confidence level upper limit of

$$C \leqslant 5800 C_V = 8.1 \times 10^{-46} \text{ erg cm}^3. \qquad (7)$$

This represents the first quantitative information on the M-$\bar{M}$ coupling constant.[13] This experiment can be modified for greater sensitivity, particularly when more intense muon beams become available.

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FOUR-PION DECAY OF THE f^0 MESON*

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The reaction $\pi^- p \to f^0 n \to 2\pi^+ 2\pi^- n$ has been observed at 5 Gev/c with $\sigma = 11.5 \pm 4$ μb ($1.20 < m_{4\pi} < 1.32$, $|t| < 0.2$ GeV^2).

The f^0 meson was first observed by Selove et al.[1] and by Viellet et al.[2] in the reaction $\pi^- p \to \pi^+\pi^- n$. The existence of the f^0 has been confirmed in many experiments and its quantum numbers, $J^P = 2^+$, $I^G = 0^+$, appear firmly established.[3] Evidence for decay modes other than $f^0 \to 2\pi$ is less clear. In particular only upper limits appear to have been given for the decay mode $f^0 \to 4\pi$.[4]

We report here the observation of a peak in the 4π mass spectrum from the reaction

$$\pi^- p \to \pi^+\pi^+\pi^-\pi^- n. \qquad (1)$$

The position of the peak, the highly peripheral mode of its production, and its decay distributions all suggest that the peak is due to the decay $f^0 \to 4\pi$.

The study is based on a 4.0-event/μb sample of four-prong interactions produced in the 72-in. hydrogen bubble chamber by a 5-GeV/c π^- beam at the Lawrence Radiation Laboratory. In this sample 4144 events are consistent with Reaction (1) by kinematics and ionization.

Figure 1 shows the 4π mass spectrum for all 4144 events and for 336 events with small momentum transfers to the nucleon ($|t| < 0.2$ GeV^2). In the sample with small momentum transfers a peak is seen near the lower end of the spectrum. Our best estimates for the mass and width are

$$m_{4\pi} = 1.27 \pm 0.01 \text{ GeV}, \quad \Gamma = 0.09 \pm 0.03 \text{ GeV}.$$

Inspection of the spectra suggests that additional peaks at higher masses may also exist, but the present data are inadequate to warrant definite conclusions. This uncertainty makes it difficult, however, to obtain a reliable estimate of the background level near the 1.27-GeV peak. We assume tentatively that the background is low and return to this question later.

Figure 2 shows various decay distributions for 78 events with $1.18 < m_{4\pi} < 1.36$ and $|t| < 0.2$

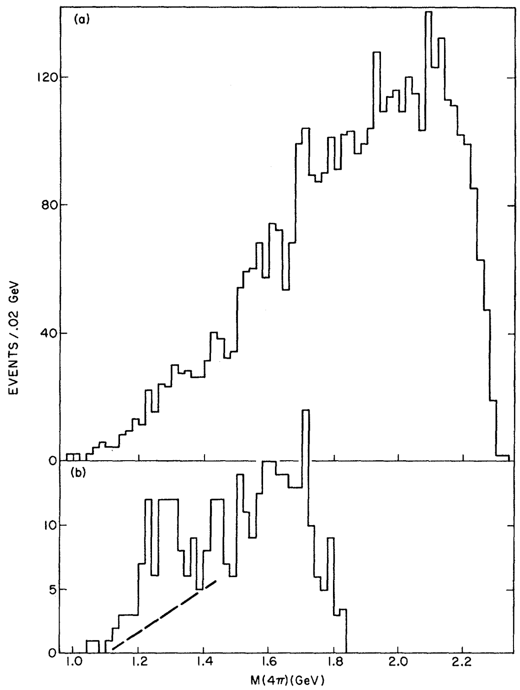

FIG. 1. (a) 4π mass distribution for all events. (b) 4π mass for events with momentum transfer squared to neutron less than 0.2 $(\mathrm{GeV})^2$. Dashed curve is estimated background in region of f^0 (cf. Fig. 3).

