Observation of Atomic Antihydrogen

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We report the background-free observation of atomic antihydrogen, produced by interactions of an antiproton beam with a hydrogen gas jet target in the Fermilab Antiproton Accumulator. We measure the cross section of the reaction $\overline{p}p \rightarrow \overline{H}e^- p$ for $\overline{p}$ beam momenta between 5203 and 6232 MeV$/c$ to be $1.12 \pm 0.14 \pm 0.09$ pb. [S0031-9007(98)05685-3]

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The *CPT* theorem states that the product of the charge conjugation (*C*), parity (*P*), and time reversal (*T*) operations is an exact symmetry of nature. *CPT* invariance is a property of any quantum field theory that is constructed from fields which form a finite-dimensional representation of the Lorentz group, have local interactions invariant under the proper Lorentz group, and are described by a Hermitian Lagrangian [1]. This includes all of the elements of the standard model of particle physics, but not all possible extensions to it. Notably, string theories may not require *CPT* invariance [2]. Consequently, tests of *CPT* invariance are of fundamental importance.

CPT invariance implies that every particle state must have a corresponding antiparticle state, with equal mass, spin, and lifetime, and equal but opposite charge and magnetic moment. The hydrogen atom is the best studied of all physical systems; antihydrogen is therefore the ideal system for the study of *CPT* in atomic interactions. A program is underway at CERN to construct a facility dedicated to low energy $\overline{p}$ and $\overline{H}$ experiments [3]. The goal is to produce $\overline{H}$ in a magnetic trap, and to perform spectroscopic measurements of comparable precision to those made using H [4].

In this Letter, we report an observation of atomic $\overline{H}$. Both this experiment and the only previous experiment to report $\overline{H}$ (CERN PS-210 [5]) were based on a suggestion of Munger, Brodsky, and Schmidt [6] that $\overline{H}$ atoms are formed in the collisions of high energy $\overline{p}$'s with nuclei. These atoms are made at large momenta and can be identified through ionization into components.

The layout of our experiment, Fermilab E862, is shown in Fig. 1. The experiment was run parasitically to E835, a study of $\overline{p}p$ resonant annihilation into charmonium using the Fermilab Antiproton Accumulator and an internal hydrogen gas jet target [7]. The energy of the $\overline{p}$ beam and the density of the target were determined by E835. The results presented here are based on data collected between November 1996 and September 1997 with $\overline{p}$ beam momentum above 5200 MeV$/c$.

Atoms of antihydrogen were formed in the reaction $\overline{p}p \rightarrow \overline{H}e^- p$ when a positron, created as a member of an e^+e^- pair by a beam $\overline{p}$ in the Coulomb field of a target p, was captured by the beam $\overline{p}$. This process involves momentum transfer of order $m_e c$, so the $\overline{H}$ atoms were produced with $\gtrsim 0.9995$ of the beam momentum, and did not separate from the $\overline{p}$ beam until the beam was deflected 87 mrad by the storage ring dipole magnet 18 m downstream of the gas jet target. The vacuum pipe through this magnet was modified to allow the neutral $\overline{H}$ to exit the storage ring [8]. Six meters downstream, the atom was ionized in a thin carbon foil that was mounted on a wheel so that it could be removed from the beam line by remote control. The components e^+ and $\overline{p}$ each retained the velocity of the atom (although the e^+ direction was changed by multiple scattering in the foil); the momentum was shared in the ratio of the masses (0.511/938). The e^+ and $\overline{p}$ were

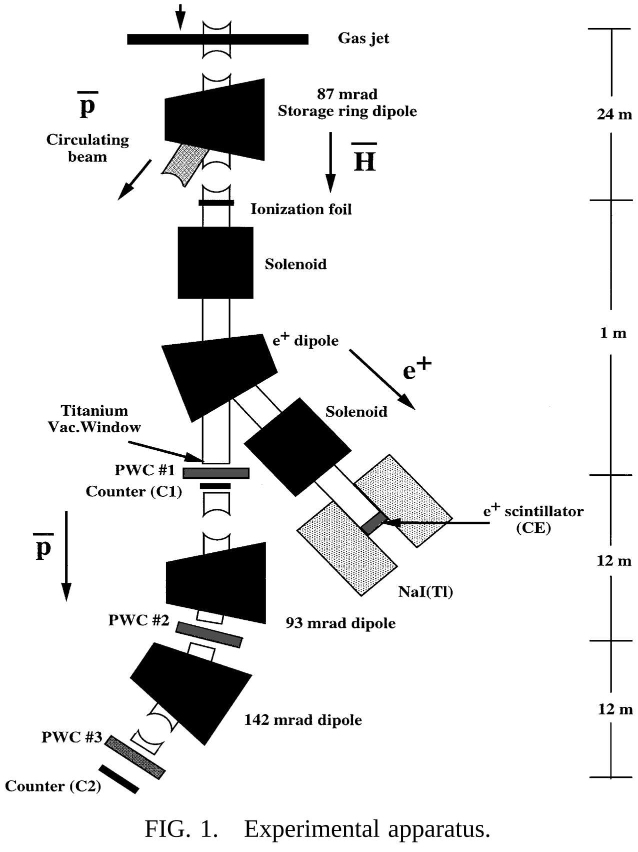

FIG. 1. Experimental apparatus.

