Observation of Three Narrow Neutral Mesons in the Vicinity of 950 MeV*

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In a scintillation-counter experiment, we have observed two narrow, neutral mesons in addition to the well-established η'(958) in the reaction $\pi^-p \to M^0n$ at 2.4 GeV/c. We observe a mass of 940.5 ± 1.7 MeV, $\Gamma < 10.4$ MeV for the M^0(940), and a mass of 962.9 ± 1.7 MeV, $\Gamma < 5.9$ MeV for the δ^0.

In an experiment at the Argonne zero-gradient synchrotron we have observed neutrons and charged particles from the reaction $\pi^-p \to$ anything $+n$. Measurement of the neutron time of flight established the missing mass of the particles recoiling against the neutron, and a peak in the time-of-flight spectrum indicated neutral nonstrange-meson production in the two-body process $\pi^-p \to M^0n$.

Figure 1 shows the plan view of our apparatus. Neutrons produced in the 25-cm-long liquid-hydrogen target were observed at a distance of 8.5 m from the target by an array of twenty plastic scintillators. Each scintillator had a detection efficiency[1] between 15 and 19% for neutrons of 15–300 MeV. Neutron velocities in the region $\beta = 0.15$ to 0.65 were accepted. These slow neutrons correspond, in the case of two-body processes, to forward meson production. The signature of an event was $HS_1S_2S_3\bar{A}_1\bar{A}_2\bar{S}_4(\overline{NA})N$, where H and S_1 were scintillation counters at the first focus of the beam. H was a seven-element hodoscope which measured the momentum of each beam particle to ± 0.29%. The counters A_1 and A_2 were used to veto interactions in S_2 and S_3. Counter S_4 subtended a maximum angle of 1.3° from the hydrogen. NA was an array of scintillators in front of the neutron counters. N denotes a neutron signal in the acceptable time interval. To summarize, an event consisted of a beam particle into the hydrogen, no charged particle out within ~1.3° of the beam line, and a neutron with an acceptable time of flight. Information from scintillators surrounding the hydrogen target was used only in the data analysis. These scintillators consisted of an array of sixteen arranged to form a cylinder coaxial with the beam, an array of sixteen ("front" array) which formed an 8×8 two-dimensional grid at the downstream end of the cylindrical array, two scintillators at the upstream end, and a 0.8-mm-thick scintillator in the beam at the center of the "front" array. There were also three γ-ray detectors, one consisting of the neutron counters themselves, the other two being simple lead-scintillator sandwiches which subtended a total laboratory solid angle of 1.22 sr.

The neutron time of flight and one bit for each scintillation counter were stored on paper or magnetic tape for later analysis. The ratio of the target-empty event rate to the target-full event rate depended somewhat on the charge multiplic-

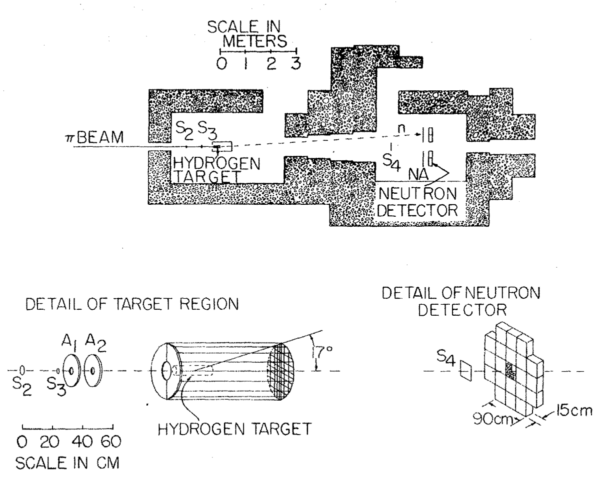

FIG. 1. Plan view of the apparatus.

ity of the final state, but for the two-charge final states was − 3.7%. At 2.4 GeV/c, 1.8×10^6 events were accumulated in four days of accelerator time. At a mass of 950 MeV, the range in laboratory angles for the detected neutrons ($1.0^\circ \lesssim \theta_{lab} \lesssim 5.3^\circ$) corresponded to the interval in the square of the four-momentum transfer (t) of $0.00002 \lesssim |t - t_{min}| \lesssim 0.0006$ (GeV/c)^2.