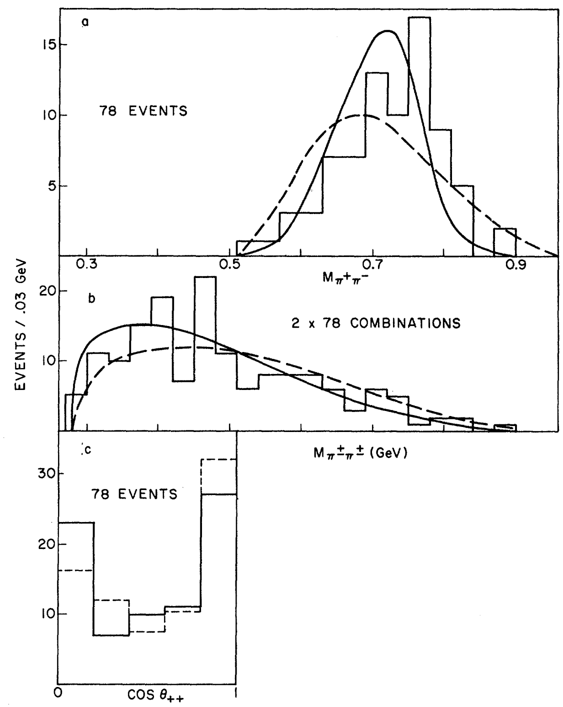

FIG. 2. Events with $1.18 \leq M(4\pi) \leq 1.36$ GeV and $|t| \leq 0.2$ $(\mathrm{GeV})^2$. (a) Histogram of highest mass $\pi^+\pi^-$ combination (of 4). Solid curve is the result of model given in text, and dashed curve is result of a $\rho\rho$ phase space calculation. (b) Mass of like $\pi\pi$ ($\pi^+\pi^+$ and $\pi^-\pi^-$) combinations. Curves have same meaning as in (a). (c) Folded distribution in $\cos\theta_{++} = \hat{p}_{++}\cdot\hat{p}_{in}$ in 4π rest frame. Dashed histogram is the prediction of model given in text with ρ_{00} of $f^0 = 1$.

GeV^2. We note the following features. (a) The distribution in the highest $\pi^+\pi^-$ mass for each event [Fig. 2(a)] appears to peak near the ρ mass. (b) The mass distribution for like pion pairs [Fig. 2(b)] peaks at low masses. (c) Figure 2(c) shows the folded distribution in $\cos\theta_{++} = \hat{p}_{++}\cdot\hat{p}_{\mathrm{in}}$, where $\vec{p}_{++}$ is the sum of the momenta of the momenta of the two positive π's and p_{in} is the momentum of the incident π^- (all momenta in the 4π frame). Before folding, the distribution showed a moderate amount of forward-backward asymmetry:

$$(F-B)/(F+B) = (47-31)/78 = 0.22 \pm 0.11.$$

The folded distribution is strongly anisotropic. From the moments we find the following coefficients, A_L, in a Legendre polynomial expansion for $\cos\theta_{++}$:

$$A_0 \equiv 1, \quad A_2 = 0.44 \pm 0.30,$$
$$A_4 = 1.19 \pm 0.41, \quad A_6 = 0.39 \pm 0.55.$$

The presence of a P_4 term in the angular distribution implies $J \geq 2$. The absence of a corresponding peak in the $(4\pi)^-$ spectrum (not shown) in the reaction $\pi^-p \to \pi^+\pi^-\pi^-\pi^0 p$ in the same experiment (after ω^0 events have been removed) suggests that $I = 0$. It seems reasonable then to assume that the peak is due to $f^0 \to 4\pi$. To test this assumption we have compared the decay distributions with an obvious model for the $f^0 \to 4\pi$ decay. The model is based on the following observations:

(a) The data suggest that at least one $\pi^+\pi^-$ pair is a ρ. For an $I = 0$ 4π state the opposing $\pi^+\pi^-$ pair must also have $I = 1$, hence odd spin. Since the mass of the pair opposite a ρ has necessarily a mass below the ρ mass we may assume this pair to have spin 1. We conclude that the most likely mechanism for decay is $f^0 \to \rho + \rho$.

(b) Since $m(f^0) < 2m(\rho)$ it seems reasonable to expect that the two ρ^0's are emitted mainly in a relative s state. If the d-wave amplitude is neglected, the $f^0 \to 4\pi$ amplitude is completely determined apart from uncertainties in the $\rho \to \pi\pi$ decay width (including its mass dependence) and apart from a possible form factor in the $f \to \rho\rho$ decay amplitude.

There are two diagrams corresponding to the pairings $(\pi_1^+\pi_3^-,\ \pi_2^+\pi_4^-)$ and $(\pi_1^+\pi_4^-,\ \pi_2^+\pi_3^-)$. Calling, for instance, $\vec{q}_{13}$ the momentum of π_1^+ in the $\pi_1^+\pi_3^-$ frame, the decay amplitude for a magnetic substate M is

$$A_M = T_{2M}(\vec{a}_{13}, \vec{a}_{24}) + T_{2M}(\vec{a}_{14}, \vec{a}_{23}), \qquad (2)$$

with a typical argument

$$\vec{a}_{13} = \vec{q}_{13}(m_\rho^2 - m_{13}^2 - im_\rho\Gamma_{13})^{-1} f_{\rho\pi\pi}(m_{13}),$$

$$\Gamma_{13} = \gamma_\rho (q_{13}/q_0)^3 (m_\rho/m_{13}) f_{\rho\pi\pi}^2(m_{13}).$$

In (2), T_{2M} is a spherical tensor of the second rank,[5] $f_{\rho\pi\pi}$ is a form factor in the ρ decay,[6] and q_0 is the momentum of a π from a ρ decay when $m_{\pi\pi} = m_\rho$.

