely ruled out for $C = +1$; $2^{\pm}$ is not favored, and is quite unlikely in view of the background subtraction. Only the assignment $J^{PC} = 0^{-+}$ completely agrees with the data in Figs. 2 and 3.[9]

For the $\eta 2\pi$ system, $C = G = +1$ implies $T = 0$ or 2 for the final state of the decay. The absence of 3π decay (see Fig. 1a) implies that the decay into $\pi^+\pi^-\eta$ is not electromagnetic.[10] Thus this meson decays strongly into $\pi^+\pi^-\eta$ as well as electromagnetically into $\pi^+\pi^-\gamma$, yielding $T = 0$, since $T = 2$ is ruled out by the production reaction.[11]

The branching fractions for the various modes are given in Table II. The assignment of $T = 0$ implies that the major portion of the all-neutral decay is $\pi^0\pi^0\eta$; a 2γ mode is allowed, but should be very small. The search for "visible" gamma rays discussed above has yielded 25 all-neutral events.[12] Fig. 4a shows the distribution of M^2[neutrals + (0, 1, or 2)γ]. It is apparent that the neutral mode of decay of this meson involves a larger number of photons on the average than does the background. Using a detection efficiency of ~4% per gamma ray,[13] and estimating the background as less than ~8 events (out of the 25), we find $(25 + 2 - 8)/0.04 = 475$ photons associated with the 54 all-neutral decays, or 8.8 ± 2.9 photons on the average. The MM^2 of all the remaining "invisible" photons in the all-neutral decay is shown in Fig. 4b, along with a phase-space curve (which ignores the "π^0 resonances" among the photons in the decay). Both pieces of data are consistent with most of the all-neutral decay being due to $\pi^0\pi^0\eta$. No events were observed that correspond to 2γ or $\pi^0\gamma$ decay; the upper limits for such decay are given in Table II.

In summary, we conclude that the 958-MeV $\eta 2\pi$ meson[14] has the quantum numbers $TJ^{PG} = 00^{-+}$, a heavier eta-like meson.[15] It remains to be seen whether it is the ninth pseudoscalar meson--i.e., a unitary singlet as conjectured by Gell-Mann and Schwinger and others[16]--or the T = 0 member of a heavier pseudoscalar octet as conjectured by Zemach.[17]

We wish to acknowledge the support and cooperation of all Bevatron and bubble-chamber personnel, and of the scanning and measuring staffs, as well as the many other physicists involved in this K^- experiment. We especially thank Professor Luis W. Alvarez for his stimulation and encouragement, Dr. Joseph J. Murray and Dr. Janice Button-Shafer for providing the K^- beam, and Professor Charles Zemach for helpful discussions.

Table I. Simplest matrix elements for decay into the $\pi^+\pi^-\gamma$ system, via electric-(E. D.) and magnetic-(M. D.) dipole transitions. Here we have $\underset{\sim}{p} = \underset{\sim}{p}_{\pi^+} - \underset{\sim}{p}_{\pi^-}$, $\underset{\sim}{k}_E = \hat{a} \times \underset{\sim}{p}_\gamma$, $\underset{\sim}{k}_M = (\hat{a} \times \underset{\sim}{p}_\gamma) \times \underset{\sim}{p}_\gamma$, $\underset{\sim}{q}_E = \underset{\sim}{p} \times \underset{\sim}{k}_E$, and $\underset{\sim}{q}_M = \underset{\sim}{p} \times \underset{\sim}{k}_M$; $\hat{a}$ is a unit pseudovector along the direction of the magnetic field of the photon, and θ is the angle between the π^+ and γ in the dipion rest frame.