The absolute uncertainties in the time-of-flight measurements and the beam momentum are estimated to be ± 0.3 nsec and ± 0.4%, respectively. These effects correspond to mass uncertainties of ± 1.0 MeV and ± 2.0 MeV at a mass of 950 MeV. The mass resolution depended on the time resolution of the twenty neutron counters [1.27 nsec full width at half-maximum (FWHM)], the momentum resolution of a single hodoscope element (0.68% FWHM), and the lengths of the target and the neutron counters. At 950 MeV, these effects give contributions of 4.1, 3.4, and 6.8 MeV, respectively, to yield a total mass resolution of 8.6 MeV (FWHM).

We have been able to separate to a degree the pure two-charge (plus neutron) events from the two-charge-plus-neutrals (plus neutron) events. One way of doing this was to use the information from the γ detectors. Another way was to use the measured azimuthal angles of the charged particles. Since the missing mass is produced at a laboratory angle of less than 1°, a pure two-body decay gives two particles whose difference in azimuthal angles is 180°. However, for a three-body decay this difference will be distributed from 0 to 180°. A Monte Carlo simulation of our apparatus shows that a pure two-particle missing mass gives events in which the measured difference of their azimuthal angles is in the interval 147–180°.

In Fig. 2(a), the total uncut mass distribution obtained at 2.4 GeV/c is shown. The overall shape of this spectrum can be explained qualitatively by the form of our c.m. solid-angle acceptance as a function of missing mass. The fact that this spectrum is relatively smooth is evidence that there were no sizable systematic biases such as rf structure or neutron backscattering from the shielding capable of generating narrow bumps. In general, systematic biases in the mass spectra would be expected to be relatively independent of the final-state topology. A Monte Carlo simulation of our experiment shows that kinematic reflections of N^* resonances do not produce narrow enhancements in our mass spectra.

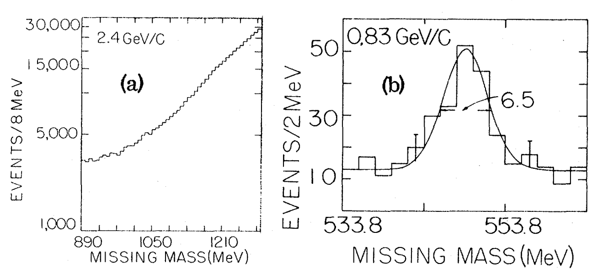

FIG. 2. (a) Total uncut mass spectrum for $\pi^- p \to$ (missing mass) + neutron at 2.4 GeV/c. (b) η signal. Mass spectrum for $\pi^- p \to$ (all neutrals) + neutron at 0.83 GeV/c. The curve is a least-squares fit to the data.

As a check of the system, we have observed the η^0 meson at an incident momentum of 0.83 GeV/c and the ρ^0 and ω^0 mesons at 1.5 GeV/c. Figure 2(b) shows the data in the η^0 mass region taken at 0.83 GeV/c. We observe a mass of[2] 548.8 (± 0.4, ± 1.3) MeV for the η, a value which agrees with the world average of 548.8 ± 0.6 MeV.[3] We measure the differential cross section at $\approx 0^\circ$ for $\pi^- p \to \eta^0 n$ to be 8.3 ± 2.1 mb/(GeV/c)^2, in agreement with published data.[4]

