†This work was begun and partially completed while the author was at Princeton University, Princeton, N. J.

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OBSERVATION OF A $pp\bar{p}$(3755) ENHANCEMENT IN THE REACTION $\pi^+p \rightarrow \pi^+pp\bar{p}$ AT 8.4 BeV/c*

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(Received 29 November 1967)

The existence of nucleon isobars having masses of 3030, 3230, 3245, and 3695 MeV has been reported in different experiments.[1-3] We report the observation of a narrow enhancement seen in the $pp\bar{p}$ invariant-mass spectrum in a study of the reaction $\pi^+p \rightarrow \pi^+pp\bar{p}$. If this enhancement is interpreted as the $pp\bar{p}$ decay of a nucleon isobar, then the resonance parameters are $M = 3755 \pm 8$ MeV and $\Gamma = 40 \pm 20$ MeV.

The sample of events for this study is obtained from a systematic investigation of π^+p interactions at 8.45 BeV/c in a 65 000-picture exposure[4] of the Brookhaven National Laboratory 80-in. hydrogen bubble chamber. The events are part of a sample of approximately 15 000 events having the topology of four prongs and no kinks. In addition, all events in the sample have at least one outgoing track clearly identifiable as a proton on the scanning table. This restriction corresponds to a proton momentum below about 1 BeV/c, and it was made to enrich the sample of events for the study of pionic resonances.[5]

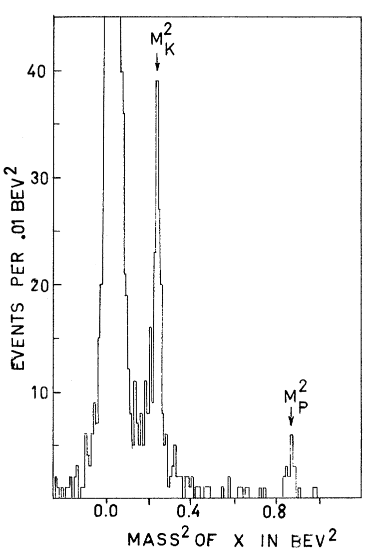

FIG. 1. Distribution in the square of the $X^\pm$ rest mass for 2964 events of the type $\pi^+p \rightarrow \pi^+pX^+X^-$. X^+ and X^- here represent any long-lived particle-antiparticle pair. Each event is plotted twice due to the X^+-π^+ ambiguity. The peak centered at 0.02 BeV^2 has a height of 2356 and a half-width of 0.007 BeV^2.

Events corresponding to the reaction $\pi^+p \rightarrow \pi^+pp\bar{p}$ were identified in the following way: All four-prong events not consistent with momentum conservation, assuming no neutrals to be present, were first rejected. The remaining events were assumed to correspond to reactions of the type $\pi^+p \rightarrow \pi^+pX^+X^-$, where X^+ and X^- represent any long-lived particle-antiparticle pair. After adjusting only the incoming momentum, so as to conserve momentum exactly, energy conservation was then used to calculate the rest mass of the X particle.[6] The resulting distribution in the X mass squared, in Fig. 1, shows three clearly separated peaks, corresponding to the following reactions:

$$\pi^+p \rightarrow \pi^+p\pi^+\pi^-, \text{ 2779 events;} \quad (1)$$

$$\pi^+p \rightarrow \pi^+pK^+K^-, \text{ 162 events;} \quad (2)$$

$$\pi^+p \rightarrow \pi^+pp\bar{p}, \text{ 21 events.} \quad (3)$$

Each event is plotted twice, as the X^+ and the π^+ tracks are generally indistinguishable. Calculating the X mass using the wrong assignment of tracks will introduce some background only for events corresponding to Reactions (2) and (3).

