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Observations of Narrow Antiproton-Neutron Resonances near Threshold*†

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The behavior of the $\bar{p}n$ annihilation cross section has been observed above and below threshold by studying annihilations in deuterium at low energies with a ±2.5-MeV resolution. It varies inversely to the $\bar{p}n$ relative momentum except for a pronounced resonance with $(M, \Gamma) = (1897 \pm 1, 25 \pm 6)$ associated with large proton momenta (200 to ~300 MeV/c) and a narrower one (consistent with resolution) at ~1932 MeV associated with lower (100–200 MeV/c) proton momenta. Since the production of these $I=1$ states varies with the $\bar{p}n$ relative momentum their spins are not zero.

During the last decade several experiments were performed in search of high-mass, nonstrange boson resonances. In spite of the plethora of the reported effects no well-established[1,2] resonances beyond the g exist. The $\bar{N}N$ formation experiments yielded a number of energy-dependent phenomena[1] but none of them has as yet been confirmed.[2] On the other hand, many resonances and bound $\bar{N}N$ states are expected on the basis of nonrelativistic[3,4] and relativistic[5] $\bar{N}N$ potentials as well as from general considerations.[6]

In particular, the 1929-MeV peak observed in the CERN missing-mass spectrometer[7] has found support[8] from $\bar{p}p \to \bar{p}p$ at 180° although an alternative interpretation has been presented.[9] Carroll *et al.*,[10] extending their high-statistics $\bar{p}p$ and $\bar{p}d$ total cross-section measurements to low energies, observed a narrow peak in both $\bar{p}p$ and $\bar{p}d$ above a smooth background with $(M, \Gamma) = (1932 \pm 2, 9^{+4}_{-3})$ MeV. Because of uncertainties in Glauber corrections no firm conclusion on isospin was reached although $I=1$ has been favored.

In view of the interestingly puzzling observations[11] made with stopping and low-energy antiprotons (e.g., breakdown of S-capture dominance,[12,13] evidence of bound states,[13,14] cross sections rising faster[15] than $1/P$) we have sought an experiment for the exploration of the region around threshold with good resolution. This became possible by exploiting the kinematical consequences of the Fermi motion in deuterium and by studying events of the type

$$\bar{p} + d \to (\bar{p}n \to \text{annihilation}) + p_{\text{vis}}. \qquad (1)$$

The square of the mass of the annihilation products is given by

$$(2M_p + Q)^2 = M_d^2 + 2M_p^2 + 2M_d(\omega_p - \omega_q) - 2(\omega_p\omega_q - \vec{p}\cdot\vec{q}), \qquad (2)$$

where $\vec{p}$, $\vec{q}$ are the $\bar{p}$ and p_{vis} momenta. Q being a function of p and q, $\cos(\vec{p}, \vec{q})$ *can be positive and negative and be reached with different sets of these variables in constrast to annihilations on free-nucleon targets. An interesting aspect of this freedom is the possibility of searching for* $\bar{N}N$ *states as a function of their relative momentum* $|\vec{p}+\vec{q}|$ *and thus the ability to maximize their production which will occur at* $|\vec{q}+\vec{p}|R \simeq J$, where R is the interaction radius and J the spin of the resonance. *We further note that the sensitivity of Q on these variables is not independent of the variables themselves. Particularly it is relevant to emphasize here that for spectator momenta greater than* ~200 MeV/c, *Q is most sensitive to the beam spectator angle.*[11b,11c]

To this end, the Brookhaven National Laboratory 30-in. bubble chamber was exposed to a separated antiproton beam at the alternating-gradient synchrotron which stops at the end of the fiducial region.[16] About 10% of the 300 000 pictures have been scanned twice for events with visible protons. Antiprotons and protons have been measured only; a uniform scanning-measuring efficiency of 96% has been reached for events with proton momenta >100 MeV/c. Criteria based on curvature and residual range have been found separating unambiguously in-flight (>260 MeV/c) an-