detected in separate spectrometers. The positron was deflected through an angle of 40° by a small sector dipole, and stopped in a 2.54 cm thick scintillation counter (CE) that was exposed to the Accumulator machine vacuum. Two solenoid magnets provided a point-to-point focus between the ionization foil and counter CE. The counter was surrounded by a cylindrical NaI(Tl) counter composed of two half-cylindrical crystals, each of which was instrumented with three photomultiplier tubes. The purpose of the NaI(Tl) counter was to detect the 511 keV γ rays produced when the positron annihilated in the CE counter.

The $\overline{p}$ momentum was measured in a 24.4 m long spectrometer. The two dipole magnets in this spectrometer were energized in series with the Accumulator dipole magnets, so that a beam-momentum particle was deflected by 235 mrad, independent of the value of the beam momentum. Position measurements were provided by three proportional wire chambers with 1 mm wire spacing [9]. This spectrometer provided a measurement of track momentum relative to the nominal beam momentum, and covered the range $0.95 < p/p_{\mathrm{beam}} < 1.05$. Two scintillation counters, a 1.6 mm thick counter (C1) located just downstream of PWC#1, and a 3.2 mm thick counter (C2) located 2 m downstream of PWC#3, completed the $\overline{p}$ spectrometer. C1 and C2 were each instrumented with two photomultiplier tubes. Pulse height and leading edge timing information was recorded for each tube, and a coincidence signal of the two tubes on each counter was formed for use in triggers.

Whenever at least two of the three counter signals (CE, C1, and C2) were present within a 75 ns time window, the data acquisition system was triggered and data from all spectrometer elements were written to permanent storage. The interaction rate in the gas jet target was typically 2 MHz. In contrast, the three small scintillation counters in our apparatus registered singles rates of only ~3 Hz. The trigger rate was one every 3–5 min, and was dominated by C1-CE coincidences caused by a shower of particles.

We have a background-free sample of 57 $\overline{H}$ events. This sample was selected simply by requiring that every event contain a three-way coincidence of CE, C1, and C2, and that either PWC#2 or PWC#3 register at least one wire hit. All events thus selected were found to contain a beam momentum antiproton track and data consistent with a positron of the expected momentum.

In order to demonstrate that these three-way coincidence events were caused by antihydrogen, the ionization foil was rotated out of the beam line, and data were collected. In this configuration, $\overline{H}$ atoms ionized in the 50 μm thick titanium vacuum window 10 cm upstream of PWC#1. Since, in these events, the ionization occurred downstream of the small dipole magnet, the e^+ was not directed to the CE counter, but rather passed through PWC#1 along with the $\overline{p}$. Multiple scattering of the e^+ in the titanium window caused the e^+ to separate from the $\overline{p}$, resulting in two hits registered by the PWC. In data collected with the ionization foil out of the beam line, no three-way coincidence of CE, C1, and C2 was recorded. However, the foil-out sample does contain 13 events with a beam momentum track and a second hit in PWC#1. The larger foil-in sample contains only one such event [10].

Figure 2(a) shows the momentum spectrum of all tracks found in the foil-in data sample. Entries corresponding to events with a three-way coincidence of C1, C2, and CE are shaded. The majority of the remaining tracks were the result of the elastic scattering of beam $\overline{p}$'s from residual H atoms just upstream of the storage ring dipole. These elastically scattered $\overline{p}$'s were directed into the E862 apparatus when the scattering angle was equal and opposite to the bend angle of the storage ring dipole. These tracks provide a verification that the momentum scale of the $\overline{p}$ spectrometer is correct to 0.1%. Figure 2(b) shows the corresponding momentum spectrum from data collected with the ionization foil out of the beam line. Entries from events containing a spectator hit in PWC#1 are shaded. The shaded momentum spectra in Figs. 2(a) and 2(b) both have a mean of 0.9993. The standard deviations of the two spectra are, respectively, 0.0007 and 0.0005. Exclusive of magnet setting errors, the expected rms momentum resolution of the $\overline{p}$ spectrometer (dominated by multiple scattering) is 0.000 45 at 5700 MeV/c. The fractional momentum spread of the $\overline{p}$ beam in the Accumulator was less than 0.0002 rms.

The open histogram in Fig. 3(a) is the CE pulse height distribution for all triggers in the foil-in data set. The shaded histogram shows the response of CE in the 57 three-way coincidence events. The pulse height for each of these events is given in Fig. 3(b) as a function of the expected e^+ kinetic energy. The plot also shows the response of CE to a ^{68}Ge calibration source.

Figure 4 illustrates the response of the NaI(Tl) counter. Each axis of the plot corresponds to one half of the