All events outside the pion peak in Fig. 1 were kinematically fitted in GRIND, resulting in the numbers of events for Reactions (2) and (3) given above. None of the events fitting Reaction (3) fit any other hypothesis. In Fig. 2, the square of the four-momentum difference between the incoming π^+ and the outgoing π^+ is plotted against the $pp\bar{p}$ invariant mass. In the mass projection of this plot, a significant deviation from phase space[7] may be seen centered at 3755 MeV. In the interval 3700-3825 MeV, 14 of the 21 events are found instead of the four expected from phase space. The probability of getting a fluctuation this large anywhere in the spectrum is 5×10^{-5}.

Possible evidence against the resonance interpretation of the 3755 enhancement comes from the fact that the $p\pi^+$ invariant mass spectrum of these same events shows an enhancement near the mass of $N^*(1236)$, as may be seen in the plots in Fig. 3. In order to clarify the nature of the 3755 enhancement, we have attempted to answer the following questions: (1) If the events correspond to the final state $p\bar{p}N^*(1236)$, should a narrow peak be seen in the $pp\bar{p}$ mass spectrum at 3755 MeV? (2) If the events correspond to the final state $\pi^+N^*(3755)$, should a peak be seen in the $p\pi^+$ mass spectrum near 1236 MeV? We believe that the answer to (1) is no and the answer to (2) is yes, favoring the resonance interpretation of the 3755-MeV $pp\bar{p}$ enhancement.

To make a calculation of the $pp\bar{p}$ invariant-mass spectrum resulting from the final state $p\bar{p}N^*(1236)$ requires certain assumptions about the $p\bar{p}$ production mechanism. As an alternative procedure, we have made a Monte Carlo calculation in which 420 fake events were generated by choosing the momenta of the $p\bar{p}$ pair from one of the 21 real events and choosing the $N^*(1236)$ decay angle from each of the other 20 events.[8] The $pp\bar{p}$ mass spectrum for the fake events is the jagged curve in Fig. 2. As the fake events were generated from the real ones, it is not surprising that the agreement with the experimental distribution is somewhat better than it is for phase space. However, the discrepancy is still quite significant, as only six events would be expected in the interval 3700-3825 MeV.

A similar Monte Carlo calculation was made to determine the $p\pi^+$ invariant-mass spectrum from the final state $\pi^+N^*(3755)$. The result is as prominent a peak at the mass of the $N^*(1236)$ as seen in the experiment. The reason for this is that the $N^*(3755)$ is produced primarily at high four-momentum transfers, as seen in Fig. 2, giving rise to low-momentum π^+ in the laboratory (typically about 350 MeV/c). Owing to our scanning selection of events having a slow proton (average momentum about 700 MeV/c), the $p\pi^+$ invariant mass must neccessarily peak at a low value.

The fact that the $N^*(3755)$ is produced primarily at high four-momentum transfers may be associated with a very high spin.[9] It is not

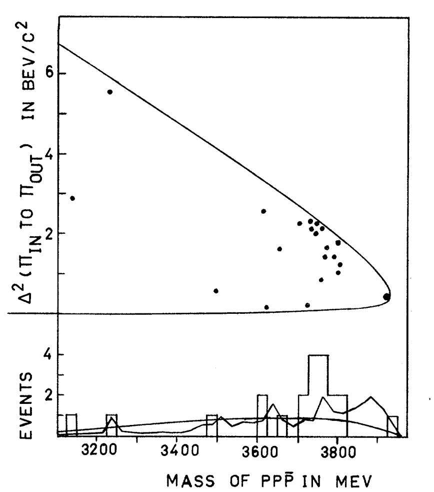

FIG. 2. Four-momentum transferred from incoming π^+ to outgoing π^+ plotted against the $pp\bar{p}$ invariant mass for 21 events having the final state $\pi^+pp\bar{p}$. In the mass projection of this plot, the smooth curve is phase space; the jagged curve is from a Monte Carlo calculation.

