tion of relativistic particles with any spin. This description preserves the consistent and causal nature of the wave equation while avoiding the difficulties of the parity-doubled theory when second quantized. In the present report we have attempted to present only the essential features of this approach. A more detailed and extended discussion will appear elsewhere.[6]

The author is grateful to Professor F. Rohrlich and Professor J. Weinberg for numerous conversations. He wishes also to thank Professor Rohrlich for his critical reading of the manuscript.

*Work supported by the National Science Foundation.

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Evidence for a Neutral Meson near 1033 MeV*

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(Received 23 August 1972)

In a scintillation-counter experiment on the reaction $\pi^- + p \to M^0 + n$ 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 $16.2^{+4.8}_{-7.5}$ MeV.

In a scintillation counter experiment at the Argonne zero-gradient synchrotron we have observed neutrons and charged particles from the reaction $\pi^- + p \to \text{anything} + n$. The apparatus has been described previously.[1-3] A pion beam incident on a liquid-hydrogen target produced neutrons which were detected in the nearly forward direction by an array of twenty 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 the incident pion and the missing mass for the accepted events is $0.000\,05 \lesssim |t - t_{\min}| \lesssim 0.0010$ (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 sixteen scintillators arranged to form a cylinder coaxial with the beam, an array of seventeen scintillators ("front array") at the downstream end of the cylindrical array, and two scintillators at the tupstream end of the cylindrical array.

At 2.4 GeV/c events were accumulated spanning the mass range 900 to 1300 MeV. Previous reports[1-3] 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 [full width at half-maximum (FWHM)].

A meson with a particular set of quantum numbers and production amplitudes will, in general, decay with some characteristic topology in the laboratory. This is especially true for our apparatus which restricts the production angle of the meson to near 0 deg. Hence, we examine a limited number of mass spectra containing events for which the detector information indicates decay topologies that make physical sense to us.

The data we discuss in this report consist primarily of events which have two charged particles in the final state. As discussed in Refs. 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 eight scintillators by eight scintillators plus a square central counter 0.8 mm thick 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 two-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

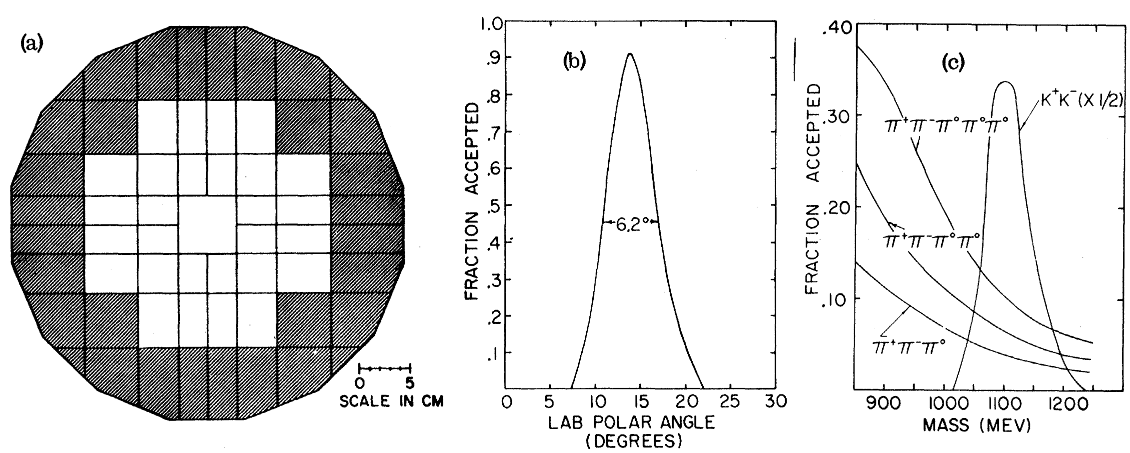

FIG. 1. (a) Scintillator layout in the front array. (b) Laboratory polar-angle acceptance for the region of the front array shown shaded in (a). (c) For various two-charge final states, the fraction of Monte Carlo events which have both charges strike the front array with at least one in the region shaded in (a).

