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Evidence for a Neutral Meson Near 1033 MeV[†]

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In a scintillation counter experiment studying the reaction $\pi^- p \rightarrow M^0 n$ at 2.4 GeV/c, we have obtained evidence for a neutral meson denoted $M^0(1033)$ with a mass of 1032.6 ± 2.3 MeV and a width of $16.2 \pm \begin{smallmatrix} 4.8 \\ 7.5 \end{smallmatrix}$ MeV.

In a scintillation counter experiment at the Argonne Zero Gradient Synchrotron we have observed neutrons and charged particles from the reaction: $\pi^- p \rightarrow \text{anything} + n$. The apparatus has been described previously.¹⁻³ A pion beam incident on a liquid hydrogen target produced neutrons which were detected in the near forward direction by an array of 20 plastic scintillators. In the case of meson plus neutron final states, the events correspond to forward meson production. At a mass of 1033 MeV the range in four-momentum transfer squared (t) between

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the incident pion and the missing mass for the accepted events is $0.00005 \lesssim |t - t_{\min}| \lesssim 0.0010 \text{ (GeV/c)}^2$. The effective mass of the particles produced with the neutron is determined primarily by the measurement of the velocity of the recoiling neutron. Information from the charged particle detector surrounding the hydrogen target is used only in the data analysis to subdivide the missing mass spectrum into categories corresponding to various topologies of the final state. The charged particle detector consisted of an array of 16 scintillators arranged to form a cylinder coaxial with the beam, an array of 17 scintillators ("front array") at the downstream end of the cylindrical array and two scintillators at the upstream end of the cylindrical array.

At 2.4 GeV/c events were accumulated spanning the mass range 900 to 1300 MeV. Previous reports¹⁻³ dealing with these data have described effects near 950 and 1150 MeV. This paper presents evidence for a neutral meson at 1033 MeV which we are unable to associate convincingly with any established meson state. We find no additional effects in our 2.4 GeV/c data with a statistical significance greater than 5 standard deviations which cannot be associated with established meson states.

The absolute uncertainties in the time of flight measurements and the beam momentum correspond to a total mass uncertainty of ± 2.5 MeV at a mass of 1033 MeV. The mass resolution at 1033 MeV is 9.4 MeV (FWHM).

The data we discuss in this report consist primarily of events which have two charged particles in the final state. As discussed in Ref. 2 and 3, the measurements of the azimuthal angles of the charged particles by the charged particle detector are particularly useful for

events with two charged particles, and cuts on the difference of the azimuthal angles do not produce mass-dependent biases.

We now discuss our measurements of the polar angles of the charged particles and the biases produced in mass spectra by cuts on these quantities. Figure 1(a) is a scale drawing of the front array. The assembly consists of a crossed array of 8 scintillators by 8 scintillators plus a square 0.8 mm thick scintillator centered on the beam line. The apparatus allows us to categorize events into approximately six different polar angle bins. The spectrum which provides the strongest evidence for a meson at ~ 1033 MeV contains those 2 charge events which have one charge strike the shaded region of the front array shown in Fig. 1(a) and the second hit anywhere in the front array. Figure 1(b) shows the results of a monte carlo calculation of the polar angle acceptance of the shaded region of Fig. 1(a). Unlike restrictions on azimuthal angles, cuts on the polar angles of the charged particles recoiling against the neutron do generate mass dependent biases. To examine this effect quantitatively, we have calculated with a monte carlo program the probability for various final states to produce one charged particle which strikes the cross-hatched region of Fig. 1(a) and a second particle which hits anywhere in the front array. In all cases, the decay products of the missing mass were assumed to be distributed according to phase space. The results of these calculations are displayed in Fig. 1(c). These results indicate that in general the acceptance does not generate enhancements except in the case of the K^+K^-n final state where structure greater than 100 MeV in width is induced. In addition one sees that

the acceptance for the described cuts increases substantially with the number of pions in the final state.