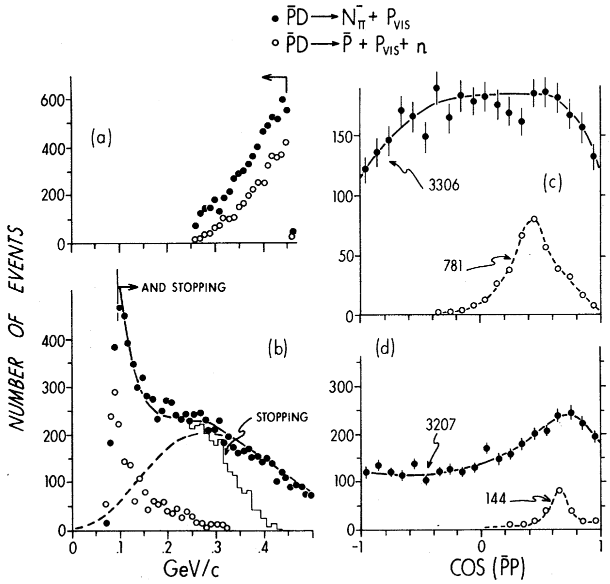

FIG. 1. (a) Antiproton momentum, (b) "spectator" momentum. For curves see text. (c), (d) Antiproton "spectator" angular distributions in the lab system. (c) "Spectator" momentum < 200 MeV/c and stopping (~ 300 MeV/c). Curves are smooth eye-drawn.

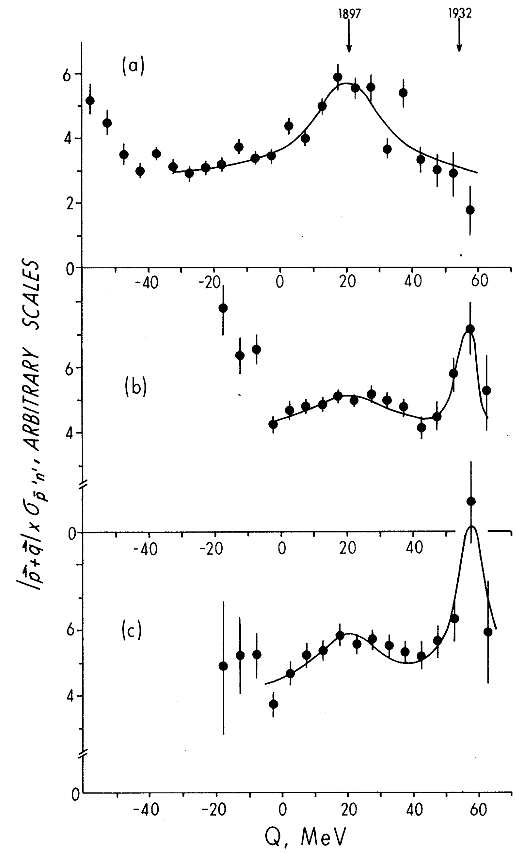

FIG. 2. See text for labels. (a), (b), (c) Cross sections extracted from events with proton momenta > 200 MeV/c and stopping, 100–200 and 100–150 MeV/c, respectively. Curves are fits to superposition of constants and resonances (see text and Table I).

nihilations from those at rest.

Figures 1(a) and 1(b) show distributions in terms of the antiproton and proton momenta. The events increase with beam momentum mainly because of the rapidly increasing path length per Δp. The proton spectrum has the Hulthén component and a substantial tail, first observed at rest,[11] described well with a $p^2 \exp(-\omega/T)$ distribution characteristic of inclusive annihilation spectra.[17] Because of these two physically distinct components we shall divide them into two groups: spectatorlike (< 200 MeV/c), nonspectatorlike (> 200 MeV/c). Furthermore, events with visible (> 100 MeV/c) and stopping protons [Fig. 1(b)] will be considered which provide unusual mass resolution. In order to correct for the biases introduced by the stopping requirements among nonspectator events, an appropriate weight is calculated for each event by Monte Carlo techniques which takes into account vertex distributions and proton-stopping fiducial volume. This weight does not vary much from unity (results do not change by using unit weights) and will be used in making all subsequent distributions.

