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[8]In Fig. 2 of Ref. 1, curve A is the postulated component for energies up to 10 GeV. It is given by $N(E)dE \propto E^{-2.4}dE$ and is seen to dip sharply at 10 GeV. In our scheme, however, the dip occurs at $E_c > 400$ GeV and this component alone (i.e., omit curve B) will represent the whole spectrum of experimental results. It is important to note that the important parameter appearing in Eq. (2) is γ and not K and that a value of γ slightly different from 2.1 ± 0.2 may be used to give good agreement with experiment if we make an appropriate change in K.

[9]P. Morrison, in Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, 1959), Vol. 46, p. 1.

[10]As the subsequent discussion will make clear, the primary acceleration region may be smaller than the confinement region. By the latter we mean a region of high magnetic field—relative to the surrounding area—from which, if the particles escape, their probability of return is practically zero.

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[13]T is best estimated from the charge spectrum of cosmic-ray nuclei, which indicates that the amount of matter traversed during the confinement time is about 2.5 g/cm^2. If the confinement region is the galactic disk, one thus infers $T \simeq 5 \times 10^{13}$ sec.

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FURTHER EVIDENCE FOR THE H MESON*

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(Received 28 September 1966)

Further evidence for the H meson is presented. The decay angular distributions are found to be consistent with $J^P = 1^+$.

We report here evidence for an enhancement near 1.0 BeV/c^2 in the $\pi^+\pi^-\pi^0$ mass spectrum from the reaction $\pi^+ + d \rightarrow \pi^+ + \pi^- + \pi^0 + p + (p)$ at 3.65 BeV/c. The data are taken from the same 3000 events from which other results have been previously reported.[1] Our results are in agreement with the properties of the "H meson" that was observed[2] in the reaction $\pi^+ + p \rightarrow \pi^+ + \pi^- + \pi^0 + N^{*++}$ at 4.0 BeV/c.

Mass spectrum.—Figure 1 shows the $\pi^+\pi^-\pi^0$ mass spectra for this experiment and separately for that of Ref. 2. In both sets of data it is required that at least one of the di-pion masses be in the rho region (650-850 MeV/c^2 for our data, 640-860 for the others). A further requirement in the ABBBHLM data is that one of the π^+p combinations is in the $N^*(1238)$ region. The curve illustrated, which applies only to our data, was calculated by multiplying that fraction of an isotropic Dalitz plot that contains at least one rho by a three-pion phase space. We have made a similar calculation using a Dalitz-plot density appropriate for an $I=0$, $J^P = 1^+$ three-pion state decaying into $\rho + \pi$ via s wave. This increases the 1-BeV/c^2 shoulder somewhat but still falls far short of explaining the bump in the data.

Using a background of this type we have fitted the data in 20-MeV/c^2 bins to a Breit-Wigner resonance form and find a central value $M = 998 \pm 10$ MeV/c^2 with a width at half maximum of 75 ± 30 MeV/c^2. This is to be compared with Ref. 2 which gives $M = 975 \pm 15$ MeV/c^2 and $\Gamma = 120$ MeV/c^2. Subtracting our resolution of 30 MeV/c^2 from our measured width gives 45 ± 30 MeV/c^2 for the width of the H meson. This procedure gives reasonable widths for both the ω^0 and A_2^0.[1]

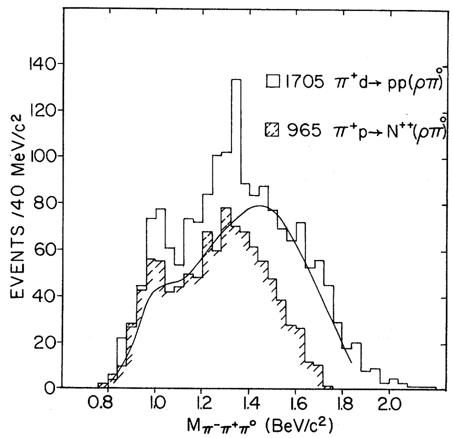

FIG. 1. Invariant mass of the $\pi^+\pi^-\pi^0$ system for events with ρ^+, ρ^-, or ρ^0. The outer histogram is data from this experiment and the superimposed shaded histogram is from Ref. 2.

Our production cross section for the H is 75 ± 15 μb above background after making the subtractions discussed below.

