EVIDENCE FOR A $T=0$ THREE-PION RESONANCE*

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The existence of a heavy neutral meson with $T=0$ and $J=1^-$ was predicted by Nambu[1] in an attempt to explain the electromagnetic form factors of the proton and neutron. Chew[2] has pointed out that such a vector meson should exist on dynamical grounds as a three-pion resonance or a bound state. Such a particle is also expected in the vector meson theory of Sakurai[3] and, as a member of an octet of mesons, according to the unitary symmetry theory[4]; and for other reasons.[5] We will refer to it as ω.

Previous searches[6] for ω have primarily been confined to the mass region $m_\omega < 3\mu$, with μ = the pion mass, where only the following radiative decay modes are allowed: $\omega \to \pi^0+\gamma$, $\omega \to 2\pi^0+\gamma$, and $\omega \to \pi^+ + \pi^- + \gamma$. The ω cannot decay into two pions.

The present search was made assuming $m_\omega > 3m_\pi$, where the decay

$$\omega \to \pi^+ + \pi^- + \pi^0 \tag{1}$$

is possible.[7] We have searched for such a 3-pion decay mode by studying the effective mass distribution of triplets of pions in the reaction

$$\bar{p} + p \to \pi^+ + \pi^+ + \pi^- + \pi^- + \pi^0. \tag{2}$$

We have measured 2500 four-prong events produced by antiprotons of 1.61 Bev/c in the 72-inch hydrogen bubble chamber.[8] The c.m. energy is 2.29 Bev. Upon fitting these 2500 four-prong events by using our kinematics program KICK, 800 four-prong events had a $\chi^2 \leq 6.5$ for hypothesis (2) and would not fit the hypothesis that no π^0 was produced (610 of these 800 had a $\chi^2 < 2.5$).

The 800 four-prong events must have some small contamination of events in which two π^0's were produced, but inspection of the "missing mass" distribution convinces us that it is <7%. Other tests confirm this low contamination. For example, the angular distribution of the π^0 is symmetric within statistics, and the momentum of the π^0 resembles the momentum distribution of the charged pions.

We have evaluated the 3-body effective mass,

$$M_3 = [(E_1+E_2+E_3)^2 - (\vec{P}_1+\vec{P}_2+\vec{P}_3)^2]^{1/2}, \tag{3}$$

for each pion triplet in Reaction (2). Each of the 800 four-prong events yields ten such quantities corresponding to the following charge states:

$$|Q|=0: \ \pi^+\pi^-\pi^0 \ (800\times 4 \text{ combinations}), \tag{4}$$

$$|Q|=1: \ \pi^\pm\pi^\pm\pi^\pm \ (800\times 4 \text{ combinations}), \tag{4'}$$

and

$$|Q|=2: \ \pi^\pm\pi^\pm\pi^0 \ (800\times 2 \text{ combinations}). \tag{4''}$$

For each value of M_3 as given by Eq. (4) we can calculate an uncertainty δM_3, by using the variance-covariance matrix of the fitted track variables, which is evaluated by KICK. By using these δM_3 we have formed the resolution function of M_3, and find that it has a half-width at half-maximum, $\Gamma_{\text{resol}}/2$, equal to 8.7 Mev. However, our input errors to KICK allow only for Coulomb scattering and estimated measurement accuracy, and do not account for optical distortion and unknown systematic errors. For example, our distributions have the correct shape but are too wide by a scale factor of about 2. This suggests that our average input error is too small by about $\sqrt{2}$. Hence, our estimate of δM_3 must be increased by about $\sqrt{2}$, and of $\Gamma_{\text{resol}}/2$ to 12 Mev. We chose 20-Mev histogram intervals for plotting our M_3 distribution.

In Fig. 1 we have plotted the M_3 distributions for the 800 Reactions (2). Distributions 1(A) and 1(B) are for charge combinations $|Q|=1$ and 2, respectively. The solid curves are an approximation to phase space.

The neutral M_3 distribution, 1(C), shows a peak centered at 787 Mev that contains 93 pion triplets above the phase-space estimate of 98. To contrast the difference between the neutral M_3 distribution and that for $|Q|>1$, we have replotted at the bottom of Fig. 1 both the neutral distribution and $\frac{2}{3}$ the sum of the $|Q|=1$ and $|Q|=2$ distributions.