With the help of (2) one may calculate various internal decay distributions and also the helicity amplitudes required to calculate angular distributions. The predictions of the model have been evaluated by employing the usual Monte Carlo technique to generate fake events distributed in phase space according to $|A|^2$ as given by (2).[6] The results, shown as the solid curves in Figs. 2(a) and 2(b), and as the dashed histogram in Fig. 2(c), appear to be in fair agreement with the data. For the angular distribution the predictions of the model depend on the assumed polarization of the f^0. The form of the angular distribution is

$$W(x) = \{\rho_{00}[1 + (10/7)Q_2P_2(x) + (18/7)Q_4P_4(x)] + 2\rho_{11}[1 + (5/7)Q_2P_2(x) - (12/7)Q_4P_4(x)] + 2\rho_{22}[1 - (10/7)Q_2P_2(x) + (3/7)Q_4P_4(x)]\}, \qquad (3)$$

with

$$|F_0|^2 + 2|F_1|^2 + 2|F_2|^2 = 1,$$

$$|F_0|^2 + |F_1|^2 - 2|F_2|^2 = Q_2,$$

$$|F_0|^2 - 4/3|F_1|^2 + \tfrac{1}{3}|F_2|^2 = Q_4,$$

$$x = \cos\theta_{++}, \qquad (3a)$$

and where $\rho_{mm'}$ is the f^0 density matrix and F_λ is a helicity amplitude, with λ referring to the sum of the spin components of $(\pi^+\pi^+)$ and $(\pi^-\pi^-)$ along $\vec{P}_{++}$. The model calculation gives

$$2|F_1|^2 = 0.19, \quad 2|F_2|^2 = 0.13.$$

The model prediction shown in Fig. 2(c) is for $\rho_{00} = 1$, which appears to fit the data about as well as the "best fit" values $(2\rho_{11} = 0.02 \pm 0.19;$ $2\rho_{22} = 0.19 \pm 0.18)$. The polarization $\rho_{00} = 1$ is of course that expected for a simple π-exchange production diagram.

In order to obtain a more reliable estimate of the polarization and of the number of $f^0 \to 4\pi$ events, we have plotted (Fig. 3) the moments of 4π-mass distributions weighted by the functions required to project the ρ_{00}, $\rho_{11} + \rho_{-1-1}$, and $\rho_{22} + \rho_{-2-2}$ components of the cross section.[7] Using the estimated background levels shown by the dashed lines shown in Fig. 3, we find $[1.20 \le M_{4\pi} \le 1.32$ GeV, $|t| \le 0.2$ (GeV)$^2]$

$$N\rho_{00} = 46 \pm 16,$$

$$N(2\rho_{11}) = -10 \pm 14,$$

$$N(2\rho_{22}) = 10 \pm 17,$$

where N is the number of f^0 events. From this we obtain our best estimate of the cross section:

$$\sigma(\pi^-p \to f^0n \to \pi^+\pi^+\pi^-\pi^-n) = 11.5 \pm 4\ \mu\text{b at } 5.0\ \text{GeV}/c$$

for $1.20 < m_{4\pi} < 1.32$ and $|t| < 0.2$ GeV^2.

In order to give a branching ratio $\Gamma(\pi^+\pi^+\pi^-\pi^-)/\Gamma(\pi^+\pi^-)$ we need to know the denominator. Inspection of the available literature[8] shows consid-

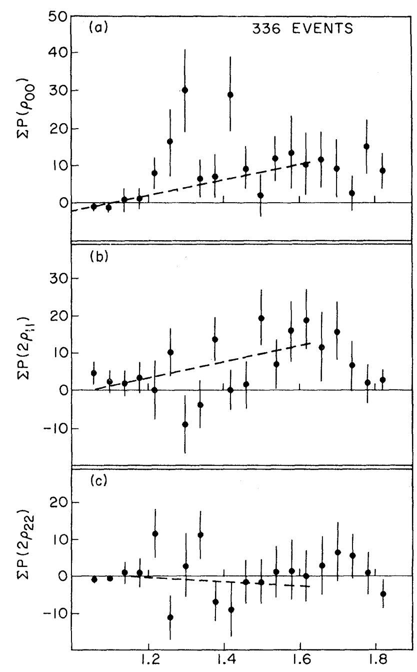

FIG. 3. Density-matrix-element projection operators summed over events $[|t| < 0.2\ (\text{GeV})^2]$ as a function of $M(4\pi)$. (a) ρ_{00} projector. (b) $2\rho_{11}$ projector. (c) $2\rho_{22}$ projector. Dashed lines are visual estimates of average background.