C	J^P	l	Mode	Matrix element	Angular dependence
+1	0^-	1	M. D.	$\underset{\sim}{p} \cdot \underset{\sim}{k}_M$	$\sin^2\theta$
	1^+	1	E. D.	$\underset{\sim}{q}_E$	$1 + \cos^2\theta$
	1^-	1	M. D.	$\underset{\sim}{q}_M$	$1 + \cos^2\theta$
	2^+	1	E. D.	$\underset{\sim}{p}\underset{\sim}{k}_E + \underset{\sim}{k}_E\underset{\sim}{p} - (2/3)I\underset{\sim}{p} \cdot \underset{\sim}{k}_E$	$6 + \sin^2\theta$
	2^-	1	M. D.	$\underset{\sim}{p}\underset{\sim}{k}_M + \underset{\sim}{k}_M\underset{\sim}{p} - (2/3)I\underset{\sim}{p} \cdot \underset{\sim}{k}_M$	$6 + \sin^2\theta$
-1	0^-			(forbidden via dipole mode)	
	1^+	0	M. D.	$\underset{\sim}{k}_M$	1
	1^-	0	E. D.	$\underset{\sim}{k}_E$	1
	2^+	2	M. D.	$\underset{\sim}{p}\underset{\sim}{q}_M + \underset{\sim}{q}_M\underset{\sim}{p}$	$1 + \cos^2\theta$
	2^-	2	E. D.	$\underset{\sim}{p}\underset{\sim}{q}_E + \underset{\sim}{q}_E\underset{\sim}{p}$	$1 + \cos^2\theta$

Table II. Decay branching ratios of the 958-MeV meson.

Mode	Events[a]	Detection[b] factor	Branching fraction
All neutrals	54 ± 11	0.30	0.25 ± 0.05
$\pi^+\pi^-$ neutrals	10 ± 8	0.27	0.05 ± 0.04
$\pi^+\pi^-\eta_N$[c]	68 ± 9	0.27	0.36 ± 0.05
$\pi^+\pi^-\eta_C$[c]	44 ± 7	0.55	0.12 ± 0.02
$\pi^+\pi^-\gamma$	42 ± 7	0.27	0.22 ± 0.04
Total	218 ± 19	—	1.00
$\pi^+\pi^-$	7 ± 6	0.27	< 0.1
$\pi^+\pi^0\pi^-$	3 ± 7	0.27	< 0.1
$2\pi^+2\pi^-$	0	0.55	< 0.01
$2\pi^+\pi^0 2\pi^-$	0	0.55	< 0.01
$3\pi^+3\pi^-$	0	1.0	< 0.005
$2\pi^+2\pi^0 2\pi^-$	0	0.55	< 0.01
$\begin{pmatrix} 2\gamma \\ \text{or} \\ \pi^0\gamma \end{pmatrix}$[d]	0	$\begin{pmatrix} 2 \\ \text{or} \\ 1 \end{pmatrix} \times (\sim 0.04) \times 0.30$	$< \begin{pmatrix} 0.15 \\ \text{or} \\ 0.3 \end{pmatrix}$

a. Number of events above background with $\Delta^2_{p,\Lambda} \leq 0.5\,(\text{BeV})^2$.

b. Number of events in the appropriate topology which were measured and which passed all acceptance criteria divided by the number found in the first scanning of approximately 525 000 pictures.

c. η_C stands for $\eta \to \pi^+\pi^0\pi^-$ and $\pi^+\pi^-\gamma$, and η_N stands for $\eta \to$ all neutrals.

d. These are of course a part of "all neutrals" listed earlier, but this is an independent result from the gamma-ray search (see text).

FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

1. G. R. Kalbfleisch, L. W. Alvarez, A. Barbaro-Galtieri, O. I. Dahl, P. Eberhard, W. E. Humphrey, J. S. Lindsey, D. W. Merrill, J. J. Murray, A. Rittenberg, R. R. Ross, J. Button-Shafer, F. T. Shively, D. M. Siegel, G. A. Smith, and R. D. Tripp, Phys. Rev. Letters 12, 527 (1964).

2. M. Goldberg, M. Gundzik, S. Lichtman, J. Leitner, M. Primer, P. L. Connolly, E. L. Hart, K. W. Lai, G. London, N. P. Samios, and S. S. Yamamoto, Phys. Rev. Letters 12, 546 (1964).

3. We note that the Syracuse-BNL collaboration has given evidence for the $\pi^+\pi^-\gamma$ decay mode also [Decay Modes and Properties of the X^0, M. Goldberg, M. Gundzik, J. Leitner, M. Primer, P. L. Connolly, E. L. Hart, K. W. Lai, G. W. London, N. P. Samios, and S. S. Yamamoto, Brookhaven National Laboratory Report BNL 8151, June 1964 (submitted to Phys. Rev. Letters)].

