Search for Narrow $\bar{p}p$ States in the Reaction $\pi^+p \to \Delta_f^{++}\bar{p}p$

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The results of a search for narrow $\bar{p}p$ states produced in the baryon-exchange reaction $\pi^+p \to \Delta_f^{++}\bar{p}p$ at 9.8 GeV/c are reported. This channel provides an enhanced sensitivity to such states compared with the reaction $\pi^-p \to \Delta_f^0\bar{p}p$. We find no evidence for such states at the 20–30-nb level in the mass range 1.9–2.3 GeV/c^2. Assuming a nucleon-exchange production mechanism, the states which have been reported in π^-p interactions at 2.02 and 2.20 GeV/c^2 would appear as > 5-standard-deviation peaks in this data.

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Using the baryon-exchange reaction

$$\pi^+p \to \Delta_f^{++}(1232)X^0, \quad \Delta_f^{++} \to \pi^+p_f, \quad X^0 \to \bar{p}p \tag{1}$$

at 9.8 GeV/c, we have searched for possible structures in the $\bar{p}p$ effective-mass spectrum from threshold to 2600 MeV/c^2. These results are from an experiment designed to search for new states in π^+p interactions leading to fast forward protons, antiprotons, or charged kaons. In particular, we have looked for evidence of two narrow peaks at 2020 and 2200 MeV/c^2 reported by Benkheiri *et al.* in the reaction

$$\pi^-p \to \Delta_f^0(1232)X^0, \quad \Delta_f^0 \to \pi^-p_f, \quad X^0 \to \bar{p}p \tag{2}$$

at 9 and 12 GeV/c in an experiment at the CERN Omega spectrometer.[1] We chose Reaction (1) to achieve the enhanced sensitivity for it predicted by most baryon-exchange descriptions of processes (1) and (2). In view of the extensive theoretical speculation concerning nucleon-antinucleon states in both quark and potential models,[2] confirmation of the existence of narrow $\bar{p}p$ states under the most favorable experimental circumstances is important.

The multiparticle spectrometer (MPS) at the Brookhaven National Laboratory alternating-gradient synchrotron was used to detect all four charged tracks from Reaction (1). Forward tracks were detected by planar chambers while cylindrical spark chambers surrounding the 61-cm-long liquid-hydrogen target measured tracks at large angles. The experimental arrangement was similar to that used in an earlier experiment to study other baryon-exchange reactions.[3]

The trigger required a forward particle with momentum ⩾ 5.5 GeV/c which did not register in an atmospheric Cherenkov counter filled with Freon 114. Momentum selection was performed by the MPS RAM (random-access memory) trigger facility,[4] which required a three-point correlation among two multiwire proportional chambers in the MPS magnet and a 112-element scintillation counter hodoscope downstream of the Cherenkov counter. Only one charged particle was allowed in the hodoscope. A multiplicity of ⩾ 3 hits was required in eight scintillation counters surrounding the hydrogen target summed with a multiwire proportional chamber 129 cm downstream of the target center.

For this data sample (roughly half of the total), about 850 000 events were recorded meeting these trigger requirements. In addition, a sample of events with known meson-exchange cross sections was collected with the same trigger requirements except that a coincidence was required with the Cherenkov counter to select forward pions. Pion elastic-scattering events at 6, 8, and 10 GeV/c were also recorded to study the momentum resolution of the fast track.

Following pattern recognition and momentum fitting, events were selected with four charged prongs coming from a common vertex within the liquid-hydrogen target volume. Most of the events had one or two prongs with insufficient track length to determine their momentum accurately. An iteration procedure was adopted which simultaneously determined whether the prongs came from a common vertex and the momentum imbalance at this vertex. Events with a momentum imbalance of ⩽ 200 MeV/c were saved for further analysis.

