L. Lavatelli, A. Minguzzi-Ranzi, R. Losi, P. Waloschek, and V. Zoboli, Nuovo cimento 15, 551 (1960); M. Chrétien, J. Leitner, N. P. Samios, M. Schwartz, and J. Steinberger, Phys. Rev. 108, 383 (1957).

[3]G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 8, 41 (1962).

# EXISTENCE AND SPIN OF THE PROPOSED "$f^0$" $\to \pi^+ + \pi^-$ RESONANCE

J. J. Veillet, J. Hennessy, H. Bingham, M. Bloch, D. Drijard, A. Lagarrigue, P. Mittner, and A. Rousset
Ecole Polytechnique, Paris, France

and

G. Bellini, M. di Corato, E. Fiorini, and P. Negri
Istituto Nazionale di Fisica Nucleare, Sezione di Milano, Italy and Istituto di Scienze Fisiche dell'Università, Milano, Italy
(Received 2 November 1962)

We have studied the reaction

$$\pi^- + p \to \pi^+ + \pi^- + n \qquad \text{(A)}$$

in the 6.1-GeV/$c$ $\pi^-$ beam at CERN. The detector was the Ecole Polytechnique 300-liter heavy-liquid bubble chamber[1] filled with a $CF_3\,Br$-$C_3H_8$ mixture (density 0.55, radiation length 52 cm) in a 17.1-kG field. A preliminary report has been presented by F. Muller.[2]

A reaction of type (A) gives rise to a two-prong (one positive, one negative) star, without pointing electron pairs. Other reactions which can give rise to similar stars are the following:

$$\pi^- + p \to \pi^- + p, \qquad \text{(B)}$$

$$\pi^- + p \to \pi^+ + \pi^- + n + x\pi^0, \qquad \text{(C)}$$

$$\pi^- + p \to \pi^- + p + x\pi^0. \qquad \text{(D)}$$

To eliminate such spurious events, we used the following methods:

(a) Ionization and range allow us to reject most of the slow protons [a large part of (B) and (D)].

(b) Kinematical analysis enables us to reject almost all the remaining elastic events [type (B)].

(c) Because of the high probability of observing gamma-ray materialization, the number of types (C) and (D) events in two-prong stars without gamma rays is not very large (about 30%). We eliminated most of these by a cutoff on the missing mass after comparing the missing-mass spectrum of events with and without observed gamma rays. These spectra are very different, because when $\pi^0$'s are produced the missing mass generally corresponds to a slow neutron plus fast pions, and is consequently much larger than the nucleon mass.

We were finally left with 457 events of which >85% are of type (A), $\lesssim$8% are type (C), and $\lesssim$7% of type (B) or (D).

We may note, in addition, that most of the events containing gamma-ray materialization described above gave $\pi^+$-$\pi^-$ effective masses smaller than 1000 MeV. On the other hand, a sample of elastic-scattering events, treated in the same way, gave masses centered around 2000 MeV.

Experimental results. –(1) We computed the mass of the "dipion" ($\pi^+ + \pi^-$) for which the individual experimental error was about ±8%; we constructed a histogram of this mass with 100-MeV intervals [Fig. 1(a)]. One observes a very high peak around 800 MeV, which is centainly connected with the $\rho$ resonance. A second peak is observed around 1250 MeV. This peak was already pointed out by us in reference 2. Selove et al.[3] have also found it and interpret it as a resonance which they suggest calling "$f^0$."

By interpolating the background, we find that this peak is statistically significant to 3.5 standard deviations. We think that this is further evidence, with comparable accuracy, of the existence of the "$f^0$." Due to our large experimental errors, we can only say that the mass value that we measured (1260 ± 35 MeV) and our width ($\Gamma \leq 200$ MeV) are consistent with the ones measured by Selove et al.

(2) To investigate this peak further, we studied, in the "dipion" rest system, the distribution of the angle $\theta^*$ between the outgoing $\pi^-$ and the beam. Fig. 1(b) shows the forward-backward asymmetry found, plotted against the dipion mass.

