Professor W. H. Barkas for his continuing interest in this work.

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[11]Several groups, seeking to demonstrate the association of the A_2^0 peak with ρ production, show plots of the 3π mass distribution for events in which no di-pion combination makes a ρ. These plots all show marked dips near 1 GeV. See, for example, C. Baltay, L. Kirsch, H. H. Kung, N. Yeh, and M. Rabin, Phys. Letters 25B, 160 (1967); Bari-Bologna-Firenze-Orsay Collaboration, Phys. Letters 25B, 53 (1967).

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OBSERVATION OF A $\rho^-\rho^0$ ENHANCEMENT AT 1710 MeV †

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In this Letter we present evidence for a strong $\rho^-\rho^0$ enhancement in the reaction $\pi^-p \to p\rho^-\rho^0$ at 8 GeV/c. We interpret the enhancement as a resonance with a mass of 1710 ± 23 MeV and a width of 162^{+58}_{-40} MeV. Branching ratios for different decay modes of the resonance are studied. The relation of this resonance to the previously reported[1-8] $g(1650)$ is discussed.

In this experiment we have studied the following reactions:

$$\pi^-p \to p\pi^+\pi^-\pi^-\pi^0 \text{ (1970 events)}, \quad (1)$$

$$\to n\pi^+\pi^+\pi^-\pi^- \text{ (783 events)}, \quad (2)$$

$$\to n\pi^+\pi^- \text{ (1321 events)}, \quad (3)$$

and

$$\to p\pi^-\pi^0 \text{ (708 events)}, \quad (4)$$

at 8 GeV/c. The interactions occurred in the Brookhaven 80-in. hydrogen bubble chamber and were separated from samples of about 20 000 two-prong and 20 000 four-prong interactions on the basis of GRIND fits and requirements of ionization consistency. Details of the event separation procedure will be published elsewhere.[9]

The $\pi^+\pi^-$ effective-mass distribution for events of Reaction (1) which are not in the $N^{*++}(1236)$ region is shown in Fig. 1(a). The curve shown is a maximum likelihood fit to the data of the form $PS(1 + a\mathrm{BW})$. The parameter a is proportional to the intensity of BW, a constant width Breit-Wigner resonance function. PS is a phase space for Reaction (1) modified by the factor e^{bt}, where t is the momentum transfer from the target to the final-state proton. To fit the distribution of this momentum transfer, a value of 3.5 was chosen for b. Production of the ρ^0 is evident. Our fit indicates that 219 ± 29 events involve ρ^0 production. An identical analysis of the $\pi^-\pi^0$ mass distribution indicates the presence of 116 ± 33 events involving ρ^- production. Since these fits were performed independently, they do not indicate the presence or absence of the reaction

$$\pi^-p \to p\rho^-\rho^0 \quad (5)$$

in our data.