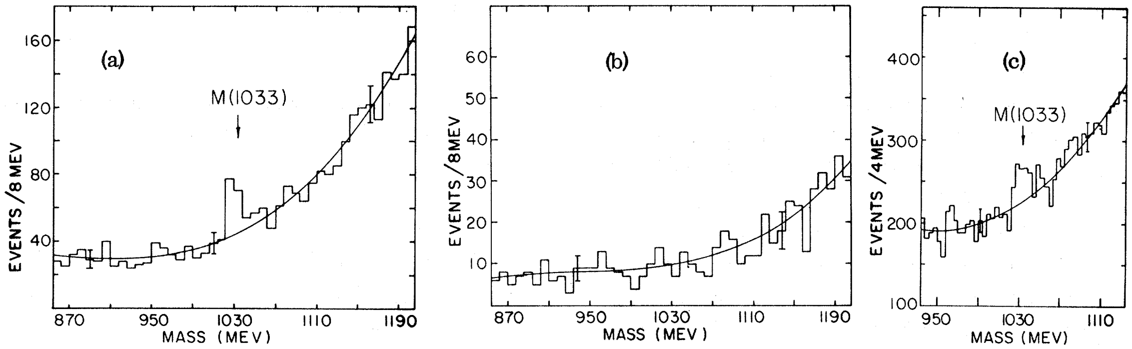

FIG. 2. (a) Mass spectrum for two-charge events which have the charged particle with the larger polar angle strike the shaded region of the front array shown in Fig. 1(a). The difference of the azimuthal angles is restricted to the range 79°–180°. (b) Mass spectrum for data with the same restrictions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

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 two pairs of crossed 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 designate[5] the $M^0(1033)$ with a mass of 1030.9 ($^{+2.9}_{-2.3}$, ± 2.5) MeV[6] and an observed width of $20.2^{+2.9}_{-5.8}$ MeV (FWHM).[7]

Figure 2(b) contains those two-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°. 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 ($17° \lesssim \theta_{1ab} \lesssim 130°$) and one in the outer $\frac{2}{3}$ of the front array ($6.5° \lesssim \theta_{1ab} \lesssim 17°$). In addition, the azimuthal angles of the two charges differ by 169°–180°. 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 to 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 ($^{+2.3}_{-2.4}$, ± 2.5) MeV[6] and $18.3^{+4.9}_{-4.6}$ 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 ± 3.7 MeV and hence are consistent. The weighted average of the two mass values is 1032.7 (± 1.8, ± 2.5) MeV. The systematic uncertainty in the mass may be reduced by comparing our mass value[1] for the η' and the world average of 957.1 ± 0.6 MeV. This yields a final value for the mass of the $M^0(1033)$ of 1032 ± 2.3 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 ± 4.3 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 $16.2^{+4.8}_{-7.5}$ 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 $\pi^- + p \to M^0(1033) + n$ of $(d\sigma/dt)_{t \cong t_{\min}} = 0.29 \pm 0.09$ mb $(\mathrm{GeV}/c)^{-2}$. 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 two-charge samples which have their azimuthal difference in the range 169° −180°, 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) cannot 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 reports[10] of mesons in the mass region 1000−1100 MeV can be categorized briefly as follows: the well-established $\varphi(1019)$, 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 $\eta_N(1080)$ 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 two charged particles both with $\theta_{\mathrm{lab}} \lesssim 11.5°$ 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 0 because of 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 $\varphi(1019)$ 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 $\varphi(1019)$ 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 on 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.

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

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[1]We measured the η' mass to be 957.2 (±0.9, ±2.2). D. L. Cheshire, R. W. Jacobel, R. C. Lamb, F. C. Peterson, E. W. Hoffman, and A. F. Garfinkel, Phys. Rev. Lett. 28, 520 (1972).