4. The $\pi^+\pi^-\eta$ Dalitz plot and related distributions are given in Fig. 3 of reference 1 and Fig. 4 of reference 3.

5. The matrix elements for $\pi^+\pi^-\eta$ decay are given in reference 3 (except for one error: the $J^P = 2^-$, $T = 1$, $C = -1$ matrix element should be made traceless; the correct angular distribution then is $1 + (1/3)\cos^2\theta$ instead of 1). We point out that the conclusions of the Syracuse-BNL collaboration for the J^P assignments are not independent of ours, since their analysis of 102 $\pi^+\pi^-\eta$ events includes our first 61 events of reference 1. In addition, we note that the 2^- matrix element for $T = 0$, $C = +1$ is a linear combination of two terms corresponding to $(\ell, L) = (0,2)$ and $(2,0)$. Consequently, $J^{PC} = 2^{-+}$ is compatible with the data, contrary to the conclusions of reference 3.

6. C. Zemach has shown that the zeroes on the Dalitz plot for higher J^P values are very similar to those considered in the text, for $\Delta J = 2, 4, \cdots$ [Phys. Rev. 133, B1201 (1964)].

7. We use here the suggestion of H.-P. Duerr and W. Heisenberg [Nuovo Cimento 23, 807 (1962)], according to which the matrix element for an electric-dipole transition must contain the factor $\underset{\sim}{k}_E = \hat{\underset{\sim}{a}} \times \underset{\sim}{p}_\gamma$, and that for a magnetic-dipole transition must contain $\underset{\sim}{k}_M = (\hat{\underset{\sim}{a}} \times \underset{\sim}{p}_\gamma) \times \underset{\sim}{p}_\gamma$. Here $\hat{a}$ is a unit pseudovector along the direction of the magnetic field of the photon, so that $\underset{\sim}{k}_E$ is a vector and $\underset{\sim}{k}_M$ a pseudovector.

8. The only $\pi^+\pi^-\gamma$ matrix element that approximates the $\pi^+\pi^-$ spectrum is $J^P = 2^-$ for $C = -1$; however, the angular distribution predicted by this matrix element does not agree with the data.

9. For dipole transitions to $\rho\gamma$, only $J = 0, 1$, or 2 is possible.

10. Reference 3 gives a more detailed argument in regards to determining the G parity of the meson.

11. In the current experiment we have also taken about 80 000 pictures of 2.63-BeV/c K^- in deuterium. The (expected) absence of an effect in this sample will be significant enough to confirm the isotopic-spin assignment.

12. The 23-1γ and 2-2γ events contain 17 conversion pairs, 8 Compton electrons, and 2 Dalitz pairs.

13. An approximate detection efficiency was determined from a sample of 199 $\Lambda\omega$ events, which yielded 13 "visible" gammas, as well as from the $2\pi^+\pi^-\gamma_V$ in the 42 $\pi^+\pi^-\gamma$ events. We have ignored differences in the gamma energy spectra of the various samples in this zero-order correction.

14. With the improved resolution of the $\Lambda\pi^+\pi^-\eta$ fits and the larger sample, our best value of the mass is $M = 958 \pm 1$ MeV and of the width is $\Gamma \leq 7$ MeV.

15. This christens the meson ${}_{+}\eta'_{\beta}$ according to the classification of A. H. Rosenfeld, Possible Classification of Particles and Resonances, in Proceedings of the 1962 International Conference on High-Energy Physics at CERN (CERN, Geneva, 1962), p. 325.

16. M. Gell-Mann, California Institute of Technology Synchrotron Laboratory Internal Report No. CTSL-20, 1961 (unpublished); M. Gell-Mann, Phys. Rev. 125, 1067 (1962); J. Schwinger, Phys. Rev. Letters 12, 237 (1964); A. Pais, Phys. Rev. Letters 12, 634 (1964); C. Becchi and G. Morpurgo, Phys. Rev. Letters 13, 110 (1964).

