Editorial of 20 July 1964 [Phys. Rev. Letters 13, 79 (1964)].

†Work performed under the auspices of the U. S. Atomic Energy Commission.

‡On leave of absence from the Weizmann Institute of Science, Rehovoth, Israel.

[1]F. Lefebvres et al., Phys. Letters 19, 434 (1965).

[2]G. Chikovani et al., Phys. Rev. Letters 25B, 44 (1967); W. Kienzle, in Proceedings of Informal Meeting on Experimental Meson Spectroscopy, Philadelphia, April, 1968 (to be published).

[3]See an experimental compilation by A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968), and references therein.

[4]The major contribution to the error in the effective mass of π^- + MM comes from the uncertainty of the incident beam momentum. Errors introduced by measurements and Coulomb scattering of the recoil protons in the laboratory momentum range ~0.3-0.9 GeV/c are of the order of 5 MeV.

[5]All mass-spectrum fits have been made with a linear background. A quadratic background gives essentially the same results. The fits with two incoherent Breit-Wigner shapes never succeed in reproducing the pronounced dip observed between the peaks. A larger width is obtained for Γ_2 if higher $t_{p\to p}$ values (0.2-0.6 GeV^2) are included, giving $\Gamma_2 \simeq 50\pm 25$ MeV.

[6]The error in the missing mass comes from errors in measurements of the fast π^- and recoil-proton tracks. It is about 35 ± 15 MeV.

[7]Since we see no $\omega(780)$ signal in the MM spectrum (see Fig. 2 inserts), we conclude that the $A_2{}^L$ does not contain $\omega\pi$ events and hence cannot be due to the B meson.

[8]Unlike the π^- + MM system in Reaction (1), the $K_1{}^0K_1{}^0$ system in Reactions (2) and (3) is not complicated by large background due to other final-state interactions; therefore no cuts are introduced in the $K_1{}^0K_1{}^0$ mass histogram.

[9]Since the $f^0(1260)$ meson can decay into $K_1{}^0K_1{}^0$ system, interference between the $I=0$ f^0 meson and the $I=1$ "A_2" meson is possible; however, this is unlikely since results from similar experiments at different energies do show a similar narrow $K_1{}^0K_1{}^0$ peak centered above 1.3 GeV. See, for example, S. U. Chung et al., Phys. Rev. Letters 12, 621 (1964); and Richard I. Hess, thesis, University of California Radiation Laboratory Report No. UCRL-16832, 1966 (unpublished).

[10]K. E. Lassila and P. V. Ruuskanen, Phys. Rev. Letters 19, 762 (1967); A Goldhaber, private communication.

[11]The triangle inequality is satisfied within statistics for the $A_2{}^H$ (1300-1330 MeV) produced in the reactions $\pi^-p\to K^-K_1{}^0p$ and $K_1{}^0K_1{}^0n$, and $\pi^+p\to K^+K_1{}^0p$ at 6 GeV/c.

[12]This is also observed in other similar experiments. See, for example, Gerson Goldhaber, in Proceedings of Thirteenth International Conference on High-Energy Physics, Berkeley, 1966 (University of California Press, Berkeley, Calif., 1967), p. 125. See also Richard I. Hess, Ref. 9. The author gave a mass and width of "$A_2{}^-$" $\to K^-K_1{}^0$ as 1317.2 ± 4.0 and 47 ± 18 MeV, and pointed out the difficulty to assign a consistent width between "$A_2{}^-$" $\to K^-K_1{}^0$ and "$A_2{}^-$" $\to \rho^0\pi^-$ from the same experiment. See S. U. Chung, thesis, University of California Radiation Laboratory Report No. UCRL-16881, 1966 (unpublished).

[13]$J^P=0^+$ assignment is ruled out by the observation of the $\rho\pi$ decay mode of the "conventional" A_2 meson.

