Evidence for a New State Produced in Antiproton Annihilations at Rest in Liquid Deuterium

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Inclusive charge-pion spectra from $\bar{p}d$ annihilations at rest have been measured in a high-statistics experiment in search of broad states. Analysis of these spectra reveals an enhancement of the π^- spectrum at 315 MeV/c. This may be interpreted as production of a new state of mass 1485 MeV/c^2 and width at most 200 MeV/c^2 recoiling against the π^-. This quasi two-body final state accounts for a large fraction of the $\bar{p}n$ annihilations.

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Annihilations of antiprotons from atomic $\bar{p}p$ and $\bar{p}d$ states have been extensively examined in search of resonant states in a mass region where the low-lying levels for several anticipated spectroscopies are expected to be. Spectroscopies based on $\bar{N}N$ potentials[1] (quasinuclear states), four-quark composites[2] (baryonium), and two-gluon states[3] (glueballs) are some of them. The $\bar{N}N$ annihilation which is rich in "$\bar{N}$-N," quarks, and gluons is expected to couple to these spectroscopies. Many searches have been made in the past and more recently at the CERN Low Energy Antiproton Ring (LEAR).[4] All of them have been done in hydrogen and have been sensitive to narrow states, and the results have been negative, or at best inconclusive.

The theory, on the other hand, typically predicts[1-3] 50–150-MeV/c^2 widths and only special mechanisms result in narrow states. Therefore, existing theories cannot be tested unless searches are extended to broader states. In this and the following Letter the first attempts to look for broad states are reported with positive results.

In the analysis reported here and in the following Letter we look for states (X^0) produced according to

$$\bar{p}+d\rightarrow \pi^- + X^0 + p_s. \tag{1}$$

Annihilations at rest limit the initial quantum numbers and consequently the states to which pionic transitions couple.[5] This should improve the chances of resolving isolated broad states.

The mass of X^0 is given by

$$M_{X^0}^2=(2m_p-E_\pi)^2-p_\pi^2 \tag{2}$$

in the approximation of zero spectator-proton momentum. About 75% of the annihilations are spectator-like.[6] In the experiment reported here, the smearing of M_{X^0} by the unmeasured spectator is less than that due to measuring errors. The Doppler smearing of the π^- momentum by the spectator has an rms, in MeV/c, of $[27\ (\mathrm{GeV}/c)^{-1}]p$.

In deuterium, the π^- and π^+ spectra produced in $\bar{p}p$ annihilations are the same by C invariance. The $\bar{p}n$ annihilations, on the other hand, may have different π^- and π^+ spectra and will certainly be different if states produced according to (1) are present. *A necessary condition, therefore, for the existence of broad states is a difference between π^- and π^+ inclusive spectra in $\bar{p}d$ annihilations.* Additionally, the difference between the π^- and the π^+ spectra can be attributed to the $\bar{p}n$ annihilations. We report in this Letter a large difference between the π^- and π^+ spectra, including a feature that may be the result of one or more broad states produced in $\bar{p}n$ annihilations.

The measurements were taken with a single-arm magnetic spectrometer at the Brookhaven National Laboratory Alternating Gradient Synchrotron (AGS). The spectrometer is described elsewhere[7,8] and the detectors used in this work are shown in Fig. 1. Antiprotons of 600 MeV/c produced at the AGS are brought to rest in a 50-cm-long, 20-cm-diameter liquid-deuterium target after passing through a degrader. About 2000 $\bar{p}$ stop per pulse. The $\bar{p}/\pi^-$ ratio in the beam is $\sim$1:200. Time-of-flight (TOF) and pulse-height measurements with beam counters provide clean antiproton triggers ($\bar{P}$). Events with at least one charged particle reaching the P counters have been recorded. The trigger

$$\bar{P}\cdot(M_3+M_4\geqslant 1)\cdot(\textstyle\sum P_i\geqslant 1)$$

is used with the first coincidence being 5 ns wide and the second 80 ns. The coincidence widths accept particles from the annihilation with $\beta>0.1$. Ten million

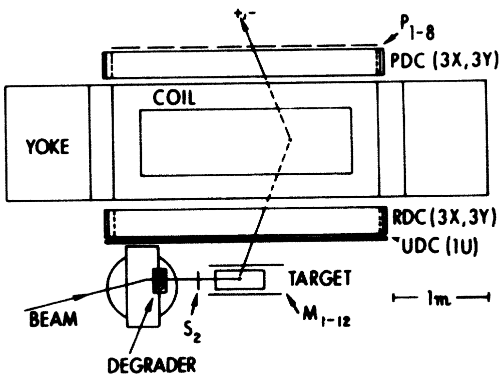

FIG. 1. Floor view of the spectrometer. The UDC-RDC and PDC drift chambers determine entrance and exit of particle from the magnetic field region. The vertical magnet gap is 28 in. M and P counters are in the trigger and measure TOF. Magnet polarity is reversed regularly during data taking and thus π^+ and π^- at any momentum were measured by identical elements of the apparatus.

