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Evidence for a Narrow $N\bar{N}$ State at 2.02 GEV/C ^{2} in 6 and 9 GEV/C Antiproton Interactions

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Abstract

We report evidence for the existence of a charged narrow state of mass $M \sim 2.02$ GeV/c^2 and width $\Gamma \lesssim 0.04$ GeV/c^2, decaying into $N\bar{N}$. The state is observed in the reaction $\bar{p}p \to p_{fast}\bar{n}\pi^+\pi^-\pi^-$ at 6 GeV/c and in $\bar{p}p \to \pi^+_{fast}\bar{p}n\pi^+\pi^-$ at 9 GeV/c in a triggered bubble chamber experiment at the SLAC Hybrid Facility.

We report the observation of a charged narrow state of mass $M \sim 2.02$ GeV/c^2 produced in $\bar{p}p$ interactions and decaying into nucleon-antinucleon.

This state is observed in the invariant mass $M(p_{fast}\bar{n})$ in the reaction

$$\bar{p}p \to p_{fast}\bar{n}\pi^+\pi^-\pi^- \qquad (1)$$

at an incident momentum of 6 GeV/c. A state of compatible mass and width is seen in the invariant mass $M(\bar{p}n)$ in the reaction

$$\bar{p}p \to \pi^+_{fast}\bar{p}n\pi^+\pi^- \qquad (2)$$

at an incident momentum of 9 GeV/c. In both cases the width of the observed effect is compatible with the experimental resolution. A neutral state of this mass, coupled to $N\bar{N}$, has previously been observed(1), but failed to reappear in an experiment performed under similar conditions(2). Other searches covering this $\bar{p}p$ mass region have also reported negative results(3),(4),(5). In our experiment, the $N\bar{N}$ mass spectrum was studied in all charged states as part of a comprehensive survey of 6 GeV/c and 9 GeV/c antiproton interactions producing at least one fast forward particle which was not an antiproton:

$$\bar{p}N \to \left\{\begin{matrix} \pi^+_{fast} \\ p_{fast} \\ \pi^-_{fast} \end{matrix}\right\} X \qquad (3)$$

The experiment was performed at the SLAC Hybrid Facility, comprising the SLAC 40" bubble chamber and upstream and downstream electronic detectors. Detailed descriptions of the apparatus have been given previously(6) and a full description of its use in this experiment, as well as of the procedures for cross-section normalisation, determination of geometrical acceptances and other experimental details is in preparation(7). The upstream detectors included a Cerenkov counter to distinguish incoming $\bar{p}$ from π^-, but not from K^-. The kaon contamination of the RF-separated beam was determined separately in a scan of the bubble chamber film for $K_{3\pi}$ decays, and found to be less than 1%. Downstream proportional chambers, situated in the fringe magnetic field of the bubble chamber, measured the momenta of fast secondary particles. Further downstream, a large Cerenkov counter was used to distinguish π from K or p. Bubble chamber picture taking was triggered on any expansion of the chamber when a reaction of type (3) was computed to have taken place with at least one fast particle of momentum greater than 2.5 or 4.0 GeV/c at incident momenta of 6 and 9 GeV/c respectively. Experimental sensitivities of 22 ev/μb at 6 GeV/c and 41 ev/μb at 9 GeV/c were obtained for $\bar{p}p$ interactions. With the chamber filled with deuterium, sensitivities of ~ 2.5 ev/μb and ~ 57 ev/μb were obtained at each of the two momenta.

Events were assigned to specific final states on the basis, first, of the results of kinematic fitting, using track measurements both from the bubble chamber and from the proportional chambers; second, using the ionization information in the bubble chamber to identify slow particles; and third, using the information from the downstream Cerenkov counter to check the identification of fast tracks. For reactions (1) and (2), events were accepted if the kinematic fit probability was greater than 4% and the angle, θ_{fast}, of the fast track with respect to the incident beam was below a momentum-dependent cut ensuring a geometric acceptance greater than 25%.