Figures 2(a) and 2(b) show the actual data corresponding to the selection described above, i.e. two charged particles in the front array with at least one in the shaded region. The events in Fig. 2(a) fall naturally into two subsets. The first has events with one charged particle in the central counter. The second consists of events where the central counter does not fire, and four counters in the front array locate the two charged particles. For this second subset where azimuthal information is available, we have selected those events for which the difference in azimuthal angles is between 79° and 180° . One observes in Fig. 2(a) an enhancement near 1033 MeV containing 63 ± 13 events above a third order polynomial curve. The curve fits the spectrum from 854 to 1206 MeV excluding the region 1018 to 1042 MeV with a confidence level of 97%. The statistical significance of the effect above this background is 5.9σ .⁴ These data indicate the existence of a meson which we designate⁵ the $M^0(1033)$ with a mass of $1030.9 (\pm 2.9, \pm 2.5) \text{ MeV}$ ⁶ and an observed width of $20.2 \pm 8.6 \text{ MeV}$ (FWHM).⁷

Figure 2(b) contains those 2 charge events which have the same polar angle restrictions as Fig. 2(a), but for which the azimuthal angular difference is in the range $0-79^\circ$. This complementary set of data shows no enhancement at 1033 MeV.

Figure 2(c) corresponds to two charge events which have one charge in the cylindrical array ($17^\circ \lesssim \theta_{lab} \lesssim 130^\circ$) and one in the outer 2/3 of

the front array ($6.5^\circ \lesssim \theta_{lab} \lesssim 17^\circ$). In addition, the azimuthal angles of the two charges differ by $169-180^\circ$. This azimuthal region which corresponds to two charged particles coplanar with the beam is heavily populated by the $\pi^+\pi^-n$ final state. The enhancement in the interval 1022-1042 MeV has a significance of 5.2σ above the second order polynomial curve.⁸ The curve fits the spectrum from 934-1134 MeV excluding the region 1022-1042 MeV with a confidence level of 58%. There are 174 ± 36 events in this enhancement. The mass and observed width of the $M^0(1033)$ determined from these data are $1034.3 (\pm 2.3, \pm 2.5) \text{ MeV}$ ⁶ and $18.3 \pm 4.9 \text{ MeV}$ respectively.⁷ We note that the data of Figs. 2(a) and 2(c) are independent samples.

The mass values as determined from the data of Figs. 2(a) and 2(c) differ by $3.4 \pm 3.7 \text{ MeV}$ and hence are consistent. The weighted average of the two mass values is $1032.7 (\pm 1.8, \pm 2.5) \text{ MeV}$. The systematic uncertainty in the mass may be reduced by comparing our mass value¹ for the η' and the world average of $957.1 \pm 0.6 \text{ MeV}$. This yields a final value for the mass of the $M^0(1033)$ of $1032.6 \pm 2.3 \text{ MeV}$. The observed widths determined from the data of Figs. 2(a) and 2(c) are also consistent. Using the larger of the asymmetric statistical errors in each case, the weighted average for the observed width is $18.7 \pm 4.3 \text{ MeV}$. Using the calculated resolution of 9.4 MeV (FWHM) with its estimated error of $\pm 5\%$, the physical width of $M^0(1033)$ is estimated to be $16.2 \pm 4.8 \text{ MeV}$.

The sum of the events in the enhancements of Figs. 2(a) and 2(c), 237 ± 38 events, yields a differential cross section for the two body process $\pi^-p \rightarrow M^0(1033)n$ of $d\sigma/dt (t \approx t_{min}) = 0.29 \pm 0.09 \text{ mb}/(\text{GeV}/c)^2$.

We find no statistically significant evidence for the $M^0(1033)$ in other two charge categories. In the overall neutral and four charge spectra there are 20 ± 25 and 9 ± 36 events respectively above background in the interval 1022 to 1042 MeV.

It is difficult in the present experiment to determine the particular final states which are contributing to the $M^0(1033)$. For example, while it is kinematically most favorable for the $\pi^+\pi^-n$ final state to populate 2 charge samples which have their azimuthal difference in the range $169-180^\circ$, the enhancement in Fig. 2(c) in fact may be due to final states with one or more neutral pions. Monte Carlo results show that the enhancement of Fig. 2(a) can not be associated with either a $\pi^+\pi^-n$ or K^+K^-n final state because of the polar angle restrictions. These results suggest that the enhancements of Figs. 2(a) and 2(c) may be due to two distinct decay modes of the $M^0(1033)$.⁹

Previous reports¹⁰ of mesons in the mass region 1000-1100 MeV can be categorized briefly as follows: the well-established $\phi(1019)$, the $\pi_N(1016)$ which is a charged KK effect, the $S^{**}(1070)$ which has been reported principally in the $K_S K_S$ channel, the $T_N(1080)$ which is a $\pi\pi$ effect and which may be related to the S^{**} , and the $A_1(1070)$ which is a 3π effect.