Isotopic spin.—We have compared our data with a compilation[3] of data on $\pi^\pm+p\to\rho^0+\pi^\pm+p$ showing the $A_1^\pm(1080)$ enhancement. It is clear from this that the H is not the neutral member of an A_1 triplet. The lack of an H effect is evidence that the H does not have $I=1$ since charge independence requires $\sigma_+^{1/2}+\sigma_-^{1/2}>\sigma_0^{1/2}$, where $\sigma_+=\sigma(\pi^++p\to H^++p)$, $\sigma_-=\sigma(\pi^-+p\to H^-+p)$, $\sigma_0=\sigma(\pi^++n\to H^0+p)$. (We have left out a factor of 2 under the radical on the right-hand side of the inequality because the $\rho^\pm\pi^0$ mode is not normally observed for $A_1^\pm$.) $I=2$ for the H is ruled out since this would mean $\sigma_+:\sigma_-:\sigma_0=3:3:4$. The observed $A_1^\pm$ cross sections at these energies are about 100 μb.

In an effort to remove some of the background from the H region we have made the following additional cuts on the data. (1) We require $\Delta^2(\text{beam}\to H)<0.85$ (BeV/c)^2. (2) $\rho^0N^{*+}(1238)$ and $\rho^+N^{*0}(1238)$ events are removed if $\Delta^2(\text{beam}\to\rho)<0.2$ (BeV/c)^2. This leaves 129 events in the H region, 0.92-1.08 BeV/c^2. These events divide into 42 $\rho^0\pi^0$, 45 $\rho^+\pi^-$, and 42 $\rho^-\pi^+$, and include 17 double-ρ events in which two of the three di-pions fall in a ρ region. If the H has $I=0$ (1, or 2) one expects the ratios of events in the above three categories to be 1:1:1 (0:1:1, or 4:1:1). Our observed numbers, as they stand, clearly favor $I=0$; however, a subtraction of 6 ± 3 events should be made from the $\rho^0\pi^0$ sample. We expect this number of $\pi^+\pi^-\gamma$ decays of the $\eta^*(959)$ meson to fall in the H-mass interval, and we cannot distinguish $\pi^+\pi^-\gamma$ from $\pi^+\pi^-\pi^0$ in this experiment. The number 6 ± 3 is based on our observed number (13 ± 5) of $\eta^*\to\pi^++\pi^-(+>2\pi^0)$ events and the published branching ratios[4] for this mode and the $\pi^+\pi^-\gamma$ mode of the η^*. We have included a correction factor of 0.82 which is based on our observed η^* Δ^2 distribution and our imposed Δ^2 cutoff of 0.85 (BeV/c)^2. The contamination is expected to fall primarily in the $\rho^0\pi^0$ events since the $\pi^+\pi^-\gamma$ mode of the η^* is mostly $\rho^0\gamma$.[4] In order to treat the background events in the ρ bands identically, three events should also be removed from the ρ^- events since these also fall in the N^{*++} region with $\Delta^2(\rho^-)<0.2$ (BeV/c)^2. The final result still favors the $I=0$ interpretation. A subtraction of these nine events would not appreciably affect the appearance of the peak.

Spin-parity.—In order to test various J^P assignments for the H we have plotted the distributions of the three polar angles θ_n, θ_m, and θ_b. The angles θ_n and θ_b are measured in the H rest frame and are defined as the angle between the beam and the H-decay-plane normal, and that between the beam and the "bachelor" pion (i.e., the one that does not make a ρ), respectively. The angle θ_m is measured in the ρ rest frame between the beam and one of the pions from the ρ. We have counted the double-ρ events as $\frac{1}{2}$ events each in the appropriate distribution. If the three $\cos\theta$ distributions are not all flat this rules out $J^P=0^\pm$ immediately. ($J^P=0^+$ is also ruled out by spin-parity conservation.) In order to test $J^P=1^\pm$ we can fit the three distributions of $\cos\theta_n$, $\cos\theta_m$, and $\cos\theta_b$ with the general form $1+A\cos^2\theta$. The three coefficients A_n, A_m, and A_b can be written in terms of one parameter, ρ_{00}, which is the central element of the 3×3 density matrix[5] for the H. The dependence on ρ_{00} for the two cases is,[6]