The invariant mass distribution $M(p_{fast}\bar{n})$ in reaction (1) is shown in Figure 1(a). A strong enhancement is seen at 2.02 GeV/c^2. The curve on this plot is the result of a maximum likelihood fit of a smooth background distribution plus a Gaussian distribution representing the peak. A good fit is obtained, with the fitted standard deviation of the Gaussian compatible with the experimental resolution, calculated from the errors on the fitted particle 4-momenta. The significance of the peak is estimated to be 6.3 standard deviations. The results of the fit are given in Table 1, where the χ^2 per degree of freedom is compared with that from a fit with background only. The $M(\bar{p}n)$ distribution in reaction (2) is presented in Figure 1(b). A peak is also seen at 2.02 GeV/c^2, but it is broader than that observed in reaction (1), and additional structure is present in the plot. In Figure 1(c) the distribution $M(\bar{p}n)$ of Figure 1(b) is repeated with an additional cut on the laboratory momenta of the outgoing n and $\bar{p}$: $p_{lab}(n) > p_{lab}(\bar{p})$. This cut suppresses background processes where the $\bar{p}$ is produced diffractively or by meson exchange, while a symmetrically decaying $\bar{p}n$ state detected with uniform acceptance will give a nucleon with momentum greater than that of the antinucleon 50 percent of the time. The signal in Figure 1(c) in the region 2.00 - 2.04 GeV/c^2 is indeed roughly half that observed in 1(b); the background level is strongly decreased, and the smaller structure seen in Figure 1(b) at 2.15 GeV/c^2 is no longer present. A good fit is obtained to the distribution of Figure 1(c), the results of which are given in Table 1. The mass and width of the effect at 2.02 GeV/c^2 are compatible with those obtained from reaction (1). The combined significance of the effects in Figures 1(a) and 1(c) is 7.6 s.d.

The production cross-sections for the M(2.02) state accepted by our apparatus in reactions (1) and (2) are also given in Table 1.

Careful consideration has been given to the possibility that the effects observed in reactions (1) and (2) arise from mis-identification of some other process. In the case of reaction (1), the fast particle is identified as a proton from the information supplied by the forward Cerenkov counter, and the slow particles are identified as pions 80% of the time from ionization of the bubble chamber tracks. This implies that the missing neutral system must contain an antineutron. A check on the consistency of the information from the Cerenkov counter has been made by plotting the $p\bar{n}$ invariant mass from events in which the fast particle is identified as a pion, but which nonetheless give a kinematic fit to reaction (1). No peak is observed in the $M(p\bar{n})$ distribution of these incorrectly fitted events. Another ambiguity of events assigned to reaction (1) is with a K^+ interpretation of the fast track; the forward Cerenkov does not distinguish K^+ from p. However, in this case the missing neutral system is likely to contain a $\overline{K^0}$, and an examination of events in which the $\overline{K^0}$ decay is seen in the bubble chamber shows that they are not sufficient in number to provide a significant contamination to reaction (1).

Similar considerations apply to the study of reaction (2), but here the overall ambiguity level is higher, as the fitted $\bar{p}$ usually has too high a momentum to be distinguished from π^- by bubble chamber ionization, and an interpretation of (2) as a multipion final state is usually possible. However, no peak is observed in the overall sample of events assigned as multipions; it occurs only in $M(\bar{p}n)$ in the sub-sample fitting reaction (2).

Taking all the above evidence into account, we believe that the peaks at M ~ 2.02 GeV/c^2 seen in Figure 1 correspond to a genuine $N\bar{N}$ effect with isospin 1.

The invariant masses of the M(2.02) with the pions produced in reactions (1) and (2) have been examined; there is no evidence for higher mass narrow states decaying into M(2.02).

Having observed an $N\bar{N}$ effect in one reaction of the general type

$$\bar{p}N \rightarrow (N\bar{N})3\pi \qquad (4)$$

at each of two energies, a careful search has been made for the effect in all such reactions at both energies and with π^+, π^- or p as the triggering particle. No signal is seen at $M(N\bar{N}) \sim 2.02$ GeV/c^2 except in reaction (1) at 6 GeV/c and reaction (2) at 9 GeV/c. Because of the limited geometrical acceptance of our apparatus, this fact does not imply any inconsistency in our results, and may be understood if one notes the following points:

(a) In $\bar{p}p$ interactions the CP invariance of the initial state implies that the phase space densities of the two C-conjugated final states $p\bar{n}\pi^+\pi^-\pi^-$ and $\bar{p}n\pi^-\pi^+\pi^+$ must be equal at P-conjugated phase space points. We have checked this equality, but the regions of phase space accepted by our apparatus in which the comparison may be made limits the test to small numbers of events.