17. C. Zemach [Phys. Rev. 133, B1201 (1964)] suggests that since the members of the π, η, K octet may be bound S-wave states of baryon-antibaryon pairs, then the binding force is so strong that there could be one or more higher-energy bound S states. These would have the same quantum numbers as the "ground state" π, η, and K, but would be heavier.

FIGURE CAPTIONS

Fig. 1. (a) Distributions of the effective mass squared of $\pi^+\pi^-\gamma$ and $\pi^+\pi^-\pi^0$ in the reactions $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \gamma$ and $K^- + p \rightarrow \Lambda + \pi^+ + \pi^- + \pi^0$. The $\pi^+\pi^-\gamma$ events in which the γ is not observed are represented by the unshaded region, while those where the $\gamma \equiv \gamma_V$ is "visible" are indicated by the vertically-lined region; the $\pi^+\pi^-\pi^0$ events are shown as the shaded region. The straight lines indicate the estimated background levels. The $\pi^+\pi^-\gamma$ resolution function is also shown, normalized to the number of events in the peak.

(b) Distribution of the missing mass squared, $MM^2(\gamma \text{ or } \pi^0)$, for the 40 $\pi^+\pi^-\gamma$ and 32 $\pi^+\pi^-\pi^0$ events in (a) having $0.90\ (\text{BeV})^2 \leq M^2(\pi^+\pi^-\gamma \text{ or } \pi^+\pi^-\pi^0) \leq 0.94\ (\text{BeV})^2$ and for the 2 $\pi^+\pi^-\gamma_V$ events. The sum of the appropriate, normalized resolution functions for $MM^2(\gamma)$ and $MM^2(\pi^0)$ is shown.

Fig. 2. Dalitz plot of the events of Fig. 1b, with $M^2(\pi^-\gamma \text{ or } \pi^-\pi^0)$ plotted versus $M^2(\pi^+\gamma \text{ or } \pi^+\pi^0)$. The quantity $M^2(\pi^+\pi^-\gamma \text{ or } \pi^+\pi^-\pi^0)$ has been normalized to $0.918\ (\text{BeV})^2$ for each event. The kinematic envelopes are shown for the two different sets of events.

Fig. 3. (a) Distribution of the effective mass squared of the $\pi^+\pi^-$ system in the 40 $\pi^+\pi^-\gamma$ events with $0.90\ (\text{BeV})^2 \leq M^2(\pi^+\pi^-\gamma) \leq 0.94\ (\text{BeV})^2$ and in the two $\pi^+\pi^-\gamma_V$ ("visible" gamma) events. The estimated background contribution to these events is cross-hatched. Shown are the curves for the predicted distributions corresponding to ($J^P = 0^-$, $C = +1$, no ρ) and ($J^P = 0^-$, $C = +1$, with ρ) matrix elements (see Table I). The curves are normalized to the number of events, excluding background.

(b) Distribution of the events in (a) in the angle $\theta_{\pi^+\gamma}$ between the π^+ and the γ, measured in the dipion rest frame. The normalized curves of $\sin^2\theta$ and $1 + \cos^2\theta$ represent the two extreme cases for the matrix elements of Table I.

Fig. 4. (a) Distribution of the square of the effective mass of the ($n\gamma$ + neutrals) system in the reaction $K^- + p \rightarrow \Lambda + n\gamma$ + neutrals, where n = 0, 1, or 2 is the number of "visible" gammas. These three cases are represented by the unshaded, shaded, and cross-hatched areas, respectively. The overall estimated background is indicated by the dashed straight line, and the normalized resolution functions are also given.

(b) Distribution of the effective mass squared of the neutrals in the events in (a) having 1 or 2 "visible" gammas. The curve represents an equal mixture of the phase-space distributions for 5 out of 6 and 9 out of 10 gammas, normalized to the number of events.

