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ADDITIONAL PROPERTIES OF THE 959-MeV MESON

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ADDITIONAL PROPERTIES OF THE 959-MeV MESON*

George R. Kalbfleisch, Orin I. Dahl, and Alan Rittenberg

(Presented by George R. Kalbfleisch)

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We present here additional information on the 959-MeV $\eta 2\pi$ meson.[1,2] We have found that this meson probably has the quantum numbers $TJ^{PG} = 00^{-+}$ and that it decays via all neutral, $\pi^+\pi^-\eta$, and $\pi^+\pi^-\gamma$ modes.

In the current 72-inch hydrogen bubble-chamber experiment, the chamber has been exposed to 2.45-, 2.55-, 2.63-, and 2.70-GeV/c K^- mesons from the Bevatron. Approximately 500 000 pictures have been taken to date. The reactions of interest in this paper are

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

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

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)—(3) in which the mass of the system recoiling against the Λ is in a wide band about 959 MeV $[0.80 \leq M^2 \leq 1.04\ (\text{GeV})^2]$, and fitted these events to the final states $\Lambda\pi^+\pi^-\gamma$ and $\Lambda\pi^+\pi^-\eta$ [including the 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 analysis of the Dalitz plots, we use only those events with

low momentum transfer $[\Delta^2_{p,\Lambda} \leq 0.5\ (\mathrm{GeV})^2]$ in order to substantially reduce the background.

The data for the $\pi^+\pi^-\eta$ decay of the 959-MeV meson are shown in Fig. 1 (background is less than about 5%). The $\eta\pi^\pm$ systems show no apparent structure, whereas the $\pi^+\pi^-$ system (Fig. 1b) indicates a possible peaking around 350 MeV. We consider the $\eta 2\pi$ system as a dipion and an η, and denote the angular momentum of the dipion as ℓ, and that between the dipion and the η as L. All J^P states except 0^+ are allowed. For $J \leq 2$, the simplest matrix elements and angular dependencies of the decay are given in Table I.[3] The angular distribution of the decay as viewed in the dipion rest frame is essentially isotropic, as is shown in Fig. 1c. This rules out $J^P = 1^-$ and 2^+ for $C = \pm 1$, and 0^- for $C = -1$. Of the remaining states shown in Table I, the $J^P = 1^+$ state for $C = \pm 1$ peaks the $M^2(\pi^+\pi^-)$ distributions at either the low or the high end. Apart from a small peak around 350 MeV, the data do not indicate that $J^P = 1^+$ is likely.

We now turn our attention to the evidence for the $\pi^+\pi^-\gamma$ decay mode. The $M^2(\pi^+\pi^-\gamma$ or $\pi^+\pi^0\pi^-)$ distribution for all $\Lambda\pi^+\pi^-\gamma$ or $\Lambda\pi^+\pi^0\pi^-$ events that do not fit $\Lambda\pi^+\pi^-$ and (or) $\Sigma^0\pi^+\pi^-$ are shown in Fig. 2b. These events fit both hypotheses. The better fit is chosen as correct, however. The MM^2 distribution (not shown) for these events show two just-resolved peaks at the γ and π^0 masses. Thus we see that the $M(\pi^+\pi^-\gamma)$ peaks at a mass of 959 MeV $[0.92\ (\mathrm{GeV})^2]$, whereas the $M(\pi^+\pi^0\pi^-)$ does not. In addition, we searched for gammas which are "visible" due to pair conversion or Compton scattering in the liquid hydrogen of the chamber. The search has yielded thus far four events that fit the 4-constraint $\Lambda\pi^+\pi^-\gamma$ hypothesis, and do not fit either $\Sigma^0\pi^+\pi^-$ or $\Lambda\pi^+\pi^0\pi^-$, 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 $(\mathrm{GeV})^2$, with two also having $\Delta^2_{p,\Lambda} \leq 0.5\ (\mathrm{GeV})^2$.

The Dalitz plot of the $\pi^+\pi^-\gamma$ system is shown in Fig. 2a. The events have a background of less than $\approx 30\%$ (see Fig. 2b). The data show a striking deviation from uniformity. The simplest matrix elements and angular dependencies for electric (E. D.) and magnetic-dipole (M. D.) transitions into $\pi^+\pi^-\gamma$ are given in Table II.[4] 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 requires in addition a strong $\pi^+\pi^-$ interaction, which can only be the ρ for the $(\pi^+\pi^-)$ masses available in the decay. Thus $C = -1$ appears to be ruled out by the $\pi^+\pi^-\gamma$ Dalitz plot. With a strong ρ final-state interaction, vanishing of the density on the boundaries can be tested only along the $\pi^\pm\gamma$ axes. The observed density of points decreases along these axes. We conclude that $J^{PC} = 0^{-+}$ is consistent with the $\pi^+\pi^-\gamma$ data; the 2^{-+} state is possible, whereas 1^{++} and 1^{-+} appear to be ruled out.