(b) Again, because of acceptance limitations in the apparatus it is not possible to determine the production mechanism of the M(2.02) in this experiment. However, the observed distributions of the momentum transfer to this state in reactions (1) and (2) indicate that it is not peripherally produced. On the other hand, Monte Carlo calculations involving models of central production of this state can provide qualitative agreement with the observed relative rates for both positive and negative triggering particles, and in particular, it is predicted that positive triggering particles are most often protons at 6 GeV/c and pions at 9 GeV/c.

(c) The absence of any signal in $M(p\bar{p})$ at 2.02 GeV/c^2 in our experiment can again be explained only in the context of a model description of the production dynamics. Indeed, it is not difficult to devise exchange models in which neutral production of an I=1 state is suppressed relative to charged production by isospin factors.

The hypothesis of central production of the M(2.02) implies increasing separation of the kinematic regions corresponding to the upper and central vertices as the centre of mass energy is increased, and therefore may explain why the state is not seen in the reaction $\bar{p}p \rightarrow p_{fast}X$ at higher energies, e.g. in our experiment at 9 GeV/c, or in the experiment of Banks et al(4), which saw no evidence for $M(2.02) \rightarrow p_{fast}\bar{p}$ at 12 GeV/c. In another recent experiment, Beusch et al(5) have looked for central production of narrow $p\bar{p}$ states in 40 GeV/c $\pi^{\pm}p$ interactions. However, if the p_{lab} dependence of the M(2.02) production cross-section is steeply falling, (e.g. as p_{lab}^{-3}), it is likely that the cross-section in the reaction studied is less than the quoted upper limit of 30 nb.

In conclusion, we have presented evidence for the existence of a narrow isovector state, coupled to $N\bar{N}$, with mass M = 2.02 GeV/c^2. Previous claims for such states have linked their existence with the predicted baryonium phenomenology(8).

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FIGURE CAPTION

Figure 1

Distributions of $M(N\bar{N})$ from reactions (1) and (2). The curves on (a) and (c) correspond to fits of background plus Gaussian functions.