One observes a general forward asymmetry,

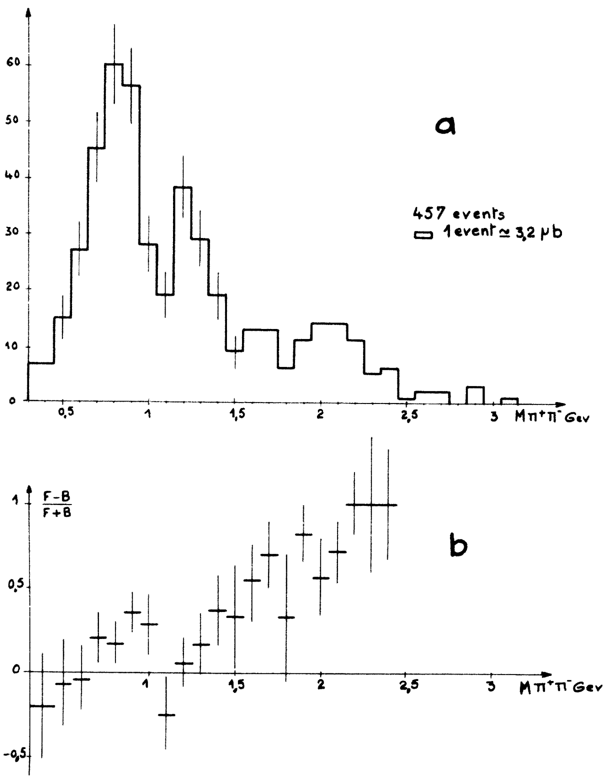


FIG. 1. (a) $\pi^+\pi^-$ mass plot for the reaction $\pi^- + p \rightarrow \pi^+ + \pi^- + n$. (b) Forward-backward asymmetry of the outgoing $\pi^-$ in the $\pi^+\pi^-$ c.m. system, relative to incident $\pi^-$. All errors are standard.

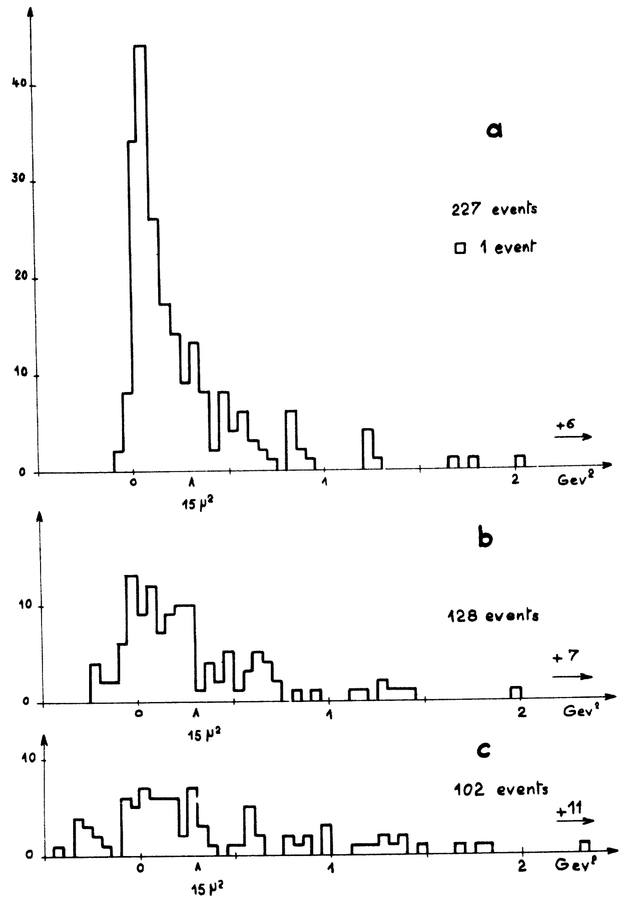


FIG. 2. Distribution of $\Delta^2$: (a) $M_{\pi\pi} < 1000$ MeV; (b) 1000 MeV $< M_{\pi\pi} < 1500$ MeV; (c) $M_{\pi\pi} > 1500$ MeV.

increasing with the mass, as one can expect from high-energy diffraction effects. However, in the "$f^0$" region, there is undoubtedly a break in the general trend. The mean of the three points at 1100, 1200, and 1300 MeV is 2.5 standard deviations away from a straight line interpolated between four neighboring points on each side. The mean asymmetry in this band is close to zero.

The coincidence of this "symmetry" with the peak described in paragraph (1) is a second argument in favor of a resonance in this region.

(3) We then tried to apply the one-pion exchange model[4] (OPE) to process (A). We first investigated the momentum transfer ($\Delta^2$) distribution for different values of the dipion mass (Fig. 2). For small masses [Fig. 2(a)], one finds a sharp maximum at about $4\mu^2$. For larger masses [Figs. 2(b) and (c)], the diagrams are more spread out (the errors being larger) but have the same shape. Nevertheless, most of the events are concentrated at $\Delta^2 < 15\,\mu^2$.

We further investigated the behavior of the $\pi^-$ distribution relative to the angle $\alpha$ between the two planes defined by the beam-proton and the beam-outgoing $\pi^-$ momenta, as suggested by Treiman and Yang.[5] In the "$f^0$" band, we found the same number of events in the four quadrants, and no significant difference between the $\theta^*$ angular distributions. The results of these two tests are not in contradiction with OPE.