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[4]Using the method of likelihood ratios [J. C. Orear, UCRL Report No. UCRL-8417 (unpublished)], 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. The preferred hypothesis had a confidence level of 91%.

[5]We have followed the practice, common in baryon spectroscopy, of designating enhancements by a generic label and a mass value in parenthesis. For nonstrange 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 ratios (see Orear, Ref. 4) a fit of a quadratic plus Gaussian form is found to be 1.2×10^4 times more probable than a simple quadratic fit. The preferred hypothesis had a confidence level of 55%.

[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 $\eta\pi^+\pi^-\pi^0$ and a $\pi^+\pi^-\pi^0$ decay, respectively. Unfortunately the limitations of our apparatus prevent us from reaching a definite conclusion regarding the possible decays of the $M(1033)$ even for a relatively simple decay channel such as $\pi^+\pi^-\pi^0$.

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Inclusive Photon Spectra and High-Energy Multiplicities*

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(Received 9 August 1972)

The consequences of Feynman scaling are examined for photon spectra at $x=0$ arising from π^0 decays. A consistency condition on the photon distribution is obtained. The low-transverse-momentum region is examined in detail and the contribution of bremsstrahlung computed to be $(k/\sigma_{\rm tot})d\sigma/d^3k=(\alpha/\pi^2k_\perp^2)\langle(\Delta Q_R)^2\rangle$, where ΔQ_R is the final right-moving charge minus the initial right-moving charge. This relation, together with the consistency condition, provides a new means of obtaining pertinent multiplicity information at very high energies.

Date from the CERN intersecting storage rings for photon spectra from p-p collisions at very high energies have been analyzed for photons with moderate transverse momenta.[1-3] In this paper we indicate the variety of information which can be obtained from photon spectra at very low transverse momenta. Throughout, we shall confine our discussion to the central rapidity region (where Feynman's variable, $x=p_\parallel^{\rm c.m.}/\frac{1}{2}s^{1/2}$, is zero).

There are two striking results of our analysis. The first relates the photon spectrum arising from π^0 decays at zero transverse photon momentum to the integral of the same photon spectrum over the full transverse-momentum range [Eq. (10)]. The second predicts the bremsstrahlung contribution to the photon spectrum. We find that the invariant cross section for bremsstrahlung photons is proportional to $\langle(\text{final right-moving charge}-\text{initial right-moving charge})^2\rangle/k_\perp^2$ [Eq. (13)]. If there are no correlations, this is proportional to $\langle n^{\rm ch}\rangle/k_\perp^2$ [Eq. (15)]. These results follow primarily from Feynman scaling and kinematic considerations.

*Work supported by the U. S. Atomic Energy Commission.

Photon production in the central rapidity region is dominated by four sources: (a) π^0 decays (2 photons per π^0), (b) η decays (3.2 photons per η), (c) K_s^0 decays (1.25 photons per K_s^0), and (d) bremsstrahlung from charged particles. It is difficult to separate the η and K_S^0 decays from the π^0 decays, especially because of the $\eta\to3\pi^0$ and $K_S^0\to2\pi^0$ decay modes. For this reason, and because η and K_S^0 production are significantly smaller than the π^0 production, we shall ignore η and K_S^0 as sources of photons.

We summarize first some straightforward kinematic calculations which are needed for obtaining our results. Further details will be published elsewhere.[4]

The Lorentz-invariant cross section for photon production from decays of π^0's is

$$k\frac{d\sigma}{d^3k}(\vec{k},s)=\int\frac{d^3p}{E}\left(E\frac{d\sigma}{d^3p}(\vec{p},s)\right)\frac{1}{\pi}\sigma(p\cdot k-\tfrac{1}{2}m^2), \tag{1}$$

where m is the π^0 mass, and where $E\,d\sigma/d^3p$ is the π^0 production cross section at momentum p and center-of-mass energy squared s. From (1) we see that the pions contributing to photon production at momentum k are constrained to lie on a paraboloid given by

$$p_\parallel'=p_0+(k/m^2)p_\perp'^2, \tag{2}$$