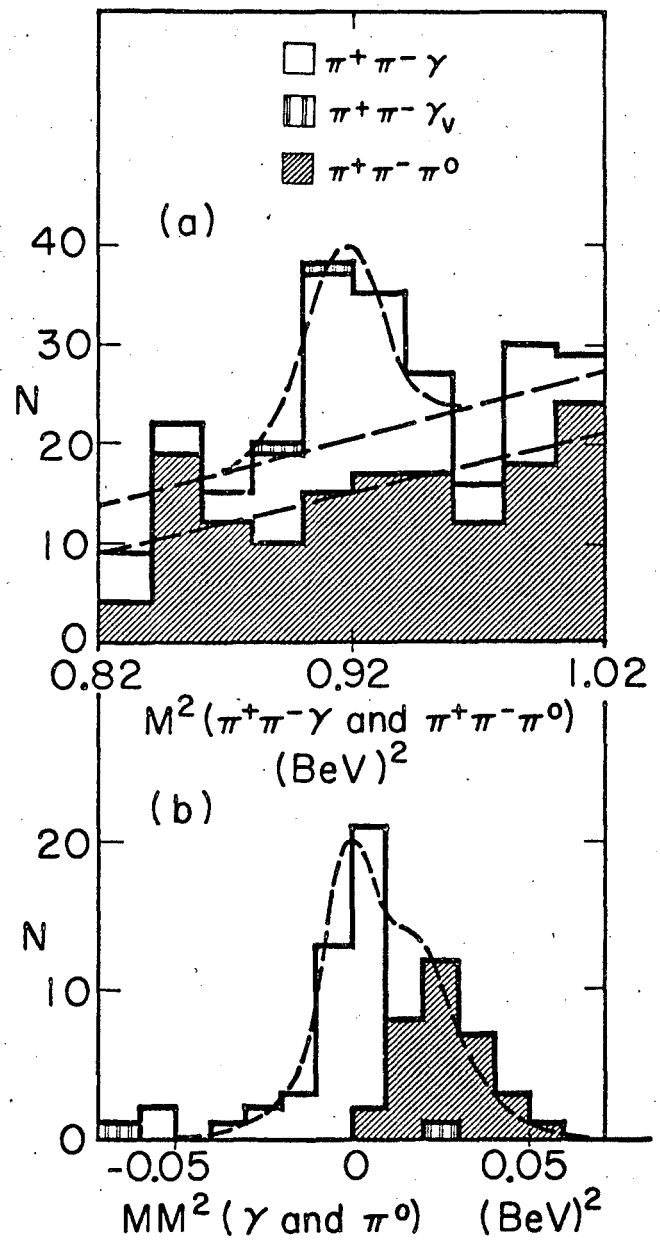

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Fig. 1

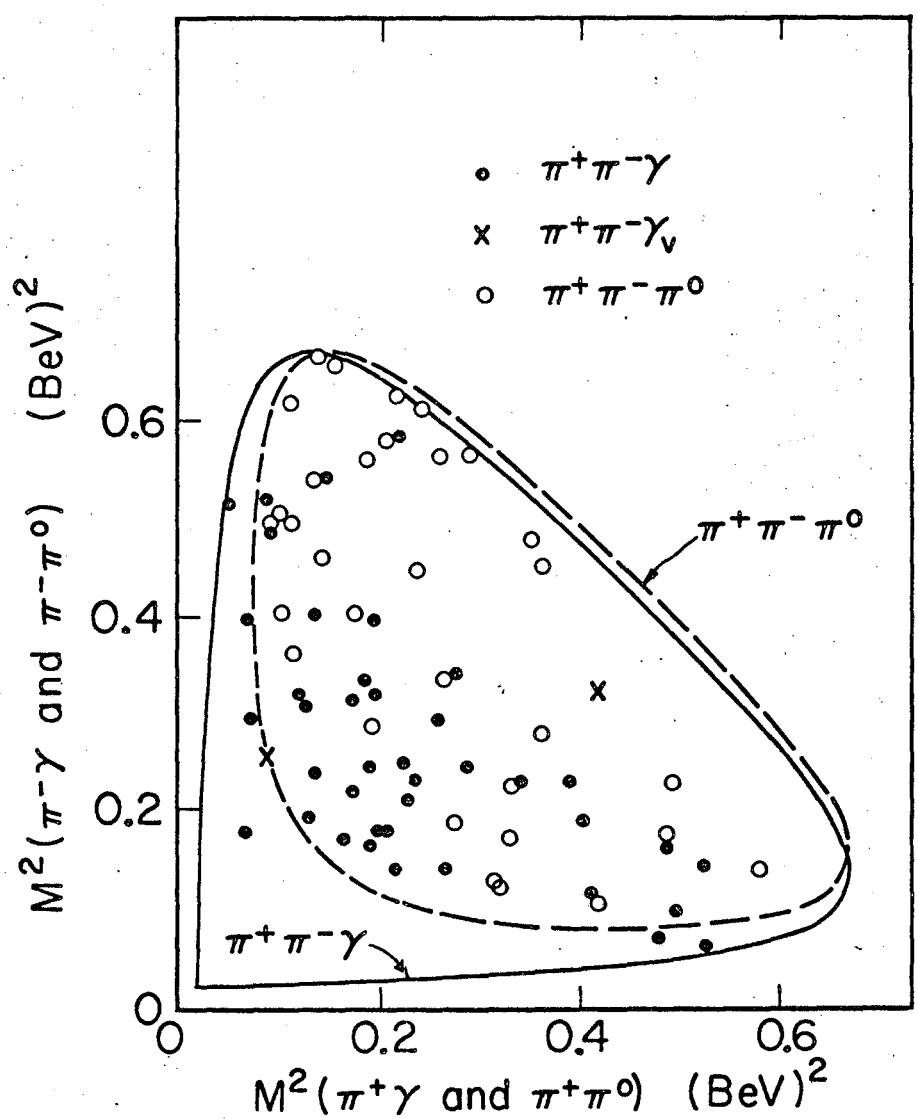

