Search for Narrow $\bar{p}p$ States Produced by Meson Exchange

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The results are reported of a search for narrow $\bar{p}p$ states in the mass range 1.9 to 2.5 GeV/c^2 produced in the meson-exchange reaction $\pi^+p \to (\bar{p}p)_f \Delta^{++}$ at 9.8 GeV/c. This measurement is sensitive to production of the controversial $S(1935)$ meson. It is also sensitive to multiquark exchange leading to the production of four-quark states. We find no evidence for narrow states at the ~20-nb level.

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The search for multiquark mesons has centered on high-mass systems coupled to nucleon-antinucleon channels, either in formation or in production experiments. Several such mesons, apparently established with reasonable statistical accuracy,[1] have subsequently failed to be confirmed.[2] Particularly troublesome is the question of the $S(1935)$, seen in earlier $\bar{p}p$ formation experiments,[3] but unconfirmed in more recent experiments.[4] A similar situation exists for the low-mass $\bar{p}p$ states observed in several different production reactions.[5]

We report here the results of a search for production of narrow $\bar{p}p$ states in the reaction

$$\pi^+p \to (\bar{p}p)_f \Delta^{++} \tag{1}$$

at 9.8 GeV/c. It has been suggested that such a meson-exchange reaction at moderate energies might provide a unique opportunity to observe the production of narrow states by four-quark exchange, a mechanism consistent with the production of objects inhibited in their decay.[6] The only previous high-sensitivity search for these states was in the reaction

$$\pi^-p \to \bar{p}pn \tag{2}$$

which is dominated by low-t, pion-exchange production.[7] The slow t falloff of our data and the data of Ref. 5 argues against pion-exchange dominance for Reaction (1). Hence Reaction (1) could be more sensitive to four-quark exchange than Reaction (2). Because high-mass exchanges appear to be low-lying, 9.8 GeV/c provides a reasonable compromise between threshold production and the expected rapid s dependence.[8]

Our experiment utilized the cylindrical and planar spark chambers of the multiparticle-spectrometer (MPS) facility at Brookhaven National Laboratory to detect all four charged tracks. Results on the baryon-exchange process $\pi^+p \to \Delta_f^{++}\bar{p}p$ from this experiment have been published.[9] To detect the meson-exchange process (1) the trigger required a single forward, negatively charged particle with momentum >4.0 GeV/c which did not fire an atmospheric Cherenkov counter. In addition at least three particles had to be detected in a system of scintillation counters and multiwire proportional chambers surrounding the 61-cm-long liquid-hydrogen target. With this trigger ~450 000 events were recorded with a triggering cross section of 12 μb.

Following pattern recognition and track fitting, a least-squares fit constrained to balance momentum was used to select events with four charged prongs and no missing particles. To identify the process $\pi^+p \to \bar{p}_f p\pi^+p$ the tracks were assigned the appropriate masses which minimized the difference in energy between the final and initial states. Figure 1 shows the resulting energy-imbalance distribution. The clear peak at 0 due to Reaction (1) is evident, accompanied by a second well-separated peak at -0.4 GeV due to the process $\pi^+p \to K_f^-K^+p\pi^+$. Events with energy imbalance $< \pm 100$ MeV were selected for the final data sample. From the known distribution of energy imbalance for $K^-K^+p\pi^+$ events and the Monte Carlo–predicted resolution for $\bar{p}pp\pi^+$, we estimate the background of non-energy-balancing events to be ~30%. Figure 2 shows the effective-mass spectrum of the slower proton and the π^+. The $\Delta(1232)$ is apparent, accounting for ~60% of the events shown.