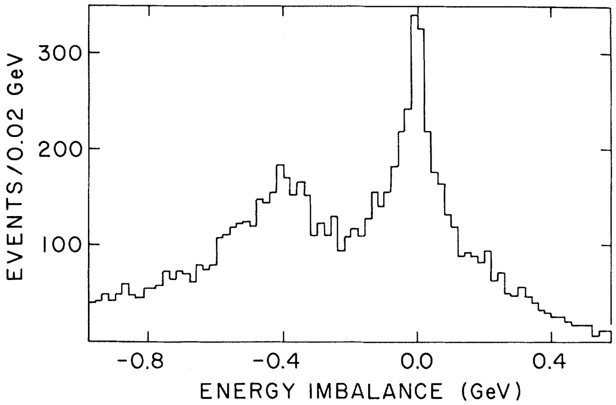

FIG. 1. Energy imbalance for all $\pi^+ p \to p_f \pi^+ \bar{p}p$ candidates with $M(p_f\pi^+) \leq 1.5$ GeV/c^2 and missing mass to the $p_f\pi^+ > 1.80$ GeV/c^2.

To identify the process $\pi^+p \to p_f\pi^+\bar{p}p$, all momentum balancing candidates were fitted to that hypothesis and the imbalance in energy calculated. Figure 1 shows the result for events having a $p_f\pi^+$ mass in the $\Delta(1232)$ region. A clear peak at 0 is evident. The background includes the process $\pi^+p \to p_f\pi^+K^-K^+$ (the second peak), reactions with a forward-K^+ trigger track, and events with additional missing particles. Events with energy imbalance ≤ 100 MeV and momentum imbalance of ≤ 150 MeV/c were selected for the final data sample.

In Fig. 2 the effective mass of the π^+ and the trigger proton is shown. The $\Delta(1232)$ is apparent, more prominent in fact than observed in $\pi^-p \to \Delta_f^0\bar{p}p$ in agreement with expectation based on isospin arguments.[5]

Figure 3(a) shows the effective-mass spectrum

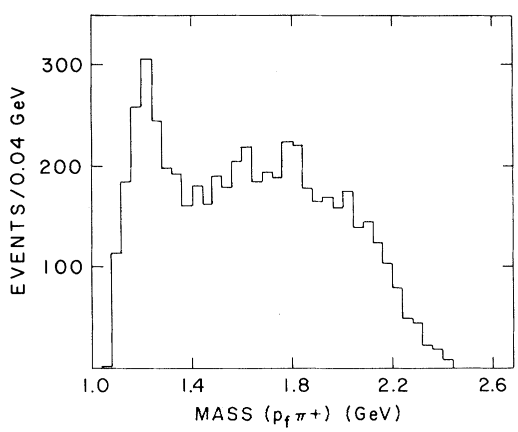

FIG. 2. Effective-mass distribution of the $p_f\pi^+$ system for all accepted events.

of the slow $\bar{p}p$ recoil system for those events satisfying the hypothesis of Reaction (1), but without the requirement of a forward Δ^{++}. There are no significant peaks.

In order to compare our results with those of Benkheiri *et al.*,[1] we have applied requirements that $|u'| < 0.6$ (GeV/c)^2 between the incident π^+ and the outgoing Δ^{++} and that the $p_f\pi^+$ effective mass be ≤ 1350 MeV/c^2. Figure 3(b) shows the effective-mass spectrum of the recoiling $\bar{p}p$ system with a forward Δ^{++}. There are 1140 events in the plot. The background is estimated to be ~32%. As can be seen from the figure, the spectrum is again smooth with no evidence for structure. A fifth-order-polynomial fit in the region