If we consider both $\pi^+\pi^-\eta$ and $\pi^+\pi^-\gamma$ decay modes, $J^{PC} = 0^{-+}$ is probable, although 2^- is possible for $C = +1$; $C = -1$ appears unlikely. 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. 2b) implies that the decay into $\eta 2\pi$ is not electromagnetic. Thus the 959-MeV meson decays strongly into $\pi^+\pi^-\eta$ as well as electromagnetically into $\pi^+\pi^-\gamma$. Then the 959-MeV meson has $T = 0$, since $T = 2$ is ruled out by the production reaction. The branching ratios will not be discussed here due to lack of space. However, they appear to be roughly consistent with the theoretically expected rates for $TJ^{PG} = 00^{-+}$.

In summary, we conclude that the 959-MeV meson is consistent with the assignment of the quantum numbers $TJ^{PG} = 00^{-+}$, a heavier eta-like meson. It remains to be seen whether it is the ninth pseudoscalar meson, i. e., a unitary singlet as conjectured by Gell-Mann[5] and Schwinger,[6] or the $T = 0$ member of a heavier pseudoscalar octet as conjectured by Zemach.[7]

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, and Professor Charles Zemach for helpful discussions.

Table I. Simplest matrix elements for decay into the $\pi^+\pi^-\eta$ system. Here we have $\underset{\sim}{p} = \underset{\sim}{p}_{\pi^+} - \underset{\sim}{p}_{\pi^-}$, $\underset{\sim}{P} = -(\underset{\sim}{p}_{\pi^+} + \underset{\sim}{p}_{\pi^-}) = \underset{\sim}{p}_{\eta}$, and $\underset{\sim}{q} = \underset{\sim}{p} \times \underset{\sim}{P}$; I is the unit dyadic and θ is the angle between the π^+ and the η in the dipion rest frame. (See reference 3.)

C	J^P	ℓ	L	Matrix element	Angular dependence
+1	0^-	0	0	1	1
	1^+	0	1	$\underset{\sim}{P}$	1
	1^-	2	2	$\underset{\sim}{p} \cdot \underset{\sim}{P}\, \underset{\sim}{q}$	$\sin^2\theta \cos^2\theta$
	2^+	2	1	$\underset{\sim}{pq} + \underset{\sim}{qp}$	$\sin^2\theta$
	2^-	0	2	$\underset{\sim}{PP} - I\underset{\sim}{P}^2/3$	1
	2^-	2	0	$\underset{\sim}{pp} - I\underset{\sim}{p}^2/3$	1
-1	0^-	1	1	$\underset{\sim}{p} \cdot \underset{\sim}{P}$	$\cos^2\theta$
	1^+	1	0	$\underset{\sim}{p}$	1
	1^-	1	1	$\underset{\sim}{q}$	$\sin^2\theta$
	2^+	1	2	$\underset{\sim}{Pq} + \underset{\sim}{qP}$	$\sin^2\theta$
	2^-	1	1	$\underset{\sim}{pP} + \underset{\sim}{Pp} - 2I\underset{\sim}{p} \cdot \underset{\sim}{P}/3$	$1 + \cos^2\theta/3$

Table II. Simplest matrix elements for decay into the $\pi^+\pi^-\gamma$ system. 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 (see reference 4).

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.	$\underset{\sim}{p}\underset{\sim}{q}_E + \underset{\sim}{q}_E\underset{\sim}{p}$	$1 + \cos^2\theta$

FOOTNOTES AND REFERENCES

* Work 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, 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, S. S. Yamamoto, Phys. Rev. Letters 12, 546 (1964).

3. C. Zemach has shown that the zeroes on the Dalitz plot for higher J^P values are very similar to those given in Table I when ΔJ is $2, 4, \cdots$. [Phys. Rev. 133, B1201 (1964)].