In Fig. 3(a) the effective-mass spectrum of the forward $\bar{p}p$ system is shown. The spectrum is smooth with no evidence for narrow peaks. A smooth polynomial curve over the region 1.88 to 2.6 GeV/c^2 yields an acceptable fit. The $\bar{p}p$ effective-mass spectrum for events of Reaction (1) [$M(p\pi^+) < 1.4$ GeV/c^2] is given in Fig. 3(b). Again

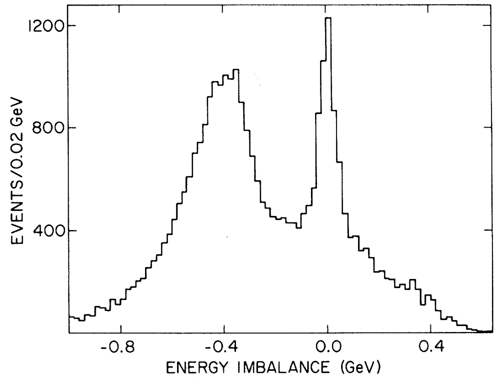

FIG. 1. Energy imbalance for the hypothesis $\pi^+ p \to \bar{p}_f p p \pi^+$. Events satisfying the hypothesis appear in the peak at 0; the second peak is due to the reaction $\pi^+ p \to K_f^- K^+ p \pi^+$.

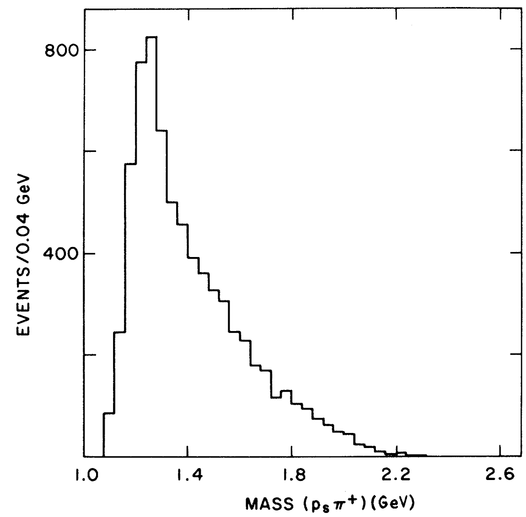

FIG. 2. Effective-mass distribution of the π^+ and the slower p for energy-balancing events.

there is no evidence of narrow peaks; a smooth curve again gives an adequate fit to the data.

With use of a Monte Carlo program that simulated the spark-chamber coordinates, the $\bar{p}p$ effective-mass resolution (a standard deviation σ) was determined to vary linearly from 4 to 11 MeV/c^2 over the range of $\bar{p}p$ masses from 1.9 to 2.5 GeV/c^2. The program correctly reproduced the observed narrow width of the forward $\Lambda^0 \to p\pi^-$ ($\sigma = 3.5$ MeV/c^2) detected with the fast-forward-proton trigger of this experiment. It also yielded the overall sensitivity shown in Fig. 4, calculated assuming a t' distribution to the $\bar{p}p$ of $e^{-2.5t'}$ and that the $\bar{p}p$ decayed isotropically in its Jackson frame. Since our trigger included the requirement of a single fast-forward particle, the efficiency calculated for masses below 2 GeV/c^2 depends on the specific t' and decay distributions assumed. At 1950 MeV/c^2, for example, plausible alternate choices for these distributions produce ~25% variations in the efficiency.

The efficiency includes the geometric acceptance [~12% at $M(\bar{p}p) = 2.0$ GeV/c^2]. It also includes losses due to particle absorption [(15 ±3)%], μ contamination in the π beam [(9±3)%], interactions of the fast track with the downstream

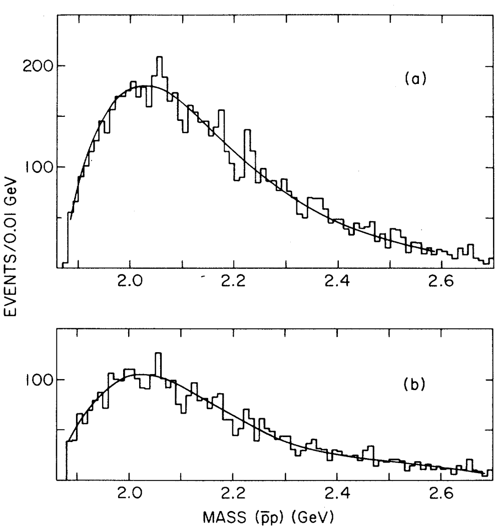

FIG. 3. (a) Effective-mass distribution of the $\bar{p}$ and the faster p for energy-balancing events. (b) Same as in (a) but requiring $M(p\pi^+) < 1.4$ GeV/c^2. The solid lines are polynomial fits to the data.