Consequently, we treated the reaction (A) as a $\pi$-$\pi$ scattering for the lower values ($<15\,\mu^2$) of $\Delta^2$. We plotted in the "$f^0$" band ($1100 < M_{\pi\pi} < 1400$) the distribution of $\cos\theta^*$ (the $\pi^-$ scattering angle). The result [Fig. 3(a)] is symmetrical and has definite forward and backward peaks. The odds against a flat law giving such a distribution are around 100 to 1. This distribution suggests that the relative angular momentum of the two outgoing pions in the "$f^0$" region is probably not zero, and that therefore the "$f^0$" does not have zero spin.

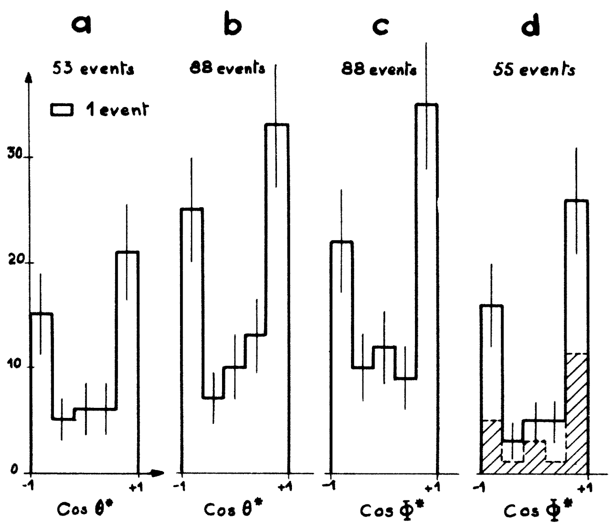


FIG. 3. Angular distributions of the outgoing $\pi^-$ in $\pi^+\pi^-$ rest system in "$f^0$" region (1100 MeV $< M_{\pi\pi} <$ 1400 MeV). Distributions relative to incident $\pi^-$ ($\theta^*$): (a) $\Delta^2 < 15\,\mu^2$; (b) all $\Delta^2$. Distributions relative to dipion direction ($\Phi^*$): (c) all $\lambda$; (d) solid line, $\lambda < 4°$; dashed line, $\lambda < 2°$. All errors are standard.

(4) To investigate this point further, we studied, for all "$f^0$" events (with no $\Delta^2$ cutoff), the angular distribution of the decay $\pi^-$ in the dipion rest system, relative to fixed axes. Figs. 3(b) and 3(c) show the distribution of $\cos\theta^*$ and $\cos\Phi^*$ (angles of the decay $\pi^-$ with the beam and dipion directions, respectively). Both are, within errors, symmetrical and sharply peaked backward and forward (the slight forward excess can be attributed to background). A straightforward calculation of the odds against a flat law giving such a distribution gives, in each case, about 500 to 1. We also, in analogy with the Adair argument,[6] plotted the $\cos\Phi^*$ distribution for very small values of the angle $\lambda$ between the dipion and the beam in the laboratory system. This plot is shown in Fig. 3(d), for $\lambda < 2°$ and for $\lambda < 4°$. These two distributions are quite similar, and the odds against a flat law are larger than 500 to 1 in the $\lambda < 4°$ case.

The four methods just described, which are summarized in Fig. 3, are certainly not independent measurements of the anisotropy. Nevertheless, the results of these various analyses are consistent and definitely favor a nonzero spin for the "$f^0$." On a purely statistical basis, the odds are 500 to 1.

Conclusion.—The existence of "$f^0$" resonance is supported both by the significant mass peak at 1260 ± 35 MeV, and by the backward-forward decay symmetry observed. Analyses of angular distributions described in paragraphs (3) and (4) give a strong indication that "$f^0$" spin is larger than zero.

Selove et al. have found that the "$f^0$" isotopic spin is probably zero. They also found that its width is rather large, which means that it decays through strong processes. If we take these results into account, we easily derive that its spin must be an even integer.

Combination of all these results leads to the conclusion that "$f^0$" spin is most probably 2. This suggests its identification with the particle predicted in the Chew and Frautschi scheme.[7]

We wish to thank Professor L. Leprince-Ringuet for his sustained interest. We express our deep gratitude to Dr. Omnès, who greatly helped us with interpretation during the whole of the work. Finally, we thank the CERN proton synchrotron and heavy-liquid groups without the good will and cooperation of which this work would not have been possible.

[1]M. Bloch, A. Lagarrigue, P. Rançon, and A. Rousset, Rev. Sci. Instr. 32, 1302 (1961).

[2]J. Hennessy, J. J. Veillet, M. di Corato, and P. Negri, reported by F. Muller at the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published).

[3]W. Selove, V. Hagopian, H. Brody, A. Baker, and E. Leboy, Phys. Rev. Letters 9, 272 (1962).

[4]G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

[5]S. B. Treiman and C. N. Yang, Phys. Rev. Letters 8, 140 (1962).

[6]R. K. Adair, Phys. Rev. 100, 1540 (1955).

[7]G. F. Chew and S. C. Frautschi, Phys. Rev. Letters 8, 41 (1962).