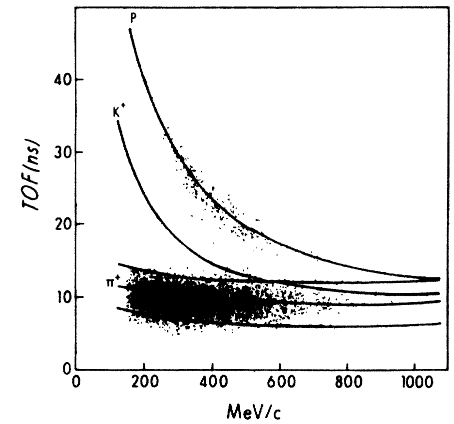

FIG. 2. The TOF of a sample of positive particles as a function of their momenta. The lower band is the pion band with lines showing the location of the peak of the pion distribution and the ± 3-ns limits. The upper band is the proton band which is well separated from the pion band below 600 MeV/c. Between the proton and pion bands a line indicates where kaons would be found. The pions were selected within the band around the π^+ curve and according to the weights discussed in text.

triggers were recorded on tape in 200 h of running time. During data collection, the polarity of the magnetic field was reversed at regular intervals. The twelve M counters measure the charge multiplicity of the event.

The analysis of the data was performed with improved[8] programs which were used in $\bar{p}p$ experiments.[7] Briefly, the RDC-UDC and PDC drift-chamber modules, which are outside the magnetic field, give the straight-line segments of a particle's trajectory as it enters and leaves the magnetic field. The particle momentum is obtained from these segments by use of a simple dipole formula that has been checked by passing Monte Carlo–generated particles through the spectrometer magnetic field which has been mapped to an accuracy of $1{:}10^3$. Peaks in μ^+ and π^- spectra from $K^+(\text{stop}) \rightarrow \mu^+(\nu)$ and $\bar{p}n \rightarrow \pi^-(\pi^0)$ are in agreement with expected momentum resolution and energy scale.[8] The resolution is better than 10 MeV/c up to 400 MeV/c and rises to 45 MeV/c at 900 MeV/c. The μ^+ peak has an rms of 5.4 ± 0.5 MeV/c and the overall momentum resolution, including spectator smearing, has an rms in MeV/c equal to $5 + 1.7p + 50p^2$, where p is the pion momentum in GeV/c.

The TOF between M and P counters (2.5 m separation) is measured with an accuracy of ± 1.5 ns and shows well separated pion and proton bands with negligible background (Fig. 2). Contribution of kaons, constituting $\sim 3\%$ of the pions at production of which only a fraction survive to the P counters, is insignificant. The π^+ and π^- were required to be within ± 3 ns of the expected TOF. Pion spectra were weighted by the probability $P_\pi/(P_\pi + P_p)$ based on TOF. These weights have no effect in the region below 600 MeV/c.

The conclusions of this Letter depend upon having identical efficiencies for π^+ and π^-. For one magnet polarity, π^- trajectories are primarily through the right side of the spectrometer, π^+ trajectories through the left side. Reversing the magnet polarity (the magnitude and sign of magnetic field were monitored with a Hall probe; the magnitude was monitored to better than one part in 10^3) interchanges left and right for the pions, so that when the number of pions observed in each polarity is normalized to the same number of stopping $\bar{p}$'s, the overall experimental efficiencies for π^+ and π^- are the same even if the left and right sides of the spectrometer are not equally efficient. The normalizing $\bar{p}$ flux factor can be calculated from the data and must by definition be independent of momentum for isotropic emission of pions. This factor, as a function of momentum, is shown in Fig. 3. The small slope in the figure is probably due to inflight contamination which gives rise to nonisotropic emission of pions. The value of the factor calculated from the data is consistent with counter information on the number of $\bar{p}$'s. Also important is the obvious smoothness of the dependence of the normalization factor on the momentum and the fact that the essential conclusions of this paper are insensitive to the exact value of the normalizing factor.

The acceptance of the spectrometer has been calculated by passing Monte Carlo–generated pions through its known aperture and magnetic field. It is found that the acceptance rises from the threshold at 130 MeV/c to a maximum at 200 MeV/c and remains essentially constant thereafter.