erable scatter in the estimates of both the cross section for $\pi N \to fN$ and the f^0 width. Since we do not wish to discuss or evaluate these discrepancies, we will simply take as a rough guess from the available data that $\sigma(\pi^- p \to f^0 n \to \pi^+\pi^- n) \approx 120$ μb at 5 GeV/c (with the same cuts used for the 4π data). This gives[9] a branching ratio

$$\frac{f^0 \to \pi^+\pi^+\pi^-\pi^-}{f^0 \to \pi^+\pi^-} \approx 10\%.$$

In order to get a rough idea of the $|t|$ dependence of the cross section we have carried out a similar analysis on the data without a $|t|$ cut. We find $N\rho_{00} = 69 \pm 21$ events (all t), in good agreement with the t distribution observed for $f^0 \to \pi^+\pi^-$.[10]

We have not discussed the possibility that the observed peak at 1.27 GeV could be the $D(1285)$. We note however that the width and $|t|$ distribution of our peak are in apparent disagreement with that quoted for the D.[11] We would also require that the spin of the D be ≥ 2.

We wish now to comment briefly on the narrow peak at $m_{4\pi} \sim 1.42$ GeV. The present data are clearly not sufficient to establish the presence of a resonance. If we suppose that the peak is not a statistical fluctuation, the data (Fig. 3) suggest that it may also have $J^P = 2^+$, and may therefore possibly correspond to the enhancement observed by Beusch et al.[12] in $K_1^0 K_1^0$.

We take pleasure in acknowledging the work of J. Kirz and O. Dahl in setting up the beam used in this experiment. We wish also to thank C. G. Howard and T. R. Palfrey for communicating to us their $\pi^- p \to \pi^+\pi^- n$ 5-GeV/c data prior to publication. Finally we wish to express our gratitude for the work of our engineers, scanners, and measurers.

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[5]$T_{22}(a_{13}, a_{24})$ for example, is proportional to $[(a_{13})_x + i(a_{13})_y]\,[(a_{24})_x + i(a_{24})_y]$.

[6]The form of Γ used is that of J. D. Jackson, Nuovo Cimento 34, 1644 (1964). The results presented here are rather insensitive to the choice of γ_ρ and $f_{\rho\pi\pi}$. The results shown were obtained with any of the choices $\gamma_\rho = 0.120$ or 0.148 GeV, $f_{\rho\pi\pi} = 1$ or $(1+q_0^2/0.71)^2/(1+q^2/0.71)^2$. We have bypassed the uncertainties in the energy dependence of $\Gamma(f^0 \to 4\pi)$ by forcing the $m_{4\pi}$ distribution of the fake events to be the same as the observed distribution.

[7]The projectors are

$$P(\rho_{00}) = 0.2 + P_2/Q_2 + 1.8P_4/Q_4,$$

$$P(\rho_{11} + \rho_{-1-1}) = 0.4 + P_2/Q_2 - 2.4P_4/Q_4,$$

$$P(\rho_{22} + \rho_{-2-2}) = 0.4 - 2P_2/Q_2 + 0.6P_4/Q_4,$$

where Q_2 and Q_4 are given in Eq. (3a).

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ELECTROMAGNETIC DECAY OF THE $Y_0^*(1520)$†

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The decay of the $Y_0^*(1520) \to \Lambda + \gamma$ has been discovered in the reaction $K^- + p \to \Lambda +$ neutrals. The angular distribution and polarization of the Λ are consistent with a pure electric dipole transition. The cross section yields a partial width for the decay of 0.15 ± 0.03 MeV.

(A) Experimental procedure.—An exposure of 1.3×10^6 pictures in the Berkeley 25-in. hydrogen bubble chamber has yielded about 51 000 reactions of the type $K^- + p \to \Lambda +$ neutrals, $\Lambda \to p + \pi$. Among these reactions we have identified 258 events in which the missing mass of the neutral is consistent with zero and is kinematically cleanly separated from the mass of the neutral pion. The incident momenta ranged from 270 to 470 MeV/c. Most of the path length was close to