Table 1

FITS TO $N\bar{N}$ MASS DISTRIBUTIONS

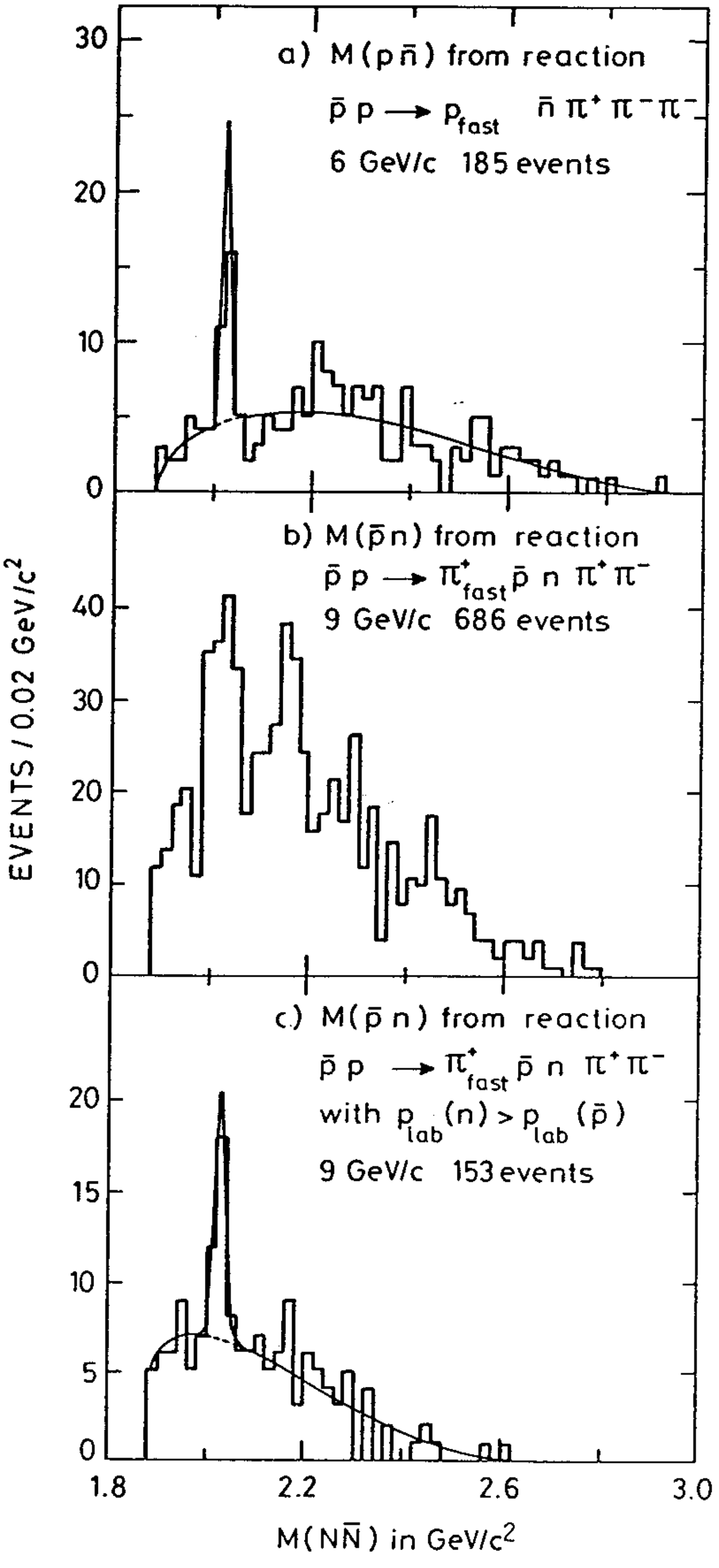
Reaction	Fig.	Mass GeV/c^2	Standard Deviation of Gaussian GeV/c^2	χ^2/n.d.f.$^{(*)}$	Statistical Significance$^{(\dagger)}$	Resolution at $M(N\bar{N})=2.02$ GeV/c^2 GeV/c^2	Cross-Section μb$^{(\ddagger)}$
$\bar{p}p \to p_{fast}\bar{n}\pi^+\pi^-\pi^-$ 6 GeV/c	1a	2.022±0.006	0.014±0.013	17.6/20 (41.0/23)	6.3 s.d.	0.013	1.2±0.4
$\bar{p}p \to \pi^+_{fast}\bar{p}n\pi^+\pi^-$ 9 GeV/c, $p_{lab}(n) > p_{lab}(\bar{p})$	1c	2.026±0.005	0.020±0.011	10.0/15 (25.9/18)	4.6 s.d.	0.011	1.1±0.4

[*] The numbers in parentheses are the χ^2/n.d.f. of fits with background only.

[†] The statistical significance is given by $n_s/\sqrt{n_B}$, where n_B is the background contribution to the fit in the region $2.00 < M < 2.04$ GeV/c^2, and the signal n_s is the number of events above background in this region.

[‡] The cross-sections correspond to the numbers of events observed with ($p_{fast} > 2.6$ GeV/c, $\Theta_{fast} < 0.15$ rad.) at 6 GeV/c and ($p_{fast} > 4.2$ GeV/c, $\Theta_{fast} < 0.15$ rad.) at 9 GeV/c, corrected for the geometrical acceptance in this region.

FIGURE 1


a) M(p n̄) from reaction
p̄ p ⟶ p_fast n̄ π⁺ π⁻ π⁻
6 GeV/c 185 events
b) M(p̄ n) from reaction
p̄ p ⟶ π⁺_fast p̄ n π⁺ π⁻
9 GeV/c 686 events
c) M(p̄ n) from reaction
p̄ p ⟶ π⁺_fast p̄ n π⁺ π⁻
with p_lab(n) > p_lab(p̄)
9 GeV/c 153 events
0
10
20
30
40
5
15
EVENTS / 0.02 GeV/c²
1.8
2.2
2.6
3.0
M(NN̄) in GeV/c²