STUDY OF $A_2{}^-$ in $\pi^-p\to\pi^-p\eta^0$ AT 5 BeV/c*

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(Received 25 March 1968)

We report a study of the reaction $\pi^-p\to\pi^-p\eta^0\to\pi^-p\pi^+\pi^-\pi^0$ at 5.0 BeV/c, which gives clear evidence for $A_2{}^-\to\eta^0\pi^-$. The observed branching ratio is $R=(A_2{}^-\to\eta^0\pi^-)/[A_2{}^-\to(\rho\pi)^-]=0.23\pm 0.08$, and the observed polarization of the A_2 is $2\rho_{11}\simeq 1, \rho_{1-1}=\rho_{-11}\simeq 0.5$. We also obtain evidence for $A_2{}^-\to X^0\pi^-$ with an observed branching ratio of $(A_2{}^-\to X^0\pi^-)/[A_2{}^-\to(\rho\pi)^-]=0.07\pm 0.03$.

The A_2 meson resonance at 1300 MeV is known to decay primarily by $\rho\pi$, $\eta\pi$, and $K\bar{K}$ modes.[1] The decay branching ratios are still uncertain, and the spin and parity determination rests primarily on the $K\bar{K}$ mode. Recently a structure in the A_2 has been reported,[2] indicating that the A_2 may be composed of two peaks. In our data with poorer statistics, we do not observe a splitting, and we therefore have treated all the data together.

A total of 172 η^0 events were observed in 55 000 four-prong events obtained in the 72-in. hydrogen bubble chamber at the Lawrence Radiation Laboratory. These events were selected from $\pi^-p\to\pi^-p\pi^+\pi^-\pi^0$ events chosen by the following criteria: (a) Each event had to be compatible kinematically ($\chi^2<10$ for the one-constraint hypothesis) and by ionization with the $\pi^-p\to\pi^-p\pi^+\pi^-\pi^0$ hypothesis. (b) Events which were also compatible with $\pi^-p\to\pi^-p\pi^+\pi^-$ ($\chi^2<40$ for the four-constraint fit) were rejected. (c) Events which were also compatible by ionization and kinematics with $\pi^- p \to \pi^-\pi^-\pi^+\pi^+ n$ were rejected if the neutron hypothesis gave a much better fit than the π^0 hypothesis.

The $\pi^+\pi^-\pi^0$ mass spectrum for the events thus selected shows a clear η^0 peak over a small background. The final sample of 172 accepted η^0 events was chosen by requiring the events to satisfy the kinematics of η^0 production and decay: Events with $\chi^2 < 15$ for the two-constraint fit were accepted. The criterion used is essentially equivalent to selecting events with an observed $\pi^+\pi^-\pi^0$ mass within 3 or 4 standard deviations of the η^0 mass.

We observe no significant structure in the $p\pi^-$ or $p\eta^0$ mass spectra (not shown) of these events. The $\eta^0\pi^-$ spectrum, Fig. 1(a), shows a clear peak at $M(\eta^0\pi^-) \simeq 1.3$ BeV; the position and width of this peak agree with those of the $A_2 \to \rho\pi$ resonance. With one exception,[3] the observed branching ratio agrees with that obtained in other recent experiments,[4] but is somewhat higher than previously reported.[5]

For the purpose of obtaining branching ratios we plot in Fig. 1(b) the $\rho^0\pi^-$, $\eta^0\pi^-$, and K^0K^- mass spectra[6] for events with a four-momentum transfer to the proton in the region 0.125-1.5 BeV^2. The lower cutoff is to remove the "Deck" background in the $\rho^0\pi^-$ channel; the upper cutoff is chosen so that in all our η^0 events the proton could be identified by ionization. In the $\rho^0\pi^-$ channel a further selection was made to eliminate any possible contamination with the $N^{*++}(1236)$; for all events we look in the 3π rest frame at the direction of the outgoing proton and select only