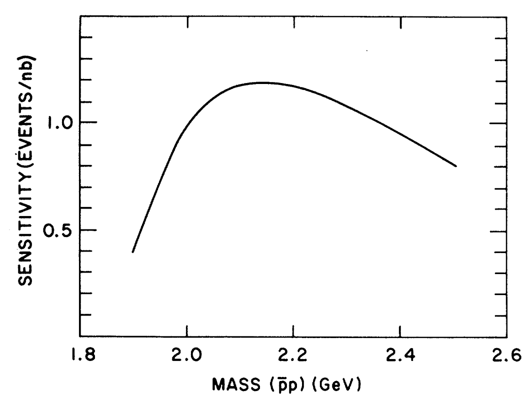

FIG. 4. Calculated sensitivity for Reaction (1) as a function of $\bar{p}p$ effective mass. The calculation assumed that the $\bar{p}p$ system was produced with an angular distribution $\propto e^{-2.5t'}$ and decayed uniformly in its center-of-mass system.

detectors [(15 ± 6)%], momentum and energy balance cuts [(11 ± 3)%], and pattern recognition failures [(32 ± 14)%]. As a check on our sensitivity we compare our data in Fig. 3 with similar data from untriggered bubble chambers. At a $\bar{p}p$ mass of 2.15 GeV/c^2, where the efficiency as a function of t' is fairly uniform, we find after correcting for background and acceptance that our cross section for $\pi^+ p \to \bar{p}p\Delta^{++}$ falls above the published measurements of Dulude and Gaidos[10] and below those of Kennedy *et al.*[11]

Our sensitivity calculation was further verified by studying the reaction

$$\pi^+ p \to \rho^0 \Delta^{++}, \quad \rho^0 \to \pi^+ \pi_f^- \tag{3}$$

obtained with an identical trigger except for the requirement that the fast-forward negative particle fire the Cherenkov counter, indicating a pion. Our corrected differential cross section in the range $0.1 < t' < 0.5$ (GeV/c)^2 agrees with published data[12] to within our estimated normalization uncertainty of ~30%. In addition, the Jackson-angle distributions of ρ^0 and Δ agree well with other measurements, indicating that the topological acceptance of four prongs is well understood.

With our $\bar{p}p$ effective-mass resolution and normalization uncertainty taken into account, 95%-confidence-level limits for the production of narrow (< 10 MeV/c^2 full width at half maximum) $\bar{p}p$ states were derived from Fig. 3 and are presented in Fig. 5.[13] These upper limits were calculated assuming that the $\bar{p}p$ resonance was produced with an angular distribution $e^{-2.5t'}$ (approximating the distribution of the state observed in Ref. 5) and decayed uniformly in its Jackson frame.

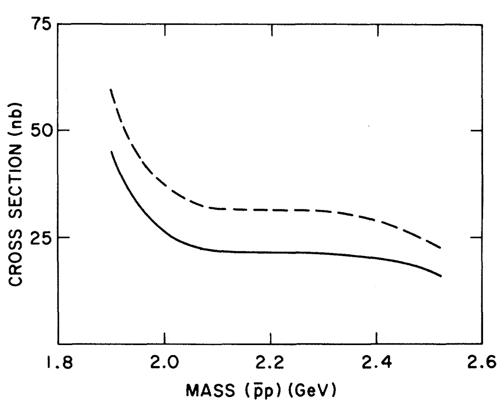

FIG. 5. 95%-confidence-level upper limits for the production cross section of narrow $\bar{p}p$ states taking into account the overall normalization uncertainty and the sensitivity of Fig. 4. The solid line is for Reaction (1) [Fig. 3(b)] and the dashed line is for the reaction $\pi^+ p \to \bar{p}pp\pi^+$ [Fig. 3(a)].

