This will present some problems of radiation damage to the crystal, particularly in its use as a polarizer, which need further consideration. In practical use it will be necessary to eliminate the shower secondaries through careful collimation.

We are grateful to Professor G. Diambrini, Dr. G. Barbiellini, Dr. G. Bologna, and Dr. G. P. Murtas for many stimulating discussions and for suggestions about the choice of the crystals to be studied; and to Dr. A. Turrin and the other members of the computation group for their assistance during the numerical computations with the IBM-1620 computer.

The use of pair production on crystals (not in a transmission experiment) for the measurement of linear polarizations had been considered previously by Barbiellini.[9]

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# EVIDENCE FOR A $T=0$ $\pi^+$-$\pi^-$ RESONANCE AT 1250 MeV*

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In recent months a great deal of attention has been given to the Regge-pole approach to elementary particle theory. If this approach, as outlined particularly by Chew and Frautschi,[1] is correct, then in some sense the existence of some unifying principle for all of the elementary particles will be indicated. One of the specific predictions of the Regge-pole approach is the existence of a spin-2 particle, having the quantum numbers of the vacuum (apart from the angular momentum), and with a mass of the order of 1.0[1] to 1.4[2] BeV. Such a particle could decay into two $\pi$ mesons and should be observed as a $\pi$-$\pi$ resonance with isotopic spin $T=0$. This Letter reports experimental evidence for the existence of a particle with isotopic spin, $G$-parity, and mass similar to those of the particle called for in the Regge pole theory.

From a run of 60 000 pictures using the 3-BeV/$c$ separated $\pi^-$ beam[3] and the BNL 20-inch hydrogen bubble chamber, at the AGS, we have so far analyzed 40% of the available two-prong reactions, and have in particular studied the reactions

$$\pi^- + p \to \pi^- + \pi^0 + p, \qquad (1)$$

$$\pi^- + p \to \pi^- + \pi^+ + n. \qquad (2)$$

Figure 1 shows the invariant-mass distributions for the $\pi$-$\pi$ system, in Reactions (1) and (2). The data show a peak at about 1250 MeV in the $\pi^-\pi^+$ mass plot in addition to the $\rho$ peak at 775 MeV. The 1250-MeV peak is not present in the $\pi^-\pi^0$ data, and we therefore identify it as $T=0$. We shall refer to this resonance, or particle, as the $f^0$ meson.

The width of the $f^0$ appears to be of the order of 100 MeV or so, full width at half maximum. This is considerably greater than our experimental resolution, which we estimate to be about 20 MeV.

Our conclusion that the 1250-MeV peak is real is based on the difference between the $\pi^-\pi^0$ and $\pi^-\pi^+$ mass plots in Fig. 1. The $\pi^-\pi^0$ mass plot, for masses above the $\rho$ peak, is completely consistent with a phase-space distribution. The $\pi^-\pi^+$ mass plot, however, is quite inconsistent with such a distribtuion. The odds against a phase-space distribution being consistent with our data are of the order of several thousand to one, when we compare the number of events in mass intervals of 50 to 100 MeV, covering the range from 1000 to 1600 MeV, with the relative numbers of events for a phase-space distribution. (These odds are calculated by a $\chi^2$ method.)