4. 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 $\underset{\sim}{k}_E = \hat{a} \times \underset{\sim}{p}_\gamma$, and that for a magnetic-dipole transition must contain $\underset{\sim}{k}_M = (\hat{a} \times \underset{\sim}{p}_\gamma) \times \underset{\sim}{p}_\gamma$. 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.

5. M. Gell-Mann has long conjectured the existence of a singlet 00^{-+} meson. [California Institute of Technology Synchrotron Laboratory Internal Report No. CTSL-20, 1961 (unpublished); Phys. Rev. 125, 1067 (1962)].

6. J. Schwinger has proposed a 0^- δ meson at a mass of ~1500 MeV [Phys. Rev. Letters 12, 237 (1964)].

7. 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 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 LEGENDS

Fig. 1(a). Dalitz plot of those $\pi^+\pi^-\eta$ events having $0.90 \leq M^2(\pi^+\pi^-\eta) \leq 0.94$ $(\mathrm{GeV})^2$ and $\Delta^2_{p,\Lambda} \leq 0.5\ (\mathrm{GeV})^2$, where M^2 has been normalized to $0.92\ (\mathrm{GeV})^2$ for the plot. Here η_c denotes $\eta \to \pi^+\pi^0\pi^-$ or $\pi^+\pi^-\gamma$, while η_N denotes $\eta \to$ all neutrals. (b) Projection of the Dalitz plot on the $M^2(\pi^+\pi^-)$ axis. The solid curve represents phase space, normalized to the total number of events. (c) Angular distribution, in the dipion rest frame for the same events, in the angle $\theta_{\eta\pi^+}$ between the η and the π^+. The dashed lines represent flat distributions.

Fig. 2(a). Dalitz plot of those $\pi^+\pi^-\gamma$ events having $0.90 \leq M^2(\pi^+\pi^-\gamma) \leq 0.94$ $(\mathrm{GeV})^2$ and $\Delta^2_{p,\Lambda} \leq 0.5\ (\mathrm{GeV})^2$, where M^2 has been normalized to $0.92\ (\mathrm{GeV})^2$ for the plot. (b) The effective-mass-squared distributions for the $\pi^+\pi^0\pi^-$ and $\pi^+\pi^-\gamma$ events. The two dashed straight lines are approximations to the background, while the dashed curve represents the resolution function for $M^2(\pi^+\pi^-\gamma)$.