Finally, we note that the state at $M(\bar{p}p) = 1955$ MeV/c^2, reported by Key *et al.*[5] to be produced with a 300-nb cross section, would appear as a > 10-standard-deviation peak in Fig. 3.

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[13]Note that three upward fluctuations and two downward fluctuations at the 2–2.5-standard-deviation level appear in Fig. 3(a). The smooth curves have $\chi^2 = 1.24$ for each degree of freedom for Fig. 3(a) and $\chi^2 = 1.27$ for each degree of freedom for Fig. 3(b) indicative of an acceptable fit. The 95%-confidence-level cross-section limits shown in Fig. 5 are derived from the smooth polynomial fits. For example, with ~300 events within our resolution a 2-standard-deviation fluctuation, at 1 event/nb sensitivity (see Fig. 4), corresponds to a limit of ~35 nb.

Observation of High-Momentum Protons from Limiting Target Fragmentation

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Measurements of the inclusive distributions of protons produced at 180° in the momentum range $0.3 \leq p \leq 1.0$ GeV/c are reported. Proton, α-particle, carbon, and argon beams in the range of kinetic energies $0.4 \leq T \leq 2.1$ GeV/nucleon (4.89 GeV for protons) were incident on C, Al, Cu, Sn, and Pb targets. The dependences of the cross sections on the projectile and target mass and on the incident energy are presented. Limiting behavior is found at energies above 1–2 GeV/nucleon. Features suggestive of nuclear correlations are discussed.

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Nuclear collisions are studied with the hope of learning details of nuclear structure or reaction mechanisms in the collisions. Precise measurement of (e,e'), $(e,e'p)$, $(p,2p)$, and (γ,p)[1] reactions have provided much information on the distributions of nucleon momenta inside nuclei up to 300–400 MeV/c. Predictions with known single-particle wave functions are in good agreement with the data. Attempts to relate the large momenta observed in (γ,p)[2] and backward (p,p')[3] reactions directly to high internal momenta indicate the presence of high-momentum components in nuclei far above those expected from single-particle wave functions. A quasielastic description was used[4] to relate backward momenta from the (p,p') reactions to internal momenta. It was stated that production from nuclei could result only from the internal motion of nucleons since backward production is forbidden in free nucleon-nucleon collisions. This conclusion would hold true, provided that multiple-scattering effects are minimal. The difficulties involved in extracting information on high internal momenta, which are associated with deviations from mean-field motion in the nucleus, have been pointed out by Gottfried.[5] In addition, Amado and Woloshyn[6] have shown that final-state interactions do not permit a simple interpretation of the backward momenta in the (p,p') reactions.[3] The determination of large internal momenta is still a fundamental experimental and theoretical problem. Nevertheless, the high momenta observed in these types of reactions provide valuable information on the production mechanisms, and possibly on internal-momentum distributions.

We have recently concluded a systematic study of the inclusive distributions of high-momentum protons produced at 180° with use of the full range of beams and energies available from the Bevalac facility. Earlier measurements[7] at angles $\theta_{\rm lab} \geq 120°$ with use of high-energy ν, γ, π, and p beams revealed that the shapes of the spectra of protons in the momentum interval $0.3 \leq p \leq 1.0$ GeV/c were insensitive to the type of the projectile and its energy. We find that at the lower incident energies, the cross sections rise rapidly with increasing bombarding energy. However, we also find that beyond 1–2 GeV/nucleon, the distributions in the momentum region $0.4 \leq p \leq 1.0$ GeV/c become relatively insensitive to the further increase of the incident energy. In comparison, projectile fragmentation studies found that the fragment distributions for $p \sim 400$ MeV/c in the projectile frame already became limiting somewhere between beam energies 0.4 and 1.05 GeV/nucleon.[8] Projectile fragmentation studies together with target fragmentation measurements provide systematic data spanning the two momentum ranges $0 \leq p \leq 0.4$ GeV/c and $0.4 \leq p \leq 1.0$ GeV/c. We find that the limiting proton distribu-