The well-established[3] $\eta'(958)$ which has been observed previously in π-N reactions[5] is evident at 2.4 GeV/c as seen in Fig. 3(a). The unshaded histogram includes events with four charged particles, all with $\theta_{lab} \lesssim 17^\circ$, events with two charged particles with $3^\circ \lesssim \theta_{lab} \lesssim 17^\circ$, and events with no charged particles for which at least one γ ray was detected. These cuts[6,7] were motivated by the known branching ratios of η'. The two-charge sample is shown in the shaded histogram. The mass and observed width[8] of the η' determined from these data are 957.2 (± 0.9, ± 2.2) and 8.1 ± 1.8 MeV. The observed signals in the neutral, two-charge, and four-charge spectra are consistent with the branching ratios of the η'.

Figure 3(b) displays events which have two charged particles in the final state, one with $3^\circ \lesssim \theta_{lab} \lesssim 17^\circ$ and the other with $17^\circ \lesssim \theta_{lab} \lesssim 130^\circ$.[6] This sample contains 62% of all our two-charge events. There are two enhancements, one at ~ 940 MeV and the second at ~ 964 MeV. The statistical significance of these effects are 4.6σ and 5.1σ, respectively, above a quadratic fit which excluded the regions 934–946 MeV and 958–970 MeV and had a confidence level of 25%. There are 187 ± 43 and 215 ± 44 events, respectively, in these enhancements. A quadratic fit over the interval 910–1002 MeV including the regions of the enhancements has a confidence level of 0.03%.

Figure 3(c) contains events of Fig. 3(b) which cannot be pure two-charge decays of the missing

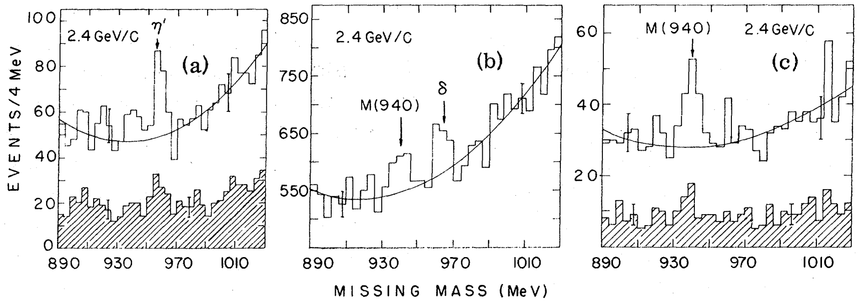

FIG. 3. 2.4-GeV/c mass spectra. (a) η' signals. Shaded region corresponds to events with two charged particles both having $3°\lesssim\theta_{lab}\lesssim 17°$. The unshaded spectrum contains the shaded sample plus those events with four charged particles all having $\theta_{lab}\lesssim 17°$, and those events with no charged particles but at least one detected γ ray. (b) $M^0(940)$ and δ^0 signals. These events have two charged particles, one with $3°\lesssim\theta_{lab}\lesssim 17°$ and the other with $17°\lesssim\theta_{lab}\lesssim 130°$. (c) $M^0(940)$ in selected subsets of (b) which cannot be populated by pure two-charge final states. The shaded region contains events where the difference in azimuthal angles of the two charges is between 147° and 180° and a γ ray is detected in the neutron counters. The unshaded sample contains the shaded sample plus events where the difference in azimuthal angles of the two charges is between 0 and 33°. In (a), (b), and (c) the curves are quadratic fits to the background.

mass. The shaded spectrum of Fig. 3(c) corresponds to those events of Fig. 3(b) for which the difference in azimuthal angles of the two charges is in the interval 147–180° and, in addition, a γ ray was detected in the neutron counters. The unshaded spectrum of Fig. 3(c) is the sum of this sample plus those events of Fig. 3(b) for which the difference in the azimuthal angles lies in the interval 0–33°. The enhancement in the interval 934–946 MeV has a significance of 5.9σ above a quadratic background. There are 55 ± 12 events in this enhancement. These data indicate the existence of a meson, the $M^0(940)$, with a mass of[8] 940.2 (± 1.3, ± 2.2) MeV and an observed width of 10.7 ± 2.1 MeV (FWHM). From the examination of the other charge topologies at 940 MeV, we estimate the branching fractions of the $M^0(940)$ to the neutral, two-charge, and four-charge final states to be 0.12 ± 0.11, 0.86 ± 0.17, and 0.02 ± 0.15.[9]