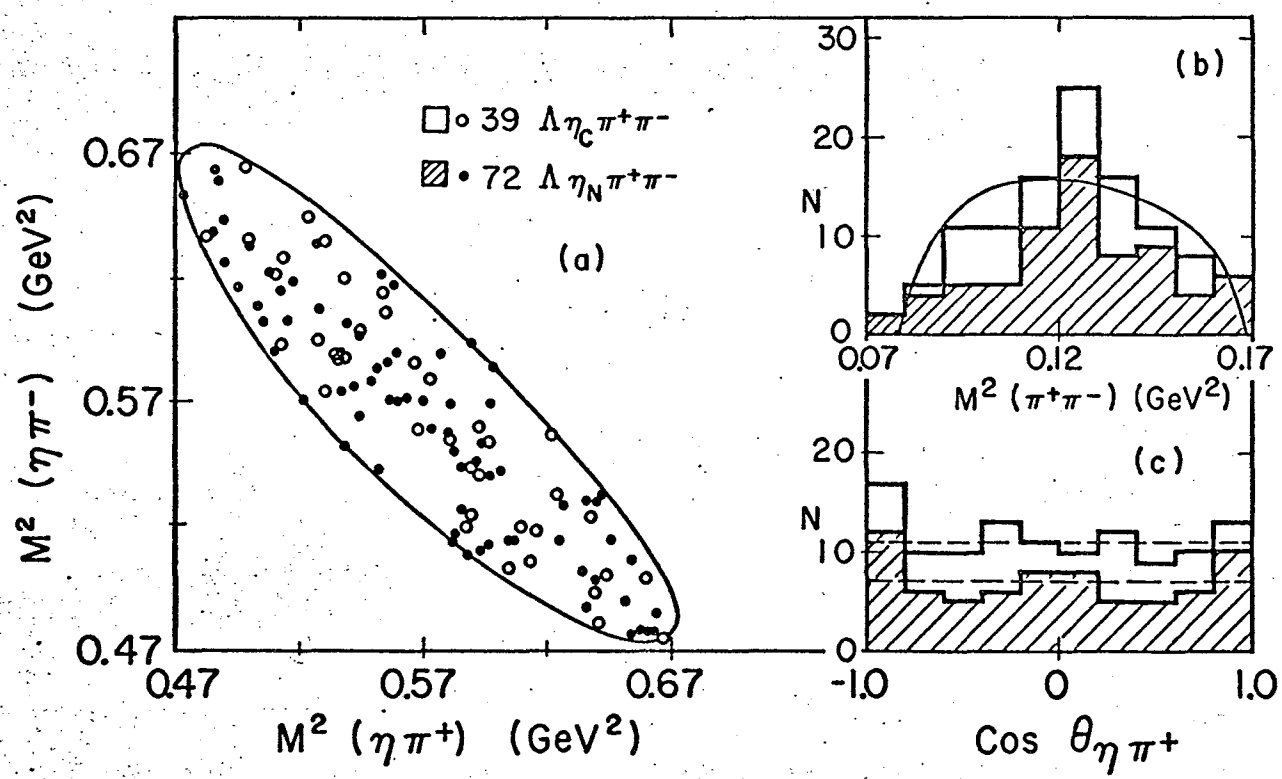

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Fig. 1.

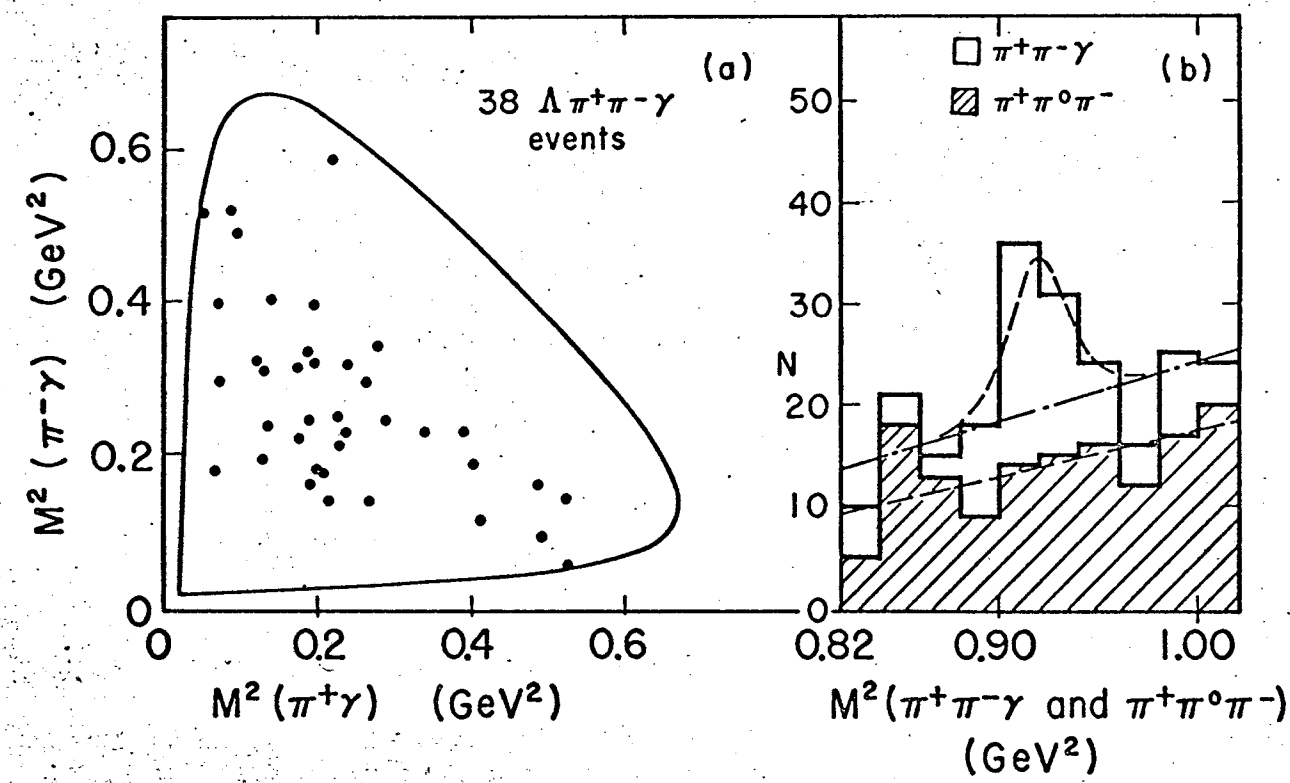

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Fig. 2.

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