Figure 2 shows the M_3 spectra with phase space subtracted. The absence of the peak in the $|Q|>0$ distributions determines the isotopic spin of the resonance,

$$T_\omega = 0.$$

The χ^2 distribution of the events in the "peak region" was compared with the χ^2 distribution of the events in the adjacent "control region," ranging from $M_3 \geq 820$ to $M_3 < 900$ Mev. These distributions agree with each other, which indicates that the events in the peak are genuine, rather than being caused by some unknown background reaction which was misinterpreted as Reaction

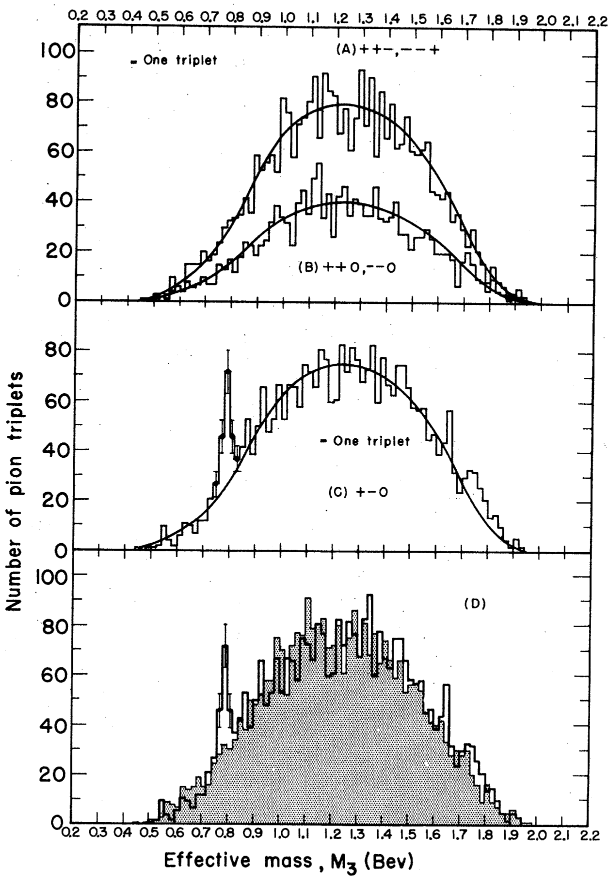

FIG. 1. Number of pion triplets versus effective mass (M_3) of the triplets for reaction $\bar{p}+p\rightarrow 2\pi^+ + 2\pi^- + \pi^0$. (A) is the distribution for the combination (4′), $|Q|=1$; (B) is for the combination (4″), $|Q|=2$; and (C) for (4), $Q=0$, with 3200, 1600, and 3200 triplets, respectively. Full width of one interval is 20 Mev. In (D), the combined distributions (A) and (B) (shaded area) are contrasted with distribution (C) (heavy line).

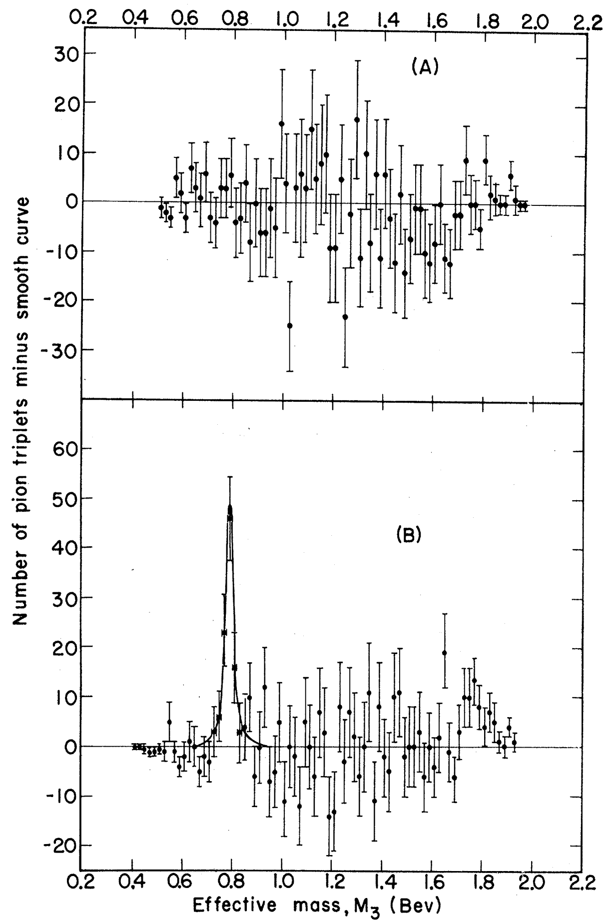

FIG. 2. (A) M_3 spectrum of the pion triplets in the combined distributions 1(A) and 1(B), with the smooth curve subtracted. (B) M_3 spectrum of the neutral pion triplets in distribution 1(C), again with the smooth background subtracted; a resonance curve is drawn through the peak at 787 Mev with $\Gamma/2=15$ Mev. The error flags are $\sqrt{N}$, where N is the total number of triplets per 20-Mev interval before subtraction of the smooth background curve.