Because of the smoothness of the acceptance and

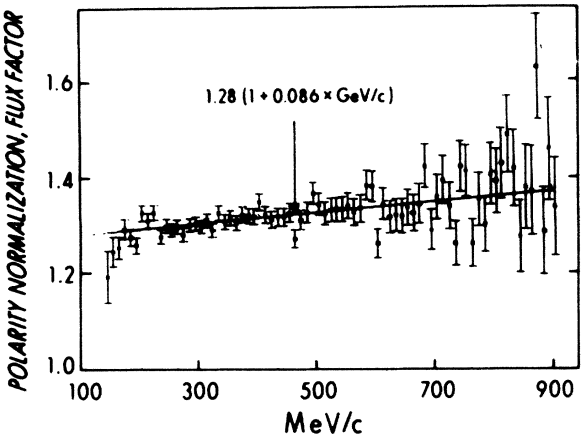

FIG. 3. The ratio of the $\bar{p}d$ annihilations of the two magnet polarities (A and B) calculated from the observed numbers of pions of each charge and polarity. The factor normalizing the number of pions observed with polarity B to the number of $\bar{p}$'s for polarity A is given by the square root of $(N_A^- / N_B^+)/(N_B^- / N_A^+)$. This number is in agreement with counter information.

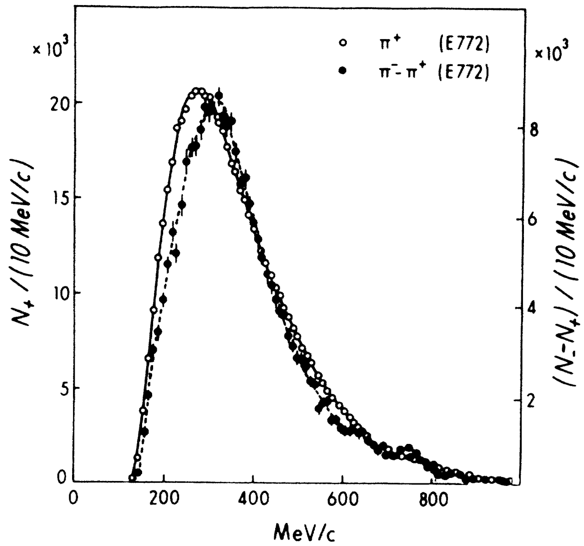

FIG. 4. The π^+ and the difference spectra. The π^+ spectrum is fitted (continuous curve) with a polynomial. The difference spectrum shows an eyeball (disconnected) fit.

the equalization of π^+ and π^- efficiencies, the observed differences between π^+ and π^- spectra cannot be instrumental. We note that our observed ratio of total π^- to total π^+ is equal to 1.38, in good agreement with the bubble-chamber measurement[9] of 1.33 ± 0.04. Moreover, the π^+, π^- spectra in $\bar{p}p$ annihilations as measured by this spectrometer are identical.[10]

Final spectra include corrections for loss of pions in 1.3 g/cm^2 of Al, 0.6 g/cm^2 of C, and 1.65 g/cm^2, on the average, of deuterium. Pion cross sections given by $\frac{1}{2}[\sigma(\pi^+ p) + \sigma(\pi^- p)]A^{2/3}$ were used for both charges. Hydrogen, which has different π^+, π^- correction factors, is negligible. The maximum correction is 17% at 270 MeV/c. In Fig. 4 the final π^+ spectrum and the difference between the π^- and π^+ are presented. As explained above, this subtraction enhances the contribution of reactions (1).

In the interpretation of the observed spectra, first, we have considered the possibility that the observed difference between π^- and π^+ spectra shown in Fig. 4 might be due to π^+, π^- final-state interactions with the spectator. On the assumption that all[6] (25%) nonspectator events which involve nucleon momenta larger than ~ 150 MeV/c are due to pion-spectator rescattering, then the fractions of π^+ and π^- that rescatter are 0.039 and 0.035, respectively. Thus, the amount of rescattering of each pion and more importantly the rescattering contribution to the difference spectrum is far too small to account for the observed effect.

Secondly, study of the spectra as a function of charge multiplicity[8] shows that the peak in the difference spectrum is independent of charge multiplicity in spite of a dependence of the π^+ and π^- spectra on multiplicity. The multiplicity independence of the peak in the difference spectrum suggests the presence of a neutral resonance produced in $\bar{p}n$ recoiling against a π^-. We thus assume that the difference spectrum is

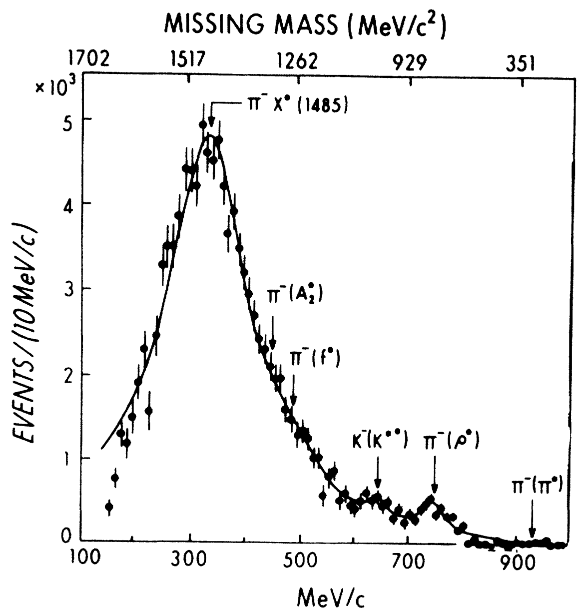

FIG. 5. The π^- minus π^+ difference spectrum after background subtraction (see text).