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Fig. 2

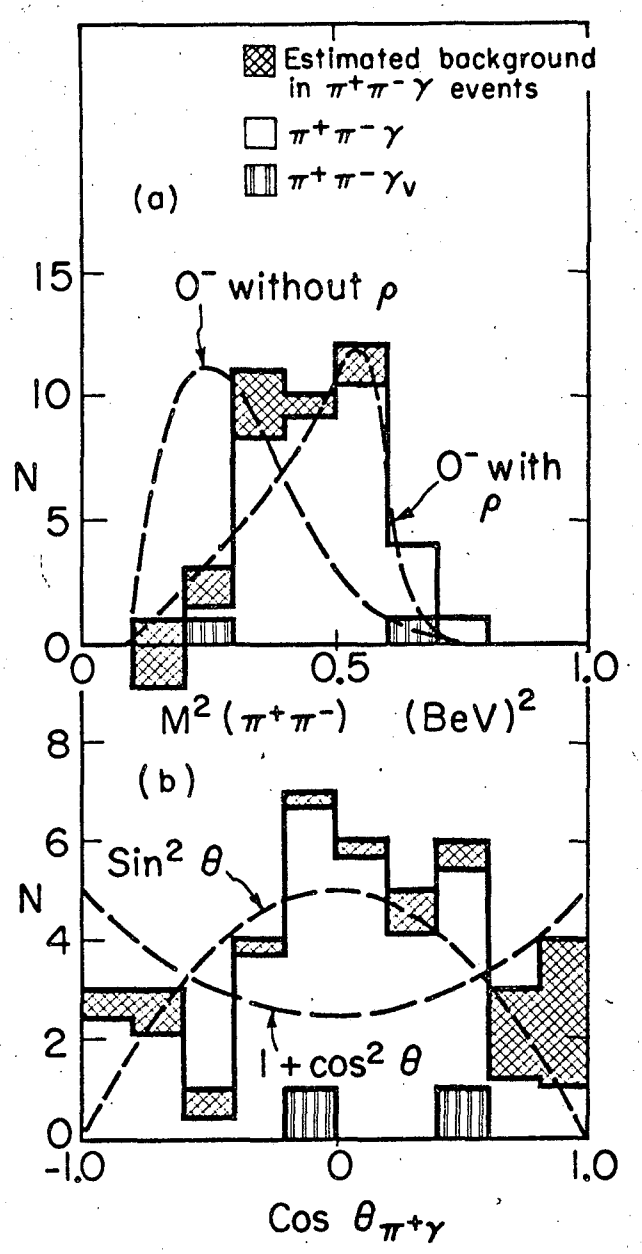

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Fig. 3