(2). The missing-mass distributions in the two regions also agree with each other, thus supporting the above conclusion.

The peak in Fig. 2(B) appears to have a half-width $\Gamma/2<15$ Mev. This is so close to our resolution, $\Gamma_{\text{resol}}/2$, of 12 Mev that we cannot unfold it without further study and at present can only conclude that

$$M_\omega = 787 \text{ Mev},$$

and

$$\Gamma/2<15 \text{ Mev}. \tag{5}$$

By using the uncertainty principle, we see that this half-width implies a mean life $\tau>4\times10^{-23}$ sec. Our ω's are produced with a typical c.m. momentum of 800 Mev/c, so that in a mean life they travel farther than 13 f.

We now assume that the ω peak is real, and want to estimate how many ω mesons it contains. As shown in Fig. 1(C), 191 triplets have M_3 values between 740 and 820 Mev. (We call this the "peak region.") However, these 191 triplets come from only 170 different four-prong events [i.e., 21 Reactions (2) have two values of M_3 in the peak region]. We use the charged M_3 distribution to estimate the background in the interval as 98 triplets, and then calculate a production of 83 ± 16 ω mesons out of 800 Reactions (2); i.e.,

$(10\pm2)\%$ of Reactions (2) proceed via

$$\bar{p}+p\rightarrow\pi^{+}+\pi^{-}+\omega. \qquad (6)$$

Among the same 800 five-pion events, we have searched for—and found—the $T=J=1$ pion-pion resonance (ρ meson).[9] We found that approximately 30% of them proceed via

$$\bar{p}+p\rightarrow2\pi+\rho. \qquad (7)$$

We have checked whether there is any correlation between the observed ρ mesons and the ω mesons. For each triplet inside the peak region, $740\leq M_3<820$ Mev, we have evaluated the effective mass of the remaining $\pi^+\pi^-$ doublet, M_2. The M_2 distribution is consistent with a continuum, starting from about 300 Mev, that has $(10\pm2)\%$ of the doublets with values of M_2 in the region of ρ, which we took to be 750 ± 50 Mev. There is no evidence that the ω and the ρ are produced in association.

Although the masses of ω and ρ differ by only 35 Mev, we believe that they cannot be the same particle, because of their different widths (the $\Gamma/2$ for ρ being 40 Mev), isotopic spin, and G-conjugation parity—which forbids $2\pi\rightarrow3\pi$.

In referring to the $T=0$ 3π resonance as ω, we have tacitly supposed that it is in fact a vector state with $J=1^-$. However, the spin and parity must be decided by experiment. Even if we assume the spin is <2, there are left three possibilities which are listed in Table I. A $T=0$ state of three pions must be antisymmetric in all pairs; hence all three pions must have different charges, i.e., $\pi^0\pi^0\pi^0$ is forbidden. The matrix element of the $\pi^+\pi^-\pi^0$ state is conveniently analyzed in terms of a single pion plus a di-pion. The pions of the di-pion are assigned momentum $\vec{P}$ and angular momentum $\vec{L}$ (in the di-pion rest frame). Then another pair of variables, $\vec{p}$ and $\vec{l}$, describe the remaining pion in the 3π rest frame. Because the state is antisymmetric in any pair, $\vec{L}$ must be odd; henceforth, we assume $L=1$. Then if $l=0$ we have a $J=1^-$ (i.e., vector) matrix element, as listed on the bottom line of Table I. Since three pions are involved, there is an intrinsic parity of $(-1)^3$, so that the corresponding "meson" is not V, but A.

If $l=1$, the matrix element can be 1+ (axial) or 0+ (scalar) corresponding, respectively, to a vector meson (ω) or a pseudoscalar (PS) meson.

Do we have enough data to distinguish between totally antisymmetric A vs S vs V matrix elements? It is convenient to make a Dalitz plot[10] [Fig. 3(D) for the peak region events, 3(A) for the control region events] that displays the threefold symmetry of three pions in an antisymmetric state. Unit area on a Dalitz plot is proportional to the corresponding Lorentz-invariant phase space, so that the density of plotted points is proportional to the square of the matrix element. It is easily shown that the size of the figure is proportional to $T_1+T_2+T_3=Q=m_\omega-(2m_{\pi\pm}+m_{\pi^0})$.[11] Because of the finite width of the peak and the control regions, Q varies from event to event, so we use normalized variables, T_i/Q. The antisymmetry allows the plot to be folded about any median, so that in Figs. 3(C) and 3(B) all the data have been concentrated into $\frac{1}{6}$ of the plot area; the statistical distribution of the events is then more evident.