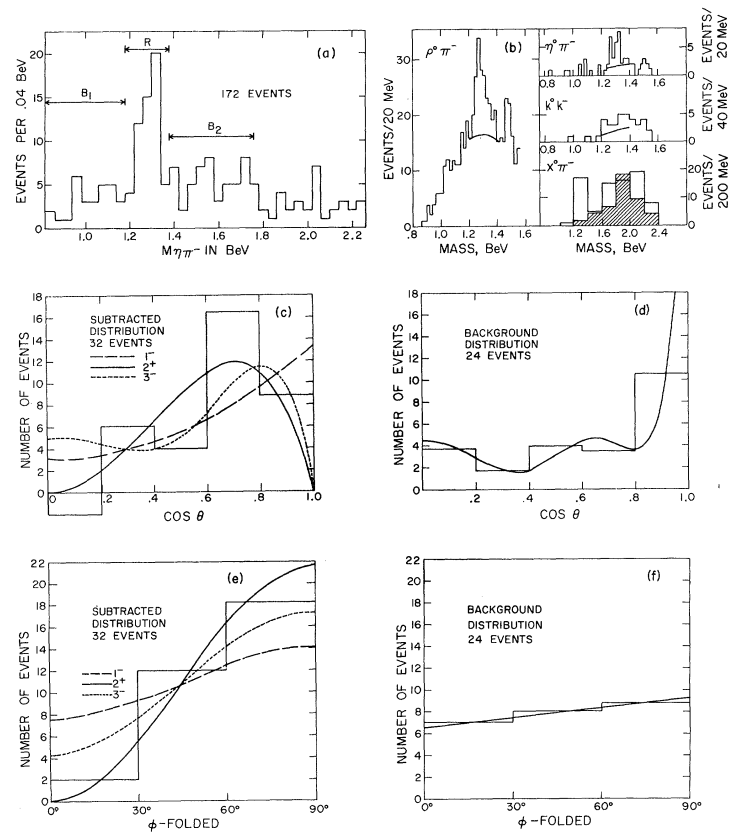

FIG. 1. (a) Distribution of $M(\eta^0\pi^-)$. B_1 and B_2 define control regions used for background subtractions and R defines the A_2 mass region. (b) Distribution of $M(\rho^0\pi^-)$, $M(\eta^0\pi^-)$, and $M(K^0K^-)$ for events with four-momentum transfer in the interval $0.125 \leq \Delta^2 \leq 1.5$. Solid curves give background levels used in computing branching ratios. The $M(X^0\pi^-)$ distributions have no selection on Δ^2 applied. (c), (d) Polar angular distributions for the $\eta^0\pi^-$ system after background subtraction and for the background used in the subtraction. Curves in (c) are for best fit to 1^-, $2^+, 3^-$ hypotheses; curve in (d) is fit with Legendre polynomials. (e), (f) Azimuthal angular distributions for the $\eta^0\pi^-$ system after background subtraction and for the background used in the subtraction. Curves in (e) represent best fit to $1^-, 2^+, 3^-$ hypotheses; straight line in (f) gives background dependence.

events in which the π^+ is emitted in the hemisphere opposite to the proton. This selection removes events with $M(p\pi^+) < 1.4$ BeV.

Figure 1(b) also shows data relevant to a possible $X^0\pi^-$ decay mode of the A_2. A search was made for evidence of $A_2 \to X^0\pi^-$ in the reaction

$$\pi^- p \to \pi^- p X^0, \quad X^0 \to \eta^0\pi^+\pi^-, \quad \eta^0 \to \text{neutrals}. \tag{1}$$

The method used to separate true X^0 events from background is rather less direct than we would have liked, because of the fact that the measurement errors on the "η^0" mass (mass of missing neutrals) and on the "X^0" mass (mass of missing neutrals $+\pi^+ + \pi^-$) increase rapidly with "X^0"π^- mass. We cannot therefore select samples from fixed-width mass bands. Figure 1(b) shows the "X^0"π^- mass distribution for two samples of events (no Δ^2 cut is applied): (a) Sample A (unshaded histogram) consists of events with observed masses within 1.5 standard deviations of the η^0 and X^0 masses. (b) Sample B (shaded histogram), the control sample, consists of events which fail to meet the criteria for sample A, but which have the observed masses within 2.0 standard deviations of the η^0 and X^0 masses. In the absence of any true X^0 production the ratio of events should be $B/A = (4^2-3^2)/3^2 = 49/63$. The observed ratios are 48/63 and 2/17, respectively, for the "X^0"π^- mass regions >1.4 BeV and 1.2-1.4 BeV. The most obvious interpretation is that there are practically no true X^0 events above the A_2 and perhaps 17-18 events in the A_2 region; the rapid increase in background above 1.6 BeV is due to the increase in measurement errors on "η^0" and "X^0" masses. We may suppose that the discrepancy between the number of events in the 1.2-1.4 and 1.4-1.6 bins is a statistical fluctuation; however, the probability of such a fluctuation is <1%.