for $J^P=1^+$ (s wave),

$$A_n=(1-3\rho_{00})/(1+\rho_{00}),$$

$$A_m=(3\rho_{00}-1)/(1-\rho_{00}),$$

$$A_b=0;$$

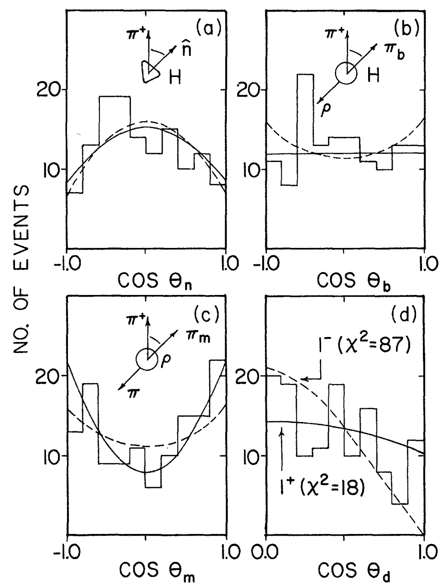

FIG. 2. Angular distributions in the H-meson region (0.92-1.08 BeV/c^2). Shown are the cosines of the angles between the beam pion and (a) the decay-plane normal, (b) the pion from the decay of the H meson, and (c) a pion from the decay of the ρ meson. The Dalitz-plot variable is shown in (d). The solid (dashed) curves assume the H meson has $J^P = 1^+$ (1^-).

for $J^P = 1^-$,

$$A_n = (3\rho_{00} - 1)/(1 - \rho_{00}),$$

$$A_m = (1 - 3\rho_{00})/(1 + \rho_{00}),$$

$$A_b = A_m.$$

These nonrelativistic equations should be valid since the velocity of the ρ in the H rest frame is ≈0.3 c. We have also neglected d-wave decay for the 1^+ case since it presumably would be small because of this small velocity and the centrifugal barrier effects.

For spin-parity 2^+ the $\cos\theta_n$ and $\cos\theta_b$ distributions should be identical and require additional $\cos^4\theta$ terms. The $\cos\theta_m$ distribution requires only terms up to $\cos^2\theta$. The five coefficients in this case can be written in terms of two parameters, ρ_{00} and ρ_{22}.[5,6] For spin-parity 2^- the $\cos\theta_m$ and $\cos\theta_b$ distributions are the same[6] and require only terms up to $\cos^2\theta$. The two coefficients in this case can again be written in terms of ρ_{00} and ρ_{22}. The $\cos\theta_n$ distribution needs an additional $\cos^4\theta$ term and also one more parameter R_0.[5]

We have made simultaneous least-squares fits to the three distributions for each of the above-mentioned J^P assignments, using the appropriate number of parameters in each case. The results are shown in Figs. 2(a), 2(b), and 2(c) for 1^+ and 1^-. The fitted values of the parameters and the χ^2 values are given in Table I. Examination of Table I indicates there is no clear choice for J^P. Considering that our H peak may contain more than 50% background, we may not be able to come to a definite conclusion about J^P.[7] The appearance of the curves on our data in Figs. 2(a), 2(b), 2(c), and 2(d) does, however, favor the 1^+ assignment. The arguments against the other choices can be summarized as follows:

(1) If we say that the $\cos\theta_b$ and $\cos\theta_m$ distributions are not compatible with being identical then this rules out 1^- and 2^- (and, of course, 0^-). The χ^2 probability for their being at least this nonidentical is 10%.

(2) If we say that the $\cos\theta_d$ distribution [see Fig. 2(d)] is not compatible with vanishing at $\cos\theta_d = 1$ then this rules out 1^- and 2^+. The description of θ_d is given below.

An independent test for J^P can be made by examining the Dalitz plot of the 3π system. We have chosen as orthogonal Dalitz-plot variables $m^2(\pi\pi)$ and $\cos\theta_d$, where θ_d is the angle between the di-pion line and "bachelor" pion in the di-pion rest frame. We have made a six-way fold of the data by ordering the kinetic energies of the three pions in the H rest frame.

Table I. Results of fitting the $\cos\theta_n$, $\cos\theta_m$, and $\cos\theta_d$ distributions for various J^P assignments.

J^P	ρ_{00}	ρ_{22}	χ^2 [a]	Probability
0^-	···	···	37 (27)	0.10
1^+	0.57 ± 0.06	···	22 (26)	0.70
1^-	0.17 ± 0.05	···	29 (26)	0.30
2^+	0.11 ± 0.04	0.36 ± 0.04	23 (25)	0.55
2^- $(R_0 = 0)$	0.00 ± 0.20	0.06 ± 0.05	28 (24)	0.25

[a]Number of degrees of freedom in parentheses.