All three competing matrix elements, being antisymmetric, must vanish where any two pions "touch" in momentum space. If two pions touch, the third must have its maximum kinetic energy [regions (d), (f), and (b) on the plot]. The resonance region points [Figs. 3(C) and 3(D)] seem to show the required depopulation at points (d), (f), and (b).

More evident, however, on the plot is the fact that near $p=0$ [points (a), (c), and (e)] the density of peak-region points is only one half of that on the control plot. This is all the more suggestive when it is remembered that even the peak-region data contain only $(43\pm7)\%$ resonance events. This depopulation at $p=0$ suggests an angular momen-

Table I. Possible three-pion resonances with $T=0$, $J\leq1$.

"Meson" Type, $\vec{J}$	$\vec{l}$, $\vec{L}$	Matrix element Type, $\vec{J}$	Simple example	Vanishes at:
V, 1−	1, 1	A, 1+	$E_-(\vec{p}_0\times\vec{p}_+)+E_0(\vec{p}_+\times\vec{p}_-)+E_+(\vec{p}_-\times\vec{p}_0)$	whole boundary
PS, 0−	1, 1	S, 0+	$(E_--E_0)(E_0-E_+)(E_+-E_-)$	$a,c,e+b,d,f$
A, 1+	0, 1	V, 1−	$E_-(\vec{p}_0-\vec{p}_+)+E_0(\vec{p}_+-\vec{p}_-)+E_+(\vec{p}_--\vec{p}_0)$	b,d,f only

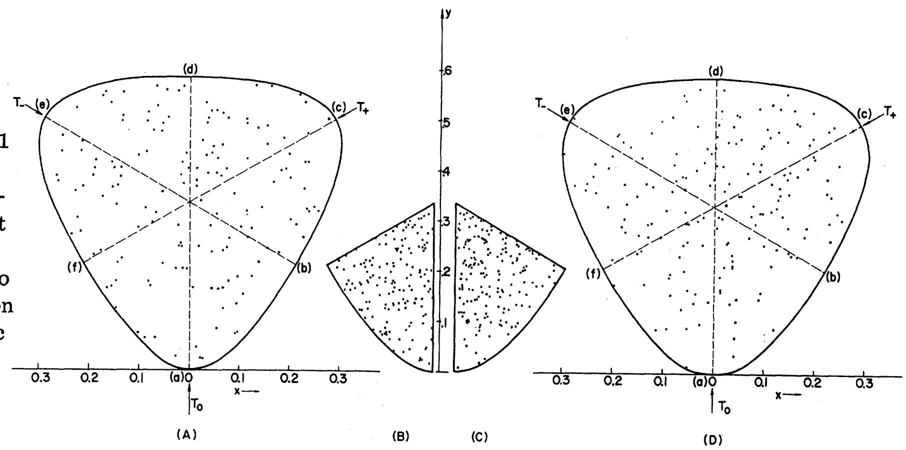

FIG. 3. (A): Dalitz plot of 171 triplets from the control region ($820 \leq M_3 < 900$); (B): folded control region plot; (D): Dalitz plot for 191 triplets in the peak region, 43 ± 7% of which are due to ω mesons; (C) folded peak region plot. T_+, T_-, and T_0 are kinetic energies of the π^+, π^-, and π^0, respectively.

tum barrier ($l > 0$) and constitutes mild evidence against a V matrix element (A meson).

The two stronger remaining candidates have A vs S matrix elements. The dashed lines in Fig. 3(D), as well as the two straight lines of the folded distribution in Fig. 3(C), correspond to equal energies of two pions. The scalar matrix element (S) of Table I vanishes when any two pions have the same energy, and therefore would require depopulation along these lines. This is not observed. An A matrix element has terms in $\vec{p}_i \times \vec{p}_j$, which vanish for collinear pions. The boundary of the plot represents collinearity, and seems indeed to be depopulated; although clearly more statistics and more detailed analysis such as investigation of polarization and alignment are needed.

We conclude that the data fit the qualitative criteria for an axial vector matrix element (ω meson); there is reasonable evidence against both an A meson and a PS meson.