We must hasten to remark that an estimate of non-X^0 events in the A_2 region based on the number of events in the B sample is not likely to be quite correct. Because of the proximity of the A_2 to the "X^0"π threshold we believe that the estimate of non-X^0 background obtained by comparing A and B events in Fig. 1(b) is low in the A_2 region. Our best estimate of the background is 2-5 events. Our estimate of the number of A_2 events in Reaction (1) is 14 ± 5 events.

Table I shows the number of observed events in each channel, the corrected number of events, and the calculated branching ratios. The subtraction for background was done in each case by use of the freely drawn background curves shown in Fig. 1(b). The errors shown include the statistical errors and the uncertainty in the background subtraction procedure. For the K^0K^- channel our data give no real evidence for a peak; hence the branching ratio given is at best an upper limit. The factors applied to the observed events to get the corrected numbers are as follows: (a) For $(\rho\pi)^-$, we multiply by 2 to account for the observed events being taken from one hemisphere only; we multiply by a factor of 1/0.84 to allow for events with ρ^0 mass outside the 0.665-0.865 BeV band; and finally we multiply by a factor of 2 to allow for the $\rho^-\pi^0$ mode which we do not observe. (b) For $\eta^0\pi^-$, we multiply by a factor of 1/0.25 to allow for the unobserved η^0 decay modes. (We have estimated the number of $\pi^+\pi^-\gamma$ which we have included in our sample and made a small correction for this.) (c) For K^0K^-, we correct for $K_L{}^0$ and $K^0 \to \pi^0\pi^0$, and include a (small) escape correction. (d) For $X^0\pi^-$, to get the corrected number of events we multiply by a factor of 3 to allow for unobserved decay modes of the X^0 and by a factor of 22/32 because no Δ^2 cut was made for this decay mode.

We now discuss briefly the four-momentum transfer distribution and the polarization of the $\eta^0\pi^-$ in the A_2 region. Referring to Fig. 1(a), we call R the A_2 region and use B_1 and B_2 as control regions. The total number of events in the A_2 re-

Table I. A_2^- branching ratios in $\pi^- p \to p A_2^-$ at 5.0 BeV/c.

Channel	Observed number of events	Corrected number of events	Ratio to $\rho\pi$
$(\rho\pi)^-$	82 ± 15.4	390 ± 73	1.0
$\eta^0\pi^-$	22 ± 6.1	88 ± 24	0.23 ± 0.08
K^0K^-	$11^{+7.0}_{-11.0}$	$35^{+22.5}_{-35.0}$	$0.09^{+0.06}_{-0.09}$
$X^0\pi^-$	14 ± 5	29 ± 10.3	0.07 ± 0.03[a]

[a]Previously reported data do not show clear evidence for this decay mode and hence only quote upper limits (Ref. 1).

Table II. χ^2's and density matrix elements for $A_2^- \to \eta^0\pi^-$ at 5.0 BeV/c.

J^P	ρ_{00}	$2\rho_{11}$	$2\rho_{22}$	$2\rho_{33}$	$2\rho_{1-1}$	$\chi_{\cos\theta}^2$	χ_φ^2
1^-	0.70 ± 0.10	0.30 ± 0.10	...	...	0.30 ± 0.10	11.0	3.6
2^+	0.00 ± 0.40	1.00 ± 0.40	0.00 ± 0.10	...	1.00 ± 0.10	5.7	0.2
3^-	0.00 ± 0.10	0.60 ± 0.14	0.40 ± 0.14	0.00	0.60 ± 0.12	9.6	1.2

gion is 56, with a background of 24 events estimated by interpolating linearly between B_1 and B_2. We find $(d\sigma/dt) \propto e^{At}$ with $A = 4.5 \pm 1.5$ (BeV)$^{-2}$ for the four-momentum transfer distribution after subtracting background. This is compatible with the distribution observed in the $A_2 \to \rho^0\pi^-$ channel.