The data of Fig. 3(c), which rather conclusively establish the $M^0(940)$, justify our procedure of excluding the interval 934-946 MeV in the fit of Fig. 3(b) which was used to evaluate the significance of the enhancement at 964 MeV. This latter effect, which we call the δ^0, has a mass of 962.0 (± 1.1, ± 2.2) MeV and an observed width of 8.3 ± 1.7 MeV (FWHM). We estimate the branching fractions of the δ^0 to the neutral, two-charge, and four-charge final states to be 0.10 ± 0.10, 0.82 ± 0.15, and 0.08 ± 0.14.[9]

The observed mass difference between the δ^0 and η' enhancements is 4.75 ± 1.40 MeV. The hypothesis that these mass values are equal has a confidence level of 7×10^{-4}.

To obtain a final mass value for the δ^0, we have subtracted from the data of Fig. 3(b) an estimated contamination of 41 ± 29 events due primarily to the $\pi^+\pi^-\gamma$ decay of the η'.[7] Using these corrected data, we obtain a mass of 962.6 (± 1.2, ± 2.2) MeV and a width of 8.4 ± 1.7 MeV.[3] The systematic uncertainty in the mass values of the $M^0(940)$ and the δ^0 can be reduced by using the world average for the η' mass of 957.5 ± 0.8 MeV. With our observed differences in mass of 17.0 ± 1.5 MeV between the η' and the $M^0(940)$, and 5.4 ± 1.4 MeV between the η' and the δ^0, we obtain final mass values and total uncertainties of 940.5 ± 1.7 and 962.9 ± 1.7 MeV for the $M^0(940)$ and the δ^0. The mean observed width for the $M^0(940)$, η', and δ is 8.8 ± 1.1 MeV, in agreement with our calculated resolution of 8.6 MeV. Using the calculated resolution with its estimated error of ± 5%, the physical widths of the $M^0(940)$, η', and δ^0 are determined to be < 10.4, < 5.7, and < 5.9 MeV (90% confidence).

The observed differential cross sections for two-body production of the $M^0(940)$, η', and δ^0 at $t=t_{min}$ are 0.52, 0.30, and 0.49 mb/(GeV/c)^2, with an overall uncertainty of ± 30%. From Ref. 5 we estimate the cross section at $t=t_{min}$ for the η' at 2.4 GeV/c to be 0.4 ± 0.2 mb/(GeV/c)^2, in agreement with our observed value.

The reports of mesons[3] in the region of 950–1000 MeV can be categorized as follows: $\eta\pi^\pm$ enhancements, $\pi^+\pi^-\pi^0$ enhancements (H meson), missing-mass searches for charged mesons, and the $M^0(953)$.[10,11] Neither the $M^0(940)$ nor the δ^0

reported here is predominantly an $\eta\pi^0$ effect.[12] An $\eta\pi^0$ final state would have 72% of its signal in the neutral spectrum, yet we observe only 27 ± 16 and 27 ± 16 events above background in the neutral spectrum for the $M^0(940)$ and the δ^0, while we would expect 481 ± 111 and 553 ± 113, respectively, based on the observed enhancements in the two-charge spectrum.