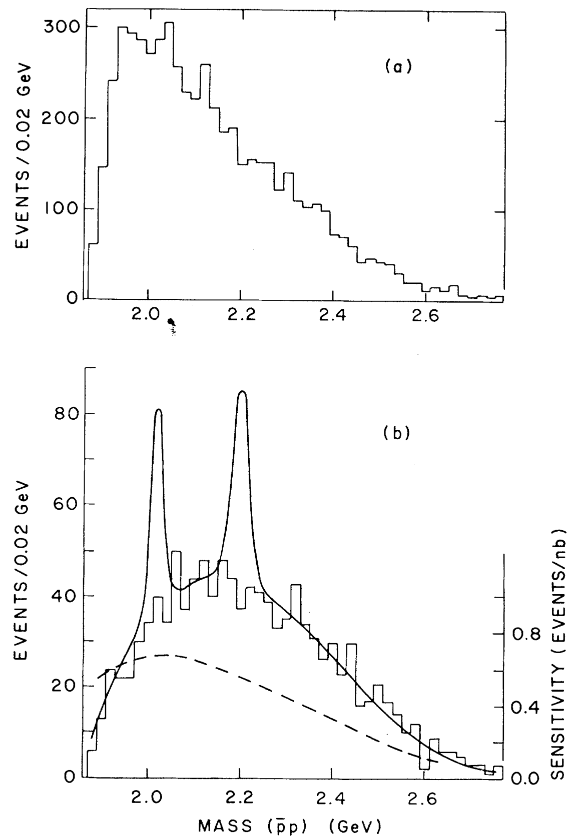

FIG. 3. (a) $\bar{p}p$ effective-mass distribution of all accepted events. (b) Same as in (a) but requiring $M(p_f\pi^+) \leq 1.35$ GeV/c^2 and $u'(\pi^+ \to \Delta^{++}) > -0.6$ (GeV/c)^2. The solid line in (b) is the sum of a polynomial fit to the mass spectrum of this experiment and the signals expected from nucleon-exchange production of the states reported in Ref. 1 at 2020 and 2200 MeV/c^2 taking into account the mass resolution and sensitivity of this experiment. The dashed line in (b) is a plot of the sensitivity vs $\bar{p}p$ effective mass and refers to the scale on the right.

from threshold to 2450 MeV/c^2 has a χ^2 of 54 for 51 degrees of freedom. The number of events in our spectrum with the Δ^{++} and u cuts is approximately equal to that of the summed 9- and 12-GeV/c data with the Δ^0 selection of Benkheiri *et al.*[1] A qualitative comparison of the two spectra indicates a similar shape outside the region of their two narrow peaks.

The Jackson-angle cut used by Benkheiri *et al.*[1] to reduce the non–baryon-exchange background was also applied. Here θ_J is the angle between the target proton and the slow proton in the $\bar{p}p$ c.m. system. The resulting $\bar{p}p$ effective-mass spectrum of Reaction-(1) events requiring $\cos\theta_J < 0$ is also without significant structure.

The following factors were included in the determination of the efficiency for the events in Fig. 3(b). For several $\bar{p}p$ effective-mass values, a Monte Carlo calculation was used to determine the geometrical acceptance, the acceptance of the triggering elements including the RAM, and losses from the selection criteria. An overall pattern-recognition efficiency of 80% was determined by visually scanning events reconstructed by the computer. Other reductions in the sensitivity were produced by absorption of the four prongs in the target and the detectors, muon contamination in the π^+ beam, and the efficiency of the vertex-finding program.

The calculated sensitivity to Reaction (1) as a function of $\bar{p}p$ effective mass is given by the dashed curve in Fig. 3(b). Including the triggering, reconstruction, and correction uncertainties, the absolute normalization error is estimated to be $\leq 20\%$. We have checked our sensitivity by measurements of elastic scattering and of the process $\pi^+p \to \rho_f^0\Delta^{++}$ which is topologically similar to Reaction (1). These cross sections agree with published data[6] to within 15%. We find that the momentum-transfer and Jackson-angle distributions for the ρ^0 and Δ^{++} agree well with other measurements, indicating that the topological acceptance for four-prong events is well understood. Finally, our cross section for the process $\pi^+p \to p_f\pi^+\bar{p}p$ with the p_f and π^+ emitted forward and the $\bar{p}$ and p emitted backward in the overall center-of-mass system is consistent with previous bubble-chamber measurements of this process.[7]

A Monte Carlo program, which generated spark positions with the appropriate spatial resolutions as determined from our elastic-scattering data, was used to determine the effective-mass resolution. This program correctly reproduced the observed narrow width of the recoil $\bar{K}^0{}_s$ in the reaction $\pi^+p \to K^+{}_f p\bar{K}^0{}_s$, with the subsequent decay $\bar{K}^0{}_s \to \pi^+\pi^-$. The width of the energy balance peak, which is related to the mass resolution, was correctly reproduced by the Monte Carlo program. The calculated standard deviations of our $\bar{p}p$ effective-mass resolution at 2000, 2200, and 2500 MeV/c^2 are 10, 14, and 19 MeV/c^2, respectively.