Figures 1(c)-1(f) show the decay angular distributions in the $\eta^0\pi^-$ frame with the usual choice of axes ($\hat{z}$ along incident π^-, $\hat{y}$ along normal to production plane). The figures show the angular distribution of the background (average of regions B_1 and B_2) and of the resonance region after background subtraction. The subtracted distributions, before folding, had all the required symmetries for a pure angular momentum state. The following features are apparent: (1) The $\cos\theta$ distribution appears to vanish at $|\cos\theta| = 1$ and $\cos\theta = 0$. (This is much more apparent when a smaller bin size is used.) A $\sin^2\theta\cos^2\theta$ distribution fits the data well. (2) The φ distribution peaks at $|\varphi| = \frac{1}{2}\pi, \frac{3}{2}\pi$ and appears to vanish at $|\varphi| = 0, \pi$. A $\sin^2\varphi$ distribution fits the data well.

A decay distribution of the form $\sin^2\theta\cos^2\theta \times \sin^2\varphi$ is expected if $J^P = 2^+$ and if the polarization matrix is $2\rho_{11} = 1$, $2\rho_{1-1} = 1$. From a simple ρ-exchange diagram one expects $2\rho_{11} = 1$ and $2\rho_{1-1}$ nearly 1 for the production of a 2^+ meson. To determine the uniqueness of this interpetation of the data, we proceed to find for the three hypotheses ($J^P = 1^-, 2^+, 3^-$) the values of the (relevant) spin-density matrix of the $\eta^0\pi^-$ system which give the best fit to the data. The results obtained by minimizing the χ^2 (sum of χ^2 for $\cos\theta$ distribution and φ distribution) are shown in Table II; the curves corresponding to these fits are shown in Figs. 1(c) and 1(e). Clearly the 2^+ hypothesis fits the data better, but the evidence against 1^- and 3^- is not very strong; we note further that our decay distributions could certainly be fitted with 4^+ or higher spin hypotheses.

As a further test that the $\rho^0\pi^-$ and $\eta^0\pi^-$ peaks in our data come from the decay of a common 2^+ parent, we have looked at the decay distribution in the $\rho^0\pi^-$ channel. From the moments of the distribution of the normal to the (3π) decay plane we find $\rho_{00} = 0.15 \pm 0.20$; $2\rho_{11} = 0.84 \pm 0.22$; $2\rho_{22} = 0.01 \pm 0.36$, assuming $J^P = 2^+$.[3] These results are clearly compatible with our results for $\eta^0\pi^-$.

We gratefully acknowledge the cooperation and assistance of the Alvarez group of the Lawrence Radiation Laboratory, especially Dr. O. I. Dahl and Dr. J. Kirz, in the acquisition of the data for this experiment. We would like to thank Dr. J. C. H. Park for helpful discussions in the analysis of the $\eta^0\pi^-$ angular distributions. Finally, we would like to thank the members of our scanning-measuring staff; the members of our programming staff, especially G. T. Scharf; and the members of our engineering staff, especially R. W. Downing and V. J. Simaitis.

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*Research supported in part by the U. S. Atomic Energy Commission.

[1]A. H. Rosenfeld et al., Rev. Mod. Phys. 40, 77 (1968).

[2]G. Chikovani et al., Phys. Letters 25B, 44 (1967).

[3]R. A. Donald et al., Phys. Letters 26B, 327 (1968).

[4]A preliminary report on the branching ratio is given in Proceedings of the Heidelberg International Conference on Elementary Particles, Heidelberg, Germany, 1967 (North-Holland Publishing Company, Amsterdam, The Netherlands, to be published). Reports at the same conference by K. Böckmann et al. and by F. Conte et al. gave essentially identical results.

[5]S. U. Chung et al., Phys. Rev. Letters 18, 100 (1967); Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Letters 10, 248 (1964).

[6]We wish to thank C. Howard, T. R. Palfrey, R. J. Sahni, and P. J. Weisbach of Purdue University for their collaboration in obtaining the strange particle events.