The antiproton-proton angular distributions in the laboratory frame are shown in Figs. 1(c), 1(d). The forward enhancement among nonspectator events [Fig. 1(d)] is a striking effect; this enhancement reflects itself as a pronounced peak at $Q \simeq 20$ MeV with a width of $\simeq 20$ MeV. We investigated whether this effect is a reflection of the two-step process $\bar{p}+d \to p_{sc}+\bar{p}_{sc}+n_s \to p_{sc}+(\bar{p}_{sc}+n_s \to \text{annihilation})$. The kinematics and dynamics of the first step have been extracted by measuring a sample of quasielastic $\bar{p}d$ events with visible recoils. After elimination, kinematically, of the coherent scattering the beam-proton angular distributions are compared with the annihilation data [Figs. 1(c), 1(d)]. Although broader, one may be tempted to interpret the enhancement in the $\bar{p}n$ annihilation data as the reflection of this two-step mechanism. *One will find it, however, hard to reconcile its absence among the spectatorlike events [Fig. 1(c)]: Scaling the forward enhancement of Fig. 1(d) (~ 800 events) about 4400 (= 800 × $\frac{781}{144}$) should be expected with their forward characteristic distribution in Fig. 1(c) while 100*

TABLE I. Results of the fits. Underlined numbers have been fixed in the fits. E, Γ in MeV. σ_i/σ_B are ratios of the resonances at maximum to "background."

Data (Fig. 2)	E_1	Γ_1	σ_1/σ_B	E_2	Γ_2	σ_2/σ_B
(a)	1897 ± 1	25 ± 6	1.1	$\cdots$	$\cdots$	$\underline{0}$
(c)	$\underline{1897}$	$\underline{25}$	0.5	$1934.4^{+2.6}_{-1.4}$	11^{+11}_{-4}	1.3
(b)	$\underline{1897}$	$\underline{25}$	0.2	$1932^{+2.4}_{-0.4}$	4.5 ± 4	1.0

is an upper limit. We thus came to the conclusion that this effect is produced by direct $\bar{p}n$ effects.

The direct $\bar{p}n$ interactions can be studied by extracting the $\bar{p}n$ cross section, $\sigma_{\bar{p}n}(Q)$, from the data. This can be done by considering Reaction (1) as deuterium stripping by the antiproton resulting in[3]

$$\frac{d^2\sigma}{dq\,d\Omega} \simeq q^2|F(q)|^2 \frac{|\vec{q}+\vec{p}|}{p}\sigma_{\bar{p}'n'}(Q). \qquad (3)$$

This relates the observed $\bar{p}n$ annihilation cross section $[\sigma(\vec{p},\vec{q})]$ to $\sigma_{\bar{p}'n'}(Q)$, where 'n' represents bound neutrons and the deuteron form factor $[q^2|F(q)|^2]$; the Z axis is parallel to $\vec{p}$. For low spectra momenta $\sigma_{\bar{p}'n'}(Q)$ should approach $\sigma_{\bar{p}n}(Q)$ and if it continues behaving as $1/P$ then

$$|\vec{p}+\vec{q}|\,\sigma_{\bar{p}'n'}(Q) = \text{const}, \qquad (4)$$

where const $\cong 24$ mb GeV/c.[15] The relative $\bar{p}n$ momentum, $|\vec{p}+\vec{q}|$, is on the average in the range of a few hundred MeV/c and in the domain of the $1/P$ behavior. After proper integration of (3) with fixed Q, $|\vec{p}+\vec{q}|\sigma_{\bar{p}'n'}(Q)$ is extracted and presented in Fig. 2 for spectator and nonspectatorlike events. Notice the following: (a) The striking bump at 20 MeV is present in all spectator momentum intervals but very pronounced for $200 < q \lesssim 300$ MeV/c. (b) A sharp peak at 55 MeV emerges clearly with decreasing spectator momenta. The position and width of this peak is consistent with the 1932-MeV peak which was first clearly observed by Carroll *et al.*[10] (c) The nature of the sudden increases at low Q is not understood at this time but might be related to off-mass-shell effects.