The "bachelor" pion is then identified as having the smallest kinetic energy and the direction of the di-pion line is identified by the pion of intermediate kinetic energy. Because of this folding, $\cos\theta_d$ does not run through its full range for all values of $m^2(\pi\pi)$. The projection of the data on the $\cos\theta_d$ axis is shown in Fig. 2(d). The curve labeled 1^+ was calculated by building a ρ enhancement into a Dalitz-plot density appropriate for a 1^+ $(I=0)$ decay,[8] and then making an average over the 3π mass, weighted according to our observed mass distribution. It gives a reasonable fit to the data. The 1^- curve is typical of the series 1^-, 2^+, $\cdots$ which gives a vanishing density at $\cos\theta_d=1$ (edge of the Dalitz plot). The 12 events in the last bin cause curves of this nature to fit very poorly, although the addition of a flat background would obviously improve the fit.

The projection of the data on the $m^2(\pi\pi)$ axis is also gives reasonable agreement with the 1^+ assignment.

We would like to acknowledge the support and help of Brookhaven National Laboratory in the taking of the pictures. We are grateful to J. D. Jackson and J. Donahue for helpful communications.

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

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[2]Aachen-Berlin-Birmingham-Bonn-Hamburg-London (I.C.)-München Collaboration, Phys. Letters 11, 167 (1964), referred to as ABBBHLM. Other evidence, for and against the H meson, may be seen in Figs. 40 and 42 of Ref. 3.

[3]A compilation of $\rho^0\pi^\pm$ mass distributions from $\pi^\pm p$ experiments with beam momenta 3.2-4.0 BeV/c has been presented by G. Goldhaber, University of California Radiation Laboratory Report No. UCRL-11971, 1965 (unpublished). We have added to this our own data from $\pi^- p$ at 3.65 BeV/c. See Fig. 41, G. Goldhaber, in Proceedings of the Thirteenth International Conference on High Energy Physics, Berkeley, California, 1966 (to be published).

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[5]S. M. Berman and M. Jacob, Phys. Rev. 139, B1023 (1965).

[6]The distribution for $\cos\theta_n$ has been taken from Ref. 5. The distributions for $\cos\theta_b$ and $\cos\theta_m$ were derived using standard nonrelativistic techniques. We illustrate this calculation for 1^-:

$$\frac{dW}{d(\cos\theta_b)}=\sum_{\rho\ \text{spin}}\{\rho_{11}|A_1{}^1|^2+\rho_{00}|A_1{}^0|^2+\rho_{-1-1}|A_1{}^{-1}|^2\}.$$

The ρ's here are the diagonal elements of the H meson's density matrix and the A's are its spin amplitudes. To describe the decay $H(1^-)\to\rho(1^-)+\pi(0^-)$ in P wave we can decompose the A's as follows:

$$A_1{}^1=(1/\sqrt{2})[Y_1{}^1(\cos\theta_b)\chi_1{}^0-Y_1{}^0(\cos\theta_b)\chi_1{}^1],$$

etc. The χ's are the ρ-meson spin functions. When we sum over ρ-meson spin we then get

$$\frac{dW}{d(\cos\theta_b)}=2\rho_{11}(|Y_1{}^1|^2+|Y_1{}^0|^2)+\rho_{00}(|Y_1{}^1|^2+|Y_1{}^{-1}|^2),$$

where we have used the fact that $\rho_{-1-1}=\rho_{11}$ and $|Y_1{}^1|=|Y_1{}^{-1}|$. We can also use $\mathrm{Tr}\rho=1$ to eliminate ρ_{11}. This gives

$$\frac{dW}{d(\cos\theta_b)}=(\text{const.})\left[1+\left(\frac{1-3\rho_{00}}{1+\rho_{00}}\right)\cos^2\theta_b\right].$$

To get the $\cos\theta_m$ distribution, instead of summing over ρ spin we integrate over $\cos\theta_b$ and then replace the ρ spin functions $\chi_1{}^m$ by the corresponding $Y_1{}^m$ spherical harmonics which describe the two-pion decay of the ρ.

[7]Background effects were studied in events with $M(3\pi)=1.04$-1.20 BeV/c^2 and the same Δ^2 and ρN^* subtractions. The plots corresponding to Figs. 2(a) and 2(b) were similar, while Fig. 2(c) was flat. The ρN^* subtraction is important in Fig. 2(b) since most of the subtracted events have $\cos\theta_b<-0.4$.

[8]J. D. Jackson and J. Donahue, private communication.