Monte Carlo calculations indicate that the 1033 MeV region of Figs. 2(a), 2(b), and 2(c) cannot be significantly populated by a K^+K^-n final state. To study the K^+K^-n channel near threshold, we have examined the spectrum containing events which have 2 charged particles both with $\theta_{lab} \gtrsim 11.5^\circ$ and for which the azimuthal angles differ by

147-180°. Since near K^+K^- threshold the K^+ and K^- make small angles with respect to the beam the acceptance of these cuts for the K^+K^- channel is large. For the $\pi^+\pi^-n$ channel the acceptance is zero due to the large Q value of the $\pi\pi$ system and consequent large opening angle of the pions. The spectrum with these restrictive cuts shows an excess of events centered near 1060 MeV consistent with the calculated acceptance for the K^+K^-n channel and published $K\bar{K}$ spectra. In the 1033 MeV region, we calculate that at least 41% of K^+K^- events would satisfy these cuts assuming that the spin of the K^+K^- system is less than 3. In the interval 1022-1042 MeV, we observe only 2.0 ± 3.7 events above a background of ~ 4 events/8 MeV. Hence, we find no evidence for a K^+K^- decay of the $M^0(1033)$ and we cannot associate the $M^0(1033)$ with the previously reported $\pi_N(1016)$ or the S^* . In addition, since the difference between the world average for the mass of the $\phi(1019)$ of 1019.5 ± 0.6 MeV and the mass of the $M^0(1033)$ is 13.1 ± 2.4 MeV, the $M^0(1033)$ is distinct from the $\phi(1019)$ on the basis of mass as well as decay modes.

Reference 10 gives 1083 ± 10 MeV and 98 ± 13 MeV for the average values of the mass and width of the $\eta_\pi(1080)$. These values are inconsistent with those of the $M^0(1033)$ reported here. Likewise, most 3π enhancements reported in the literature in this mass region have a higher mass and/or a larger width than the $M^0(1033)$. However, there is one report of a $(\rho\pi)^0$ enhancement at a mass of ~ 1040 MeV with a width $\Gamma \lesssim 50$ MeV.¹¹

We have presented evidence for a neutral non-strange meson, the $M^0(1033)$, which we have been unable to associate convincingly with any established meson state.

Footnotes and References

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Meson Spectroscopy.
4. Using the method of likelihood ratios¹² a fit to a third order
polynomial plus gaussian form is found to be 6×10^5 times more
probable than a simple third order polynomial fit, when both fits are
over the entire interval 854-1206 MeV.
5. We have followed the practice, common in baryon spectroscopy, of
designating enhancements by a generic label and a mass value in
parenthesis. For non-strange mesons we have used the generic
label M.
6. When two errors are given, the first is statistical and the second
is systematic.

7. To minimize binning effects, the mass and width were determined from data in 1 MeV bins. Resonance parameters were obtained using a gaussian form and a polynomial background.
8. Using the method of likelihood ratios¹² a fit of a quadratic plus gaussian form is found to be 1.2×10^4 times more probable than a simple quadratic fit.
9. For example, if the quantum numbers of the $M^0(1033)$ are the same as those of the pion, the enhancements of Figs. 2(a) and 2(c) may correspond principally to an $\pi\pi^+\pi^-\pi^0$ and a $\pi^+\pi^-\pi^0$ decay, respectively.
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Figure Captions

Fig. 1. (a) Scintillator layout in the front array. (b) Laboratory polar angle acceptance for the region of the front array shown shaded in (a). (c) Shows for various 2 charge final states, the fraction of monte carlo events which have both charges strike the front array with at least one in the region shaded in (a).

Fig. 2. (a) Mass spectrum for 2 charge events which have the charged particle with the larger polar angle strike the shaded region of the front array shown in Fig. 1(a). The difference of the azimuthal angles is restricted to the range $79-180^\circ$. (b) Mass spectrum for data with the same restrictions as the sample in 3(a) except that the difference of the azimuthal angles is restricted to the range $0-79^\circ$. (c) Mass spectrum for 2 charge events in which one charge struck the cylindrical array ($17^\circ \lesssim \Theta_{lab} \lesssim 130^\circ$) and the other struck the outer 2/3 of the front array ($6.5^\circ \lesssim \Theta_{lab} \lesssim 17^\circ$). In addition, the difference of the azimuthal angles is restricted to the range $169-180^\circ$.