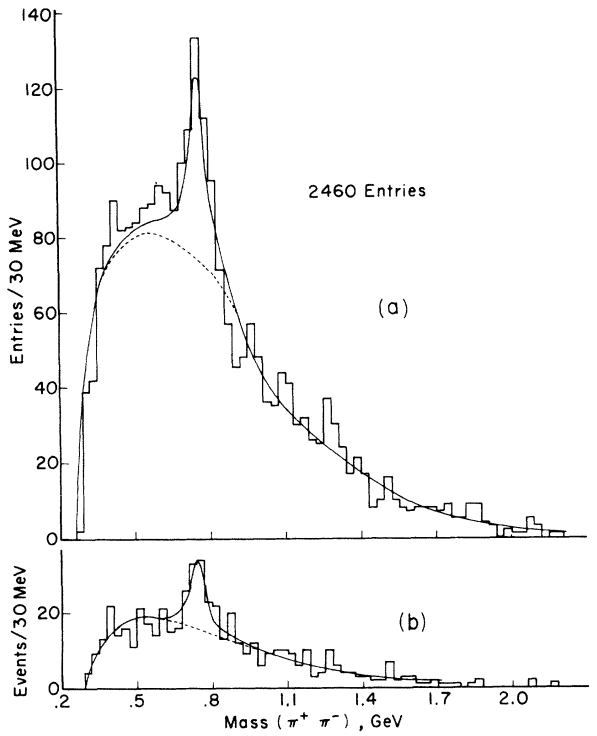

FIG. 1. Distributions of $M(\pi^+\pi^-)$ for events of the reaction $\pi^-p \to p\pi^+\pi^-\pi^-\pi^0$. Events with 1150 MeV $\leq M(\pi^+p) \leq 1310$ MeV and events with four-momentum transfer from the target to the final-state proton greater than 2.0 $(\mathrm{GeV}/c)^2$ have been excluded. The solid curves represent fits to the data including ρ^0 meson and background contributions as described in the text. The dashed curves represent the background. (a) $M(\pi^+\pi^-)$ for all $\pi^+\pi^-$ pairs in 1230 events. (b) $M(\pi^+\pi_1^-)$ for 528 events with $660 \leq M(\pi_2^-\pi^0) \leq 860$ MeV.

In order to see if Reaction (5) takes place, we have performed several tests. The results of the first test are shown in Fig. 1(b) which shows the $\pi^+\pi_1^-$ effective-mass distribution for those events in Fig. 1(a) whose $\pi_2^-\pi^0$ effective mass falls in the ρ^- region.[10] The presence of the ρ^0 meson is again evident. The number of ρ^0 events is 74 ± 17. Furthermore, if the $\pi^-\pi^0$ effective mass is plotted for those events whose $\pi^-\pi^+$ effective mass is in the ρ^0 region, a similar fit shows the presence of 65 ± 20 ρ^- events. (Both of these peaks yield parameters for the ρ mass and width consistent with accepted values.) The fact that these peaks are rather large suggests the presence of the $p\rho^-\rho^0$ final state, but in order to demonstrate the presence of double-ρ production, we must still show that these two peaks are not just due to single-ρ production of the types

$$\pi^-p \to p\rho^0\pi^-\pi^0, \tag{6}$$

$$\pi^-p \to p\rho^-\pi^+\pi^-. \tag{7}$$

Utilizing FAKE events of Reactions (6) and (7) we have determined that even if all of the 219 events produced with a ρ^0 were from Reaction (6), the $\pi^+\pi^-$ peak with a ρ^- cut should consist of only 30 ± 4 events. Similarly, for events of Reaction (7) with a ρ^0 cut, the ρ^- peak should be only 16 ± 4 events. We thus conclude that the peaks are too large to be caused solely by Reactions (6) and (7) and therefore that double-ρ production is significant.

In order to determine the number of double-ρ events in our data, we have used four measured numbers (the total numbers of ρ^0 and ρ^- events as well as the numbers of ρ^0 events in the ρ^- peak and ρ^- events in the ρ^0 peak) to determine three unknowns [the numbers of events corresponding to Reactions (5)-(7)] using a least-squares technique. The solution yields 77 ± 26 events of the reaction $\pi^-p \to p\rho^-\rho^0$, 143 ± 47 events of the reaction $\pi^-p \to p\rho^0\pi^-\pi^0$, and 42 ± 50 events of the reaction $\pi^-p \to p\rho^-\pi^+\pi^-$. (The latter two numbers exclude double-ρ production.)

An independent test for the presence of Reaction (5) was performed assuming that events on either side of the ρ^0 and ρ^- mesons in the di-pion mass spectra were good approximations to the non-ρ $\pi\pi$ background under the ρ peaks. If we require a $\pi_1^-\pi^0$ mass and a $\pi_2^-\pi^+$ mass to be simultaneously in the ρ region, 660 to 860 MeV, we get candidates for Reaction (5). If we subtract the non-ρ production as estimated from the distribution of events satisfying similar mass requirements in regions adjacent to the ρ region and then correct for true $\rho\rho$ events lost in the ρ mass cuts, we find from this test that there should be 156 ± 33 events of Reaction (5) in our sample, a number consistent with that quoted in the previous paragraph.