Fits were made over the extent of the curves shown with Breit-Wigner resonance forms superimposed on a constant background. The sequence and results are presented in Table I. The errors include off-diagonal contributions and correspond to a $\Delta\chi^2 = 1$. Although there are some significant point deviations in Fig. 2(a) we shall identify at the present the structure at ~20 MeV as the result of a single resonance. If the background cross sections are identified as the nonresonating $\bar{p}n$ annihilation cross section on free-nucleon targets (or low proton spectator momenta in deuterium) then[15] $\sigma_B p_{\text{lab}} = 24$ mb GeV/c resulting in $\sigma_B = 86$ and 50 mb at the 1897- and 1932-MeV masses, respectively. Consequently, the inelastic cross sections of these resonances at maxima (see Table I) are quite large (>50 mb) which imply[18] large (>1) spins. This is consistent with the strong dependence of the production on "spectator" momenta.

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Lamb Shift in a Strong Coulomb Potential*

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Results are given of a calculation of the self-energy radiative level shift of order α of the $2S_{1/2}$ and $2P_{1/2}$ states in a strong Coulomb potential. The shift is evaluated numerically to all orders in $Z\alpha$ for Z in the range 10–110. An estimate is obtained for the effect of terms of high order in $Z\alpha$ on the Lamb shift in hydrogen. With this estimate taken into account, the theoretical value is $\mathcal{S} = 1057.864(14)$ MHz.

Recent experiments with a variety of hydrogenlike ions have determined the values of the Lamb shift in these systems.[1] Comparison of these values to the values of the Lamb shift predicted by quantum electrodynamics is one of the fundamental tests of the theory. Furthermore, carrying out this comparison over a wide range of values of the nuclear charge Z is important in order to test whether the theory correctly predicts the Z dependence of the Lamb shift. For atomic hydrogen, new experimental techniques in measuring the Lamb shift give promise of increasing the precision of the measurements by an order of magnitude.[2] Similar precision in the theory requires knowledge of the contribution of terms of high order in $Z\alpha$. For high-Z atoms, a comparison can be made between the experimental and theoretical binding energies of the innermost electrons.[3] In this case the theoretical value of the radiative level shift in a Coulomb potential with nuclear charge Z provides a first approximation to the shift of the corresponding level in the neutral atom with the same Z. For the applications listed above, it is necessary to have accurate values predicted by quantum electrodynamics for the radiative shift of levels in a Coulomb potential for a wide range of Z.

In this Letter I report the results of a calculation of the self-energy contribution to the Lamb shift of electron levels in a strong Coulomb potential. The self-energy radiative level shift of order α of the $2S_{1/2}$ and $2P_{1/2}$ states, corresponding to the Feynman diagram in Fig. 1(a), is considered to all orders in $Z\alpha$. I have evaluated it numerically with no approximations by a slightly modified version of a method used previously to evaluate the $1S_{1/2}$-state self-energy.[4] The evaluation has been done for values of Z given by $Z = 10, 20, 30, \ldots, 110$. I have estimated the small-

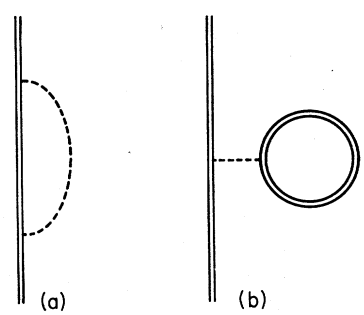

FIG. 1. Feynman diagrams for the radiative corrections of order α: (a) self-energy and (b) vacuum polarization.