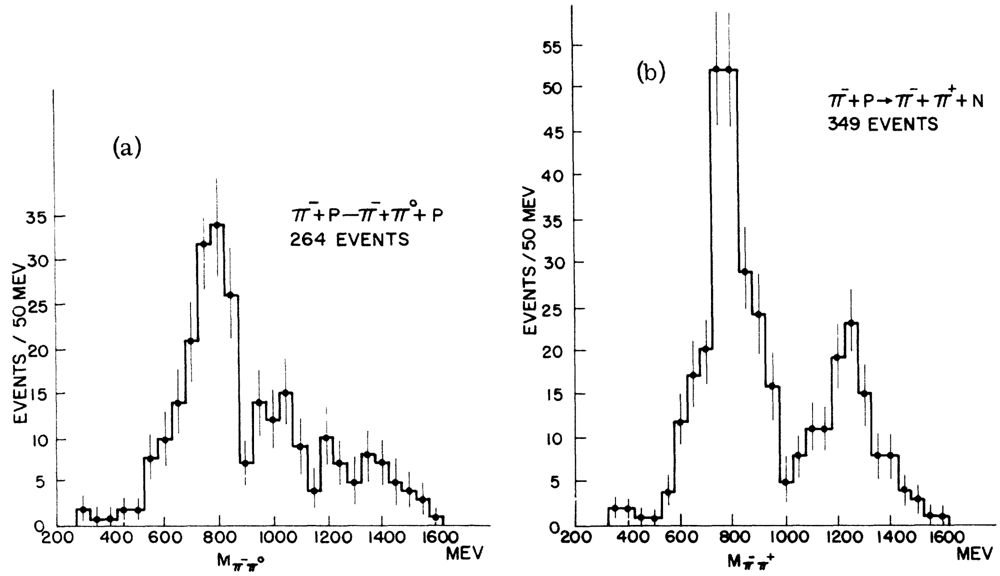


FIG. 1. (a) $\pi$-$\pi$ mass plot for Reaction (1). The cross section for this reaction is 2.5 to 3.0 mb. (b) $\pi$-$\pi$ mass plot for Reaction (2). The cross section is about 3.5 mb.

We remark that we have examined our data for possible evidence of $4\pi$ decay of the $f^0$. There is no indication of any such events with production cross section at all comparable with the cross section for $2\pi$ "decay" of the $f^0$.

Figure 2 shows Dalitz plots of the data. The principal conclusion to be drawn from these plots is that the $f^0$ peak is not an accidental result of any nucleon isobar production. There is little evidence of any isobar production at all.

Figure 3 shows a "Chew-Low"[4] plot of $\Delta^2$ vs $M_{\pi\pi}^2$, where $\Delta$ is the invariant momentum transfer to the recoil nucleon. This plot is useful for an indication of the extent to which the various individual reaction events may be interpretable as $\pi$-$\pi$ scatterings. The interpretation as $\pi$-$\pi$ scatterings is of particular interest in connection with the possible determination of the angular momentum for any $\pi$-$\pi$ resonances observed. The Chew-Low plot also displays rather directly

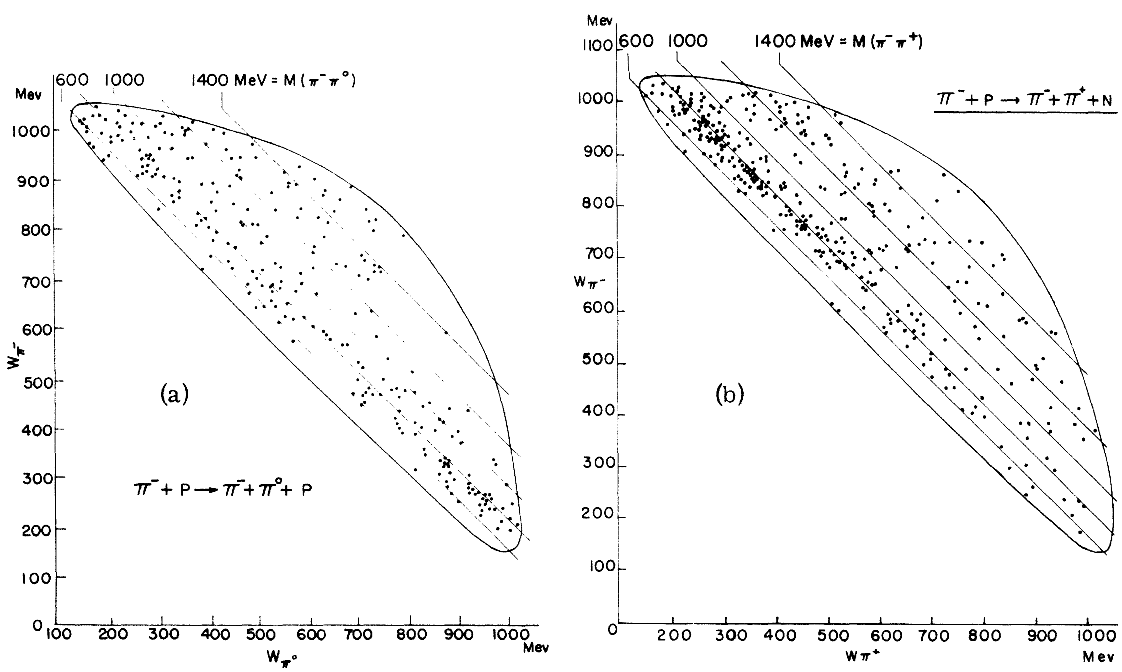


FIG. 2. Dalitz plots for (a) the $\pi^-\pi^0p$ system, and (b) the $\pi^-\pi^+n$ system.