The film used in this measurement was obtained in collaboration with J. Button, P. Eberhard, G. Kalbfleisch, J. Lannutti, G. Lynch, and N. H. Xuong; and this experiment would not have been possible without their help. It is a pleasure to thank Professor Murray Gell-Mann for his theoretical discussions. We wish to acknowledge the active participation of C. Tate, L. Champomier, A. Hussain, C. Rinfleisch, and F. Richards in the final stages of this experiment.

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[7]According to G. Sudarshan (University of Rochester, private communication) m_ω is expected to be within the limits $m_\rho < m_\omega < m_\rho + m_\pi$, where $m_\rho = 750$ Mev is the mass of the $T=J=1$ $\pi\pi$ resonance.

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[11]Specifically, Q equals the height of the exscribed triangle.

TOTAL CROSS-SECTION MEASUREMENTS OF K^+-p AND K^+-n INTERACTIONS IN THE MOMENTUM REGION 0.77 TO 2.83 Bev/c*

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Total K^+-p and K^+-n cross-section measurements have been made previously up to 0.8 Bev/c with emulsions,[1] counters,[2] and bubble chambers,[3] in the region 0.8 to 2.4 Bev/c by the M.I.T. group,[4] and at momenta above 2.7 Bev/c by the CERN[5] and Dubna[6] groups. From the data of the M.I.T., Dubna, and CERN experiments, it is difficult to arrive at a satisfactory description of the K^+-p cross section, σ_p, in the region of a few Bev/c. At the highest momentum measured by the M.I.T. group (2.4 Bev/c), σ_p was found to be 12.9 ± 1.0 mb, whereas at 2.9 Bev/c, the CERN group found $\sigma_p = 24.5 \pm 2.5$ mb. The present experiment was undertaken partly for the purpose of resolving this difficulty.

The experimental technique was similar to that used by Cook et al. to measure K^--p total cross sections.[7] The beam is illustrated in Fig. 1. A feature of the present beam not encountered in the K^- beam described in reference 7 was that the high proton counting rate (approx 2×10^6/sec) could cause accidental background. This source of accidentals was eliminated with an anticoincidence circuit designed to reject any K^+ meson that was accompanied by another beam particle within a time of ± 50 mμsec.

The hydrogen-deuterium target was 4 ft long, 6 in. in diameter, made of 0.007-in. stainless steel, and was vacuum insulated. Two transmission counters, T_1 and T_2, were used. The T_1 counter was a 12-in. × 12-in. × $\frac{1}{4}$-in. scintillator, and T_2 was a circular scintillator 9 in. in diameter and $\frac{1}{4}$

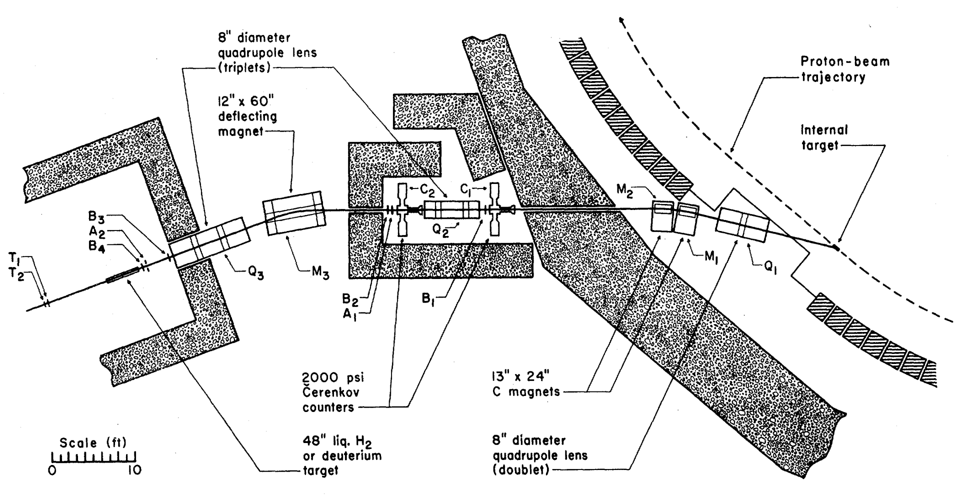

FIG. 1. Arrangement of the variable-momentum K^+ beam. M_1, M_2, and M_3 are bending magnets; Q_1, Q_2 and Q_3 are magnetic quadrupole lenses; B_1, B_2, B_3, and B_4 are coincidence counters; A_1 and A_2 anticoincidence counters; and C_1 and C_2 are gas Čerenkov counters. The transmission of the hydrogen target was measured by the scintillation counters T_1 and T_2.