From these analyses we conclude, by taking a weighted average of the two numbers, that approximately 112 events of Reaction (5) are present in our data corresponding to a cross section of ~71 μb.

Figures 2(a)-2(c) and 2(d)-2(f) show the 4π mass distributions for Reactions (1) and (2), respectively. We show in Figs. 2(a) and 2(d) the overall 4π mass distributions; in Figs. 2(b) and 2(e), the distributions which result when we require that at least one $\pi\pi$ mass fall in the ρ re-

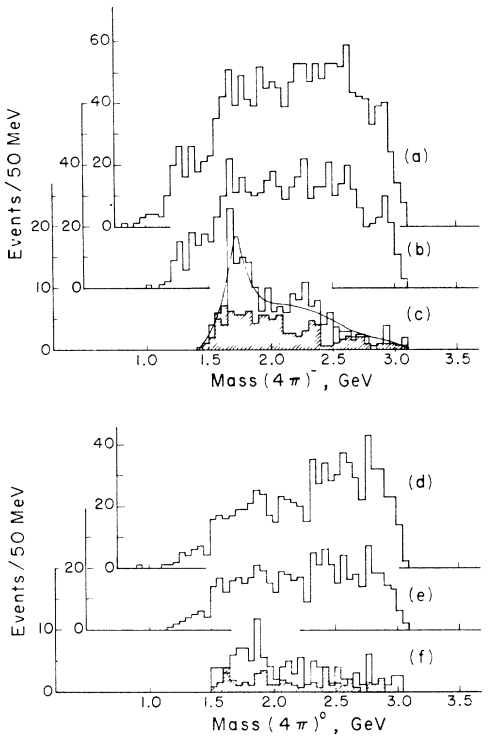

FIG. 2. Distributions of $M(4\pi)^-$ for events of the reaction $\pi^-p \to p\pi^+\pi^-\pi^-\pi^0$ [$N^{*++}(1236)$ events removed] and $M(4\pi)^0$ for events of the reaction $\pi^-p \to n\pi^+\pi^+\pi^-\pi^-$. (a) $M(4\pi)^-$ for 1501 events. (b) $M(4\pi)^-$ for 1025 events with at least one $M(\pi^+\pi^-)$ or $M(\pi^-\pi^0)$ in the ρ region (660-860 MeV). (c) $M(4\pi)^-$ for 199 events with $M(\pi^+\pi_1^-)$ and $M(\pi_2^-\pi^0)$ both in the ρ region. The shaded histogram is an estimate of the non-$\rho\rho$ background. The curve represents a fit to the data including background and a single Breit-Wigner resonance ($M = 1717 \pm 23$ MeV, $\Gamma = 162^{+58}_{-40}$ MeV). (d) $M(4\pi)^0$ for 783 events. (e) $M(4\pi)^0$ for 558 events with at least one $M(\pi^+\pi^-)$ in the ρ region. (f) $M(4\pi)^0$ for 118 events with two non-overlapping $\pi^+\pi^-$ mass combinations in the ρ region. The shaded histogram is an estimate of the non-$\rho\rho$ background as described in the text.

gion; and in Figs. 2(c) and 2(f), the distributions resulting when two $\pi\pi$ mass combinations are required to fall simultaneously in the ρ region. In addition, the shaded histograms in Figs. 2(c) and 2(f) are estimates of the non-$\rho\rho$ background in the $\rho\rho$ region described in the preceding paragraph. A $\rho^-\rho^0$ enhancement in the 1700-MeV mass region[11] is apparent in Fig. 2(c); in Fig. 2(f) there is no strong evidence for a corresponding $\rho^0\rho^0$ enhancement.[12] Since no peak occurs in the shaded histogram of Fig. 2(c), and since the peak is strong only for the $\rho^-\rho^0$ selection, we conclude that the $\rho^-\rho^0$ peak is a real $\rho\rho$ effect, which we shall hereafter refer to as g'.