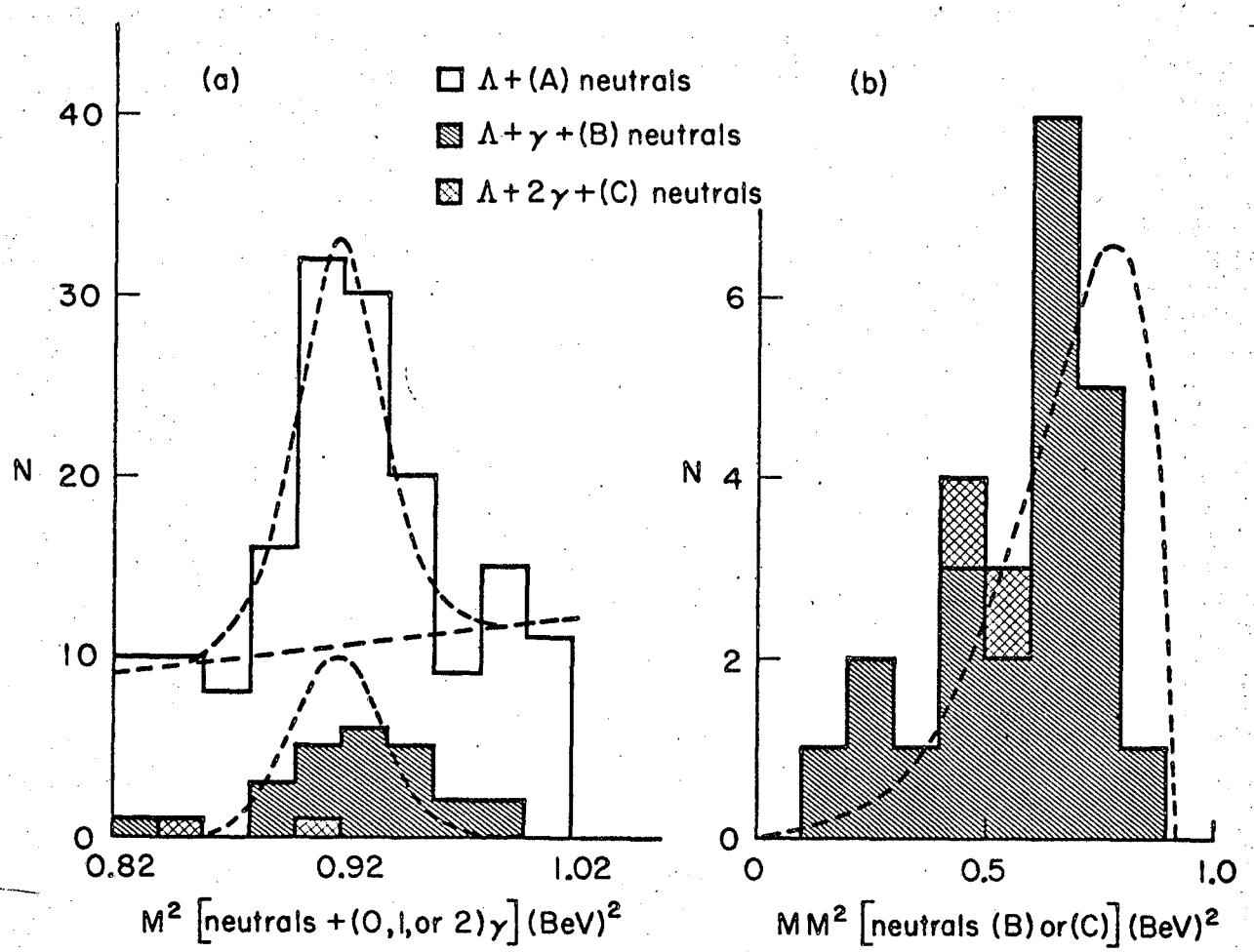

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Fig. 4

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