Regarding $\pi^+\pi^-\pi^0$ effects, we note that at least part of the $M^0(940)$ enhancement involves two charged particles and at least one neutral and is consistent with $\pi^+\pi^-\pi^0$ or $\pi^+\pi^-\gamma$ final states.[13]

The original CERN missing-mass experiment[14] reported a mass and width of 962 ± 5 MeV and $\Gamma \lesssim 5$ MeV for an enhancement referred to as the δ^-. We suggest that the δ^0 observed in the present experiment is the neutral member of an isotopic multiplet of which the δ^- is the singly charged negative member.[15]

We have observed three distinct mesons, namely, the well-known $\eta'(958)$ and the previously unobserved δ^0 and $M^0(940)$. Both the δ^0 and the $M^0(940)$ appear predominantly in final states that have two charged particles, and a substantial fraction of the $M^0(940)$ appears in a final state which has two charged particles and at least one neutral particle. Neither of these mesons decays predominantly to $\eta\pi^0$. We associate the δ^0 reported here with the $I \geq 1$ δ^- effect observed previously.[14]

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[1]The efficiency of similar neutron counters has been measured by C. Wiegand *et al.*, Rev. Sci. Instrum. 33, 526 (1962). See also R. Kurz, UCRL Report No. UCRL-11339 (unpublished).

[2]When two errors are given, the first is statistical and the second is systematic.

[3]A. Rittenberg *et al.*, Rev. Mod. Phys. 43, S1 (1971).

[4]W. B. Richards *et al.*, Phys. Rev. D 1, 10 (1970); E. Hyman *et al.*, Phys Rev. 165, 1437 (1968).

[5]See, for example, R. K. Rader, UCRL Report No. UCRL-19431, 1969 (unpublished).

[6]The angle cuts reflect our counter geometry. The intersection of the front array and the cylindrical array corresponds to an angle of 17° with respect to the center of the hydrogen target. The upstream end of the cylindrical array corresponds to an angle of 130°.

[7]The two-charge and four-charge events of Fig. 3(a) presumably correspond to the $\eta\pi\pi$ decay of the η'. This final state preferentially populates those spectra for which θ_{lab} is small because of the low Q of the decay.

[8]To minimize binning effects, all masses and widths at 2.4 GeV/c were determined from data in 1-MeV bins.

[9]We have arbitrarily increased the statistical errors on the branching ratios by 50% to account for systematic effects.

[10]M. Aguilar-Benitez *et al.*, Phys. Rev. Lett. 25, 1635 (1970).

[11]B. Maglich *et al.*, Phys. Rev. Lett. 27, 1479 (1971).

[12]The neutral member of an isospin multiplet whose charged member decays predominantly via $\eta\pi^\pm$ need not decay predominantly via $\eta\pi^0$. For example, if the $\eta\pi^\pm$ decay is electromagnetic, then $\eta\pi^0$ decay may be forbidden by C conservation.

[13]In a good mass-resolution experiment B. D. Hyam *et al.*, Nucl. Phys. B7, 1 (1968), observed a 4.5σ enhancement at 946 ± MeV, $\Gamma < 15$ MeV.

[14]W. Kienzle *et al.*, Phys. Lett. 19, 438 (1965).

[15]The masses of the δ^- and δ^0 may differ by a small amount because of electromagnetic effects.

Search for the Decay $K^+ \to \pi^+\gamma\gamma$†

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A search has been made for the rare decay mode $K^+ \to \pi^+\gamma\gamma$ using a heavy-liquid bubble chamber. No events were found. A test was made of the Fujii model which uses an off-mass-shell extrapolation of the $K_{\pi 2}$ amplitude to make predictions for this decay. The experimental upper limit on the branching ratio is reported to be 2.2×10^{-5}, and this result is consistent with the Fujii model. This result is inconsistent with the branching ratio predicted by the Fujii model.

This paper presents the relevant details and the results of an experimental bubble-chamber search for the decay $K^+ \to \pi^+\gamma\gamma$. This experiment is the first one to search for this decay in the lower end of the pion spectrum. This region is important as several theoretical models of the decay have predicted that the majority of these decays will have pions with a kinetic energy below 60 MeV.

The decay $K^+ \to \pi^+\gamma\gamma$ is expected to exist as a