composed of two components: (a) a background with approximately the same shape as the π^+ spectrum, (b) two-body resonances recoiling against the π^-. A fit to the difference spectrum has been made with use of the π^+ spectrum as "background" and adding the two-body channels $\pi^-(\rho)$, $K^-(K^*)$, $\pi^-(f)$, $\pi^-(A_2)$, and $\pi^-(X^0)$, where X^0 is a new state. The result of the fit is shown in Fig. 5 after subtraction of the background contribution.

The optimized parameters of the X^0 are (mass, width) = (1485, 200) MeV/c^2 and $B(\bar{p}n \to \pi^- X^0) = 0.21$. The Breit-Wigner functions do not include centrifugal barriers which suppress the spectrum at low π^- momentum and may explain why the fit is poor in this region. If the X^0 has $I=1$ then $B(\bar{p}n \to \pi^- X^0 + \pi^0 X^-) = 0.42$, a very large number. The branching ratios for the other two-body channels are in fair agreement with known branching ratios which have been measured in exclusive channels. The $X(1485)$ width determination is sensitive to background parametrization. Fits made with Maxwellian[10] and polynomial backgrounds[8] yield widths of ~ 100 MeV/c^2. Moreover, it is possible that the $X(1485)$ is itself an unresolved superposition of states.

The π^- inclusive spectrum from $\bar{p}d$ annihilations is different from the π^+ spectrum. This is a necessary condition for the existence of meson states produced in association with a recoil pion. Their difference can be interpreted on the assumption that a large fraction of the $\bar{p}n$ annihilations lead to one or more new states with mass 1485 MeV/c^2 and width less than 200 MeV/c^2. Such broad states have been expected on the basis of several constituent models.[1-3]

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[1]I. S. Shapiro, Phys. Rep. **C35**, 129 (1978); W. E. Buck, C. B. Dover, and J. M. Richard, Ann. Phys. (N.Y.) **121**, 47 (1979); C. B. Dover and J. M. Richard, Ann. Phys. (N.Y.) **121**, 70 (1979).

[2]See, for example, G. F. Chew and C. Rosenzweig, Phys. Rev. D **12**, 3907 (1975), and Nucl. Phys. **B104**, 290 (1976); R. L. Jaffe, Phys. Rev. D **17**, 1444 (1978); C. H. Mo and H. Hogaasen, Nucl. Phys. **B135**, 401 (1978); L. Montanet, G. C. Rossi, and G. Veneziano, Phys. Rep. **C63**, 149 (1980).

[3]See, e.g., S. Meshkov, in *Experimental Meson Spectroscopy—1983,* edited by S. J. Lindenbaum, AIP Conference Proceedings No. 113 (American Institute of Physics, New York, 1984).

[4]See, e.g., R. Klapisch, in *Proceedings of the Tenth International Conference on Particles and Nuclei, Heidelberg, Germany, 1984,* edited by B. Povh and G. zu Putlitz (North-Holland, Amsterdam, 1985), p. 207, and in *Antiproton Physics—1984,* edited by M. R. Pennington, IOP Conference Series No. 73 (Hilger, Bristol, London, 1985).

[5]C. B. Dover and M. C. Zabek, Phys. Rev. Lett. **41**, 438 (1978).

[6]T. E. Kalogeropoulos and G. S. Tzanakos, in *Antinucleon-Nucleon Interactions,* Wenner-Gren Center International Symposium Series Vol. 29, edited by G. Ekspond and S. Nilsson (Pergamon, New York, 1977).

[7]Brief description is given in T. Brando *et al.*, Phys. Lett. **139B**, 133 (1984). Details of the analysis of charged-pion and gamma spectra from $\bar{p}p$ annihilations at rest can be found in Ch. Petridou, Ph.D. dissertation, Syracuse University, 1983 (unpublished). An extensive description and performance of the apparatus is in preparation.

[8]Details of the overall experiment and of results are given in R. Debbe, Ph.D. dissertation, Case Western Reserve University, 1985 (unpublished). An extensive paper on this work is in preparation.

[9]T. Kalogeropoulos and G. S. Tzanakos, Phys. Rev. D **22**, 2585 (1980).

[10]P. Bridges *et al.*, in *Antiproton Physics—1984,* edited by M. R. Pennington, IOP Conference Series No. 73 (Hilger, Bristol, London, 1985), Sect. 5, p. 315.