A quantitative comparison between the results presented using Reaction (2) and our results using Reaction (1) requires some understanding of the dominant production mechanism. Experiments on backward elastic scattering have indicated the dominance of nucleon exchange over most of the range of momentum transfer.[8] Similarly other baryon-exchange reactions have also indicated the dominance of the nucleon exchange over the Δ exchange.[9] Finally, the authors of Ref. 1 in a subsequent publication have noted the absence of the $\bar{p}n$ partner to their $\bar{p}p$ states, and have argued that nucleon exchange is dominant.[10] With the same event-selection criteria for Reactions (1) and (2), we find that the $\pi^+p \to \Delta_f^{++}\bar{p}p$ cross section of 2.3 ± 0.4 μb is 6.5 ± 1.5 times the Reaction (2) cross section reported by Benkheiri *et al.* This is closer to the value of 9 expected from nucleon exchange than to the value of 9/4 expected if Δ exchange dominates.

Assuming nucleon exchange for the production of the peaks at 2020 and 2200 MeV/c^2, one would predict from the reported cross sections signals above our smooth background of 68 and 69 events, respectively, in bins of 40 MeV/c^2 (chosen to optimize statistically the signal-to-background ratio). These events would appear in our spectra as 7.5-standard-deviation fluctuations above a smooth background of ~78 events per 40-MeV/c^2 bin. This is illustrated by the solid curve in Fig. 3(b) showing the expected signals on top of the smooth polynomial fit to our $\bar{p}p$ mass spectrum. If we include the normalization uncertainties of the two experiments, the statistical significance of the peaks if present would still exceed 5 standard deviations.

We can also derive from Fig. 3(b) a model-independent upper limit on the cross section for production with a $\Delta_f{}^{++}$ of a narrow resonant state at any $\bar{p}p$ mass in the 1.9–2.6-GeV/c^2 range covered by our experiment. A narrow resonance in this instance has $\Gamma < 23$, 17, and 22 MeV/c^2 for $\bar{p}p$ masses of 2000, 2200, and 2500 MeV/c^2, respectively. As noted above, this approach ignores the physics of baryon exchange and the resulting

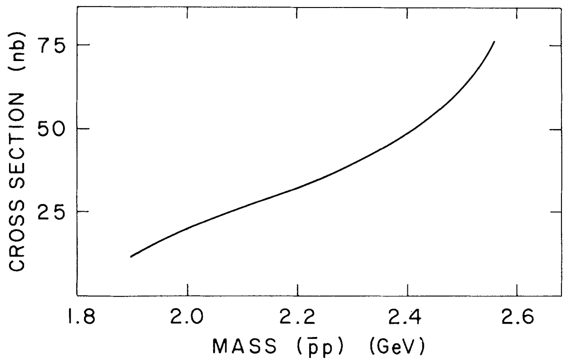

FIG. 4. 95% confidence limits for the production cross section of narrow mass $\bar{p}p$ states.

enhanced production expected in π^+p reactions. Figure 4 indicates the 95%-confidence-level cross-section limit over our mass range.[11]

In summary, we find no evidence for production of narrow $\bar{p}p$ states produced in $\pi^+p \to \Delta_f^{++}\bar{p}p$. In particular, we are unable to confirm the existence of states at 2.02 and 2.20 GeV/c^2 reported in $\pi^-p \to \Delta_f^0\bar{p}p$. Those states would appear as >5-standard-deviation effects in our experiment.

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Neutrino Mass and Spontaneous Parity Nonconservation

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In weak-interaction models with spontaneous parity nonconservation, based on the gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)$, we obtain the following formula for the neutrino mass: $m_{\nu_e} \simeq m_e^2/g m_{W_R}$, where W_R is the gauge boson which mediates right-handed weak interactions. This formula, valid for each lepton generation, relates the maximality of observed parity nonconservation at low energies to the smallness of neutrino masses.

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It is attractive to suppose that observed parity nonconservation in weak interactions is only a low-energy phenomenon, which ought to disappear at high energies. This idea has been implemented in unified gauge theories of electroweak interactions based on the gauge group $SU(2)_L \otimes SU(2)_R$