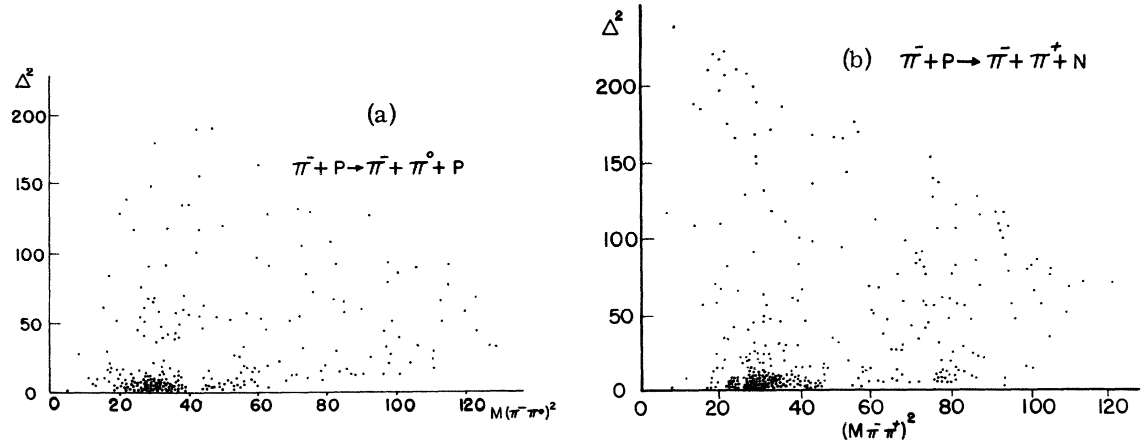


FIG. 3. Chew-Low plots for (a) $\pi^-\pi^0$ and (b) $\pi^-\pi^+$. $\Delta^2$ and $(M_{\pi\pi})^2$ are in units of the pion rest mass squared.

the distribution of production angle $\alpha$ (final nucleon angle in the overall center-of-mass system), since, for any given $M_{\pi\pi}$, $\Delta^2$ is a linear function of $\cos\alpha$.

Figure 3 shows a strong concentration of low-$\Delta$ events at the $\rho$ mass, and some concentration of low-$\Delta$ events elsewhere. We have studied the individual events also in terms of the test for peripheral nature suggested by Treiman and Yang[5]; we find that for small $\Delta^2$, less than ten, the Treiman-Yang test is satisfied—as $\Delta^2$ becomes larger, this test is no longer satisfied.

We have explored several possible methods of determining the $f^0$ spin from our data as follows: (1) from the "$\pi$-$\pi$ scattering-angle" distribution, in peripheral-type events (i.e., in low-$\Delta$ events); (2) from the magnitude of the resonant $\pi$-$\pi$ scattering cross section as inferred from peripheral-type events[6]; (3) from the apparent magnitude of final $S$-state production cross section (i.e., $S$ state for the $f^0$-neutron system), and comparison with the unitary limit. All of these tests are inconclusive, with our present data. For a $T=0$ $\pi$-$\pi$ resonance at this energy, the most likely candidates for the spin are probably 0 and 2. Our data do not permit us to choose one of these possibilities as clearly favored over the other.

Some remarks about angular distributions associated with our $\pi^+\pi^-$ events are in order.

For any group of resonant $\pi$-$\pi$ events appearing in Reaction (2), it is useful to examine the angular distribution of "decay" for the $\pi^+\pi^-$ system relative to the incoming $\pi^-$ direction, to try to gain information on the spin associated with the resonance. For peripheral events (low $\Delta$), this decay angular distribution is likely to be closely related to the angular distribution for $\pi$'s scattering on free $\pi$'s, and so could give the spin of the resonance. Even for nonperipheral events, one could hope to find evidence for spin (e.g., through the Adair analysis[7]), and perhaps polarization, of the resonant system.