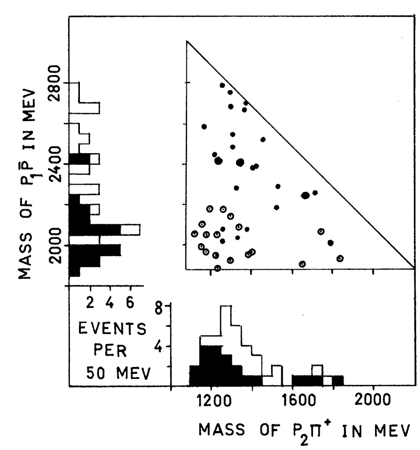

FIG. 3. $\bar{p}p_1$ invariant mass plotted against $p_2\pi^+$ invariant mass and the corresponding mass projections for 21 events having the final state $\pi^+pp\bar{p}$. Each event is plotted twice. In the scatter plot the circled points represent $p_1 = p_{fast}$ and $p_2 = p_{slow}$, and the uncircled points represent $p_1 = p_{slow}$ and $p_2 = p_{fast}$. These two cases are represented in the histograms by the shaded and unshaded areas, respectively.

clear as to which Regge trajectory an isobar with a mass of 3755 MeV may be assigned. If it is a recurrence of the $N^*(1512)$, then $J = 23/2^-$ and $I = \frac{1}{2}$.[10,11]

There is no clear evidence for other decay modes of an $N^*(3755)$ in this experiment, although some invariant-mass plots of the two final states nucleon plus four pion and nucleon plus eight pion are consistent with an $I_z = +\frac{1}{2}$ enhancement in the region[12] 3700-3800 MeV. The peak for the nine-body final state is not nearly so prominent as that seen in a previous experiment at the same energy.[3] A small peak is also seen in this mass region in the $pK\bar{K}$ invariant-mass spectrum in the final state $p\pi^+K^+K^-$. As it is difficult to determine the backgrounds, these enhancements are not at present clearly understood.

The prominence of the $pp\bar{p}$ enhancement does not necessarily imply a large branching ratio for $N^*(3755)$ into this mode. It may be due, instead, to the lack of other mechanisms for producing antiprotons in the final state $\pi^+pp\bar{p}$.

We want to take this opportunity to express our gratitude to the scanners and measurers at both Nevis Laboratory and Rutgers, who have worked on this experiment. We also wish to thank Dr. Monroe Rabin, Dr. Noel Yeh, and H. Kung for their work in the data-reduction phase of this experiment, and Wolfgang Mayer for his help during the final analysis of the experiment.

*Work supported by the National Science Foundation.

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[4]There were approximately ten tracks per picture, giving approximately 3 events/μb of cross section.

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[6]There are several advantages of this technique over straight kinematical fitting: (1) Events in which the measured variables have large errors and could therefore fake a four-constraint fit are largely eliminated. (2) A single number, i.e., m_x, indentifies the reaction rather than the relative chi squares for a number of fits. (3) One can determine the experimental resolution. If, for example, the m_x^2 distribution did not peak at K and p masses (Ref. 2), events in these mass regions would still presumably give good fits to the final states $\pi^+pK^+K^-$ and $\pi^+pp\bar{p}$, but these fits would clearly not be believable. (4) Finally, much computer time can be saved in identifying rare four-constraint final states such as this.

[7]The phase-space curve shown in Fig. 2 has not been corrected for the loss of events caused by the clear proton selection. We have estimated that this bias could modify the shape of phase space to the extent that as many as five to seven events might be expected in the $pp\bar{p}$ mass interval 3700-3825 MeV depending on the production mechanism.

[8]If the real events correspond to the final state $p\bar{p}N^*(1236)$, then the fake events so generated must have the same $pp\bar{p}$ mass distribution as the real ones, insofar as the production of the $p\bar{p}$ pair and the decay of the $N^*(1236)$ are independent processes. Any difference between the two distributions is evidence against the $p\bar{p}N^*(1236)$ interpretation. The fact that the fake events are generated from the real ones strengthens the validity of this test.

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