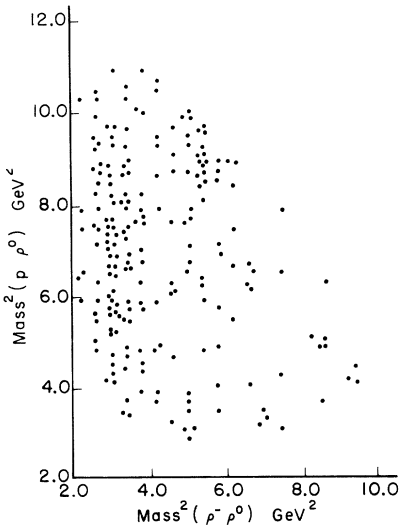

FIG. 3. Dalitz plot of $M^2(p\rho^0)$ vs $M^2(\rho^-\rho^0)$ for 199 events consistent with the reaction $\pi^-p \to p\rho^-\rho^0$. For eight events in which the choice of the $\pi\pi$ combinations for the ρ mesons is ambiguous, two points per event have been plotted.

The Dalitz plot of Reaction (5) is shown in Fig. 3. The events are seen to be concentrated along a band with low $\rho^-\rho^0$ mass; this effect is not associated with any structure in the $p\rho^-$ or the $p\rho^0$ mass distributions.

We next consider the possibility that the g' enhancement might be a Deck-type kinematic effect involving single-pion exchange. The most obvious candidate for such a mechanism involves dissociation of the beam pion into a $\rho\pi$ system combined with the process $\pi N \to N\rho$ at the baryon vertex; the virtual processes involved at the baryon vertices are $\pi^0p \to p\rho^0$ and $\pi^-p \to p\rho^-$ for Reaction (5) and $\pi^-p \to n\rho^0$ for the reaction $\pi^-p \to n\rho^0\rho^0$. The real $\pi^-p \to p\rho^-$ and $\pi^-\rho \to n\rho^0$ processes are known to have a cross section ratio of about 1:2 over a wide range of incident momentum, presumably due to the dominance of one-pion exchange. Since the reaction $\pi^0p \to p\rho^0$ cannot proceed via one-pion exchange, we expect a negligible contribution to the Deck effect from this reaction. Therefore, if we observe a $\rho^-\rho^0$ kinematic enhancement, we should observe an even larger effect in the $\rho^0\rho^0$ distribution. The absence of a strong $\rho^0\rho^0$ enhancement tends to rule out this mechanism.

We conclude that the $\rho^-\rho^0$ effect observed in this experiment is a resonance. A fit to the $\rho^-\rho^0$ mass distribution of Fig. 2(c) with a single Breit-Wigner peak and a hand-drawn estimate of background yields the value 1710 ± 23 MeV for

the g' mass and 162^{+58}_{-40} MeV for its width. The cross section for production of the g' with subsequent $\rho^-\rho^0$ decay is 60 ± 20 μb.

We have attempted to determine the g' branching ratios into $\rho\pi\pi$ and 4π. Any quantitative limits on branching ratios depend upon the background which is assumed for the 4π and the $\rho\pi\pi$ mass distributions. Since no significant enhancements are observed in Figs. 2(d)-2(f), we have used as background smooth curves drawn through the $(4\pi)^0$, $(\rho\pi\pi)^0$, and $\rho^0\rho^0$ mass distributions and normalized to the $(4\pi)^-$, $(\rho\pi\pi)^-$, and $\rho^-\rho^0$ data above 2.0 GeV. From the numbers of excess events between 1650 and 1850 MeV in Figs. 2(a)-2(c), the following upper limits at the 90% confidence level are obtained:

$$(g' \to \rho\pi\pi)/(g' \to \rho\rho) < 0.25$$

and

$$(g' \to \rho\pi\pi + 4\pi)/(g' \to \rho\rho) < 0.37.$$

In the same experiment we have observed a g^0 enhancement in the $\pi^+\pi^-$ mass distribution of Reaction (3), with a mass of 1697 ± 29 MeV and a width of 194^{+74}_{-44} MeV, produced with a cross section of 54 ± 13 μb.[13] The $g^\pm$ di-pion reported in some experiments[4,5] is not strongly produced in Reaction (4) at this energy; we find[14] an upper limit of 0.34 at the 90% confidence level for the ratio $(\pi^-p \to pg^- \to p\pi^-\pi^0)/(\pi^-p \to ng^0 \to n\pi^+\pi^-)$.