This type of analysis turns out to be not usable for the $\pi^+\pi^-$ events in our data. The reason is that the decay angular distribution is not symmetric with respect to interchange of outgoing $\pi^+$ and $\pi^-$. For the entire range of $M_{\pi\pi}$ values, there is a marked and consistent asymmetry with respect to $\pi^+/\pi^-$ interchange. The $\pi^-$ tends to go "forward"—i.e., to come out with higher laboratory energy than the $\pi^+$. This asymmetry is very strong both for the $f^0$ and the $\rho^0$.

The asymmetry could be due, for example, to "background" nonresonant events (for the $f^0$ mass region, for example, there can be contributions from $\pi^+\pi^-$ interaction in states other than $T=0$), or to final-state interaction. It may be noted, also, that the presence of the strong $\pi^+/\pi^-$ asymmetry for peripheral events is consistent with a model of $\pi$-$\pi$ scattering as proceeding predominantly through exchange of a $\rho$, or of some other $T=1$ particle.

In any event, whatever the cause, the observed $\pi^+/\pi^-$ asymmetry considerably complicates the the problem of determining the $f^0$ spin.

The work reported here can be summarized as follows. We have found evidence for a $T=0$ particle or resonance, the $f^0$, at an energy of 1250 $\pm$ 25 MeV, with a width of 100$\pm$ 50 MeV. We are not able to determine the spin.

This work would not have been possible without the contributions of many people to the equipment and operations at Brookhaven National

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# ELEMENTARY PARTICLES OF CONVENTIONAL FIELD THEORY AS REGGE POLES

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Composite states in nonrelativistic scattering theory lie on Regge trajectories[1] corresponding to poles in the angular momentum plane that move with varying energy. Simple approximations[2-5] indicate that composite particles in relativistic field theory have the same behavior. According to the Regge pole hypothesis,[6-9] particles like the nucleon, that have customarily been treated as elementary in field theory, also lie on Regge trajectories. Is that in accord with describing such particles by ordinary perturbation theory?

It has been thought that elementary particles behave in perturbation theory as objects of fixed angular momentum.[7-9] In reference 9 the *PS-PS* theory of pions and nucleons is taken as an example. (For simplicity, let us ignore here the isotopic spin of the pion.) Writing the Feynman scattering amplitude as usual in the form $A - i\gamma\cdot qB$, we have in second order

$$A = 0,$$
$$B = -g^2/(m^2-u) + g^2/(m^2-s), \qquad (1)$$

where $s$ and $u$ are the Mandelstam variables. The first term in the expression for $B$ corresponds to the nucleon, with $\alpha = J - \frac{1}{2} = 0$. (It is proportional to $s^0$.) The second term, although it represents the nucleon singularity in the $s$ channel, corresponds in the $u$ channel to an infinite sequence of angular momentum poles with $\alpha = -1, -2, -3$, etc., just like the Born approximation in nonrelativistic scattering by a Yukawa potential. Now in fourth order $B$ acquires terms that vary as $s^{-1}\ln s$ (for large $s$ and fixed $u$) and others that vary as $s^0$, but none that varies as $s^0 \ln s$. Thus the subsidiary angular momentum poles at $\alpha = -1, -2, \cdots$ may be beginning to move, as in potential scattering. For example, if $\alpha = -1$ becomes $\alpha = -1 + g^2F(\sqrt{u})\cdots$, then $s^{-1+g^2F(\sqrt{u})+\cdots}$ appears in perturbation theory as $s^{-1} + g^2F(\sqrt{u})s^{-1} \times \ln s + \cdots$; but in this order the elementary nucleon pole continues to have $\alpha = 0$.

The situation is different, however, if we replace the virtual pion in the radiative correction by a virtual neutral vector meson with mass $\lambda$ and coupling parameter $\gamma$. The amplitude $B$ then acquires terms that go, for large $s$ and fixed $u$, like $s^0 \ln s$. We suggest that the nucleon pole now moves too.

The variation of $\alpha$ for the nucleon in perturbation theory can then be studied as follows: The contribution of a Regge pole with the parity of the nucleon is given in Eq. (4.21) of reference 9. However, in order to satisfy the symmetry condition of MacDowell[10] and Frautschi and Walecka,[11] there must be a related Regge pole with the opposite parity. The two $\alpha$'s become coincident at $u = 0$ and complex conjugates of each other for $u$ negative.[12,13]

Using the two equations, we have for the com-