Since the measured mass and width of the g ($I^G = 1^+$)[15] and the g' are in good agreement, the question arises as to whether they are decay modes of the same resonance. To be consistent with this hypothesis the g' must have $I^G = 1^+$ (thus ruling out a possible $\rho^0\rho^0$ decay) and, in addition, the resonance must decay primarily into $\rho\rho$. [We find an upper limit of 0.48 at the 90% confidence level for the branching ratio[14] $(g \to \pi\pi)/(g \to \rho\rho)$.][16] If the g' and g are indeed decay modes of a single $I^G = 1^+$ resonance,[17] this resonance must have J^P in the series $1^-, 3^-, 5^-$.

This experiment was made possible by the help and cooperation of the Shutt bubble-chamber group and the alternating-gradient synchrotron personnel of Brookhaven National Laboratory. We wish to acknowledge the assistance of Mr. J. B. Annable and Mr. R. J. Schlentz with the data analysis, and the efforts of the Notre Dame scanning and measuring staff. Dr. J. W. Andrews, Dr. J. W. Lamsa, Mr. E. Harrington, Mr. W. B. Madden, and Mr. P. H. Smith have assisted in the preparation of the data.

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[10]Since there are two π^- mesons in the final state for Reaction (1), it is possible for two $\pi^-\pi^0$ combinations to form a ρ^-. In this case, we have chosen as the ρ^- that $\pi^-\pi^0$ pair whose effective mass is nearest 760 MeV.

[11]There are 40 ± 10 events above a background of ~26 events in the region $1650 \leq M(\rho^-\rho^0) \leq 1850$ MeV. In addition there are 28 ± 9 events above a background of ~21 events in the region $2100 \leq M(\rho^-\rho^0) \leq 2400$ MeV, providing some evidence for an additional $\rho^-\rho^0$ enhancement centered at a mass of 2250 MeV.

[12]In the region between 1650 and 1850 MeV there is an excess of 11 ± 7 events above an estimated background of ~15 events.

[13]N. N. Biswas et al., in Third Topical Conference on Resonant Particles, Athens, Ohio, 1967 (unpublished), and Poirier et al., Ref. 9.

[14]The ratios $(\pi^-p \to pg^-)/(\pi^-p \to ng^0)$ and $(g \to \rho\rho)/(g \to \pi\pi)$ are found by counting events above the estimated background in the mass range $1600 \leq M \leq 1800$ MeV.

[15]A recent experiment indicates that I^G is 1^+ for the g^0 meson from the absence of any $\pi^0\pi^0$ decay mode. See N. Armenise et al., in Proceedings of the International Conference on Elementary Particles, Heidelberg, Germany, 1967, edited by H. Filthuth (North-Holland Publishing Company, Amsterdam, The Netherlands, 1968).

[16]Although the $\pi\pi$ decay mode has more phase space available than the $\rho\rho$ mode, there is a greater angular-momentum barrier for $\pi\pi$ decay if $J(g) \geq 1$. For reasonable choices of interaction radii the ratio observed is consistent with $g = g'$. D. Loebbaka, private communication.

[17]The mass spectrometer experiment of Dubal et al., to be published, suggests that there may be three peaks in the 1600- to 1750-MeV region, the R_1 with mass 1630 ± 15 MeV, the R_2 at 1700 ± 15 MeV, and the R_3 at 1748 ± 16 MeV. Our $\rho^-\rho^0$ enhancement might be consistent with four-pion peaking reported by Danysz et al. (see Ref. 1) who appear to resolve two enhancements, one at 1717 ± 7 MeV and one at 1832 ± 6 MeV, both with widths about 40 MeV. We feel that our single peak could be consistent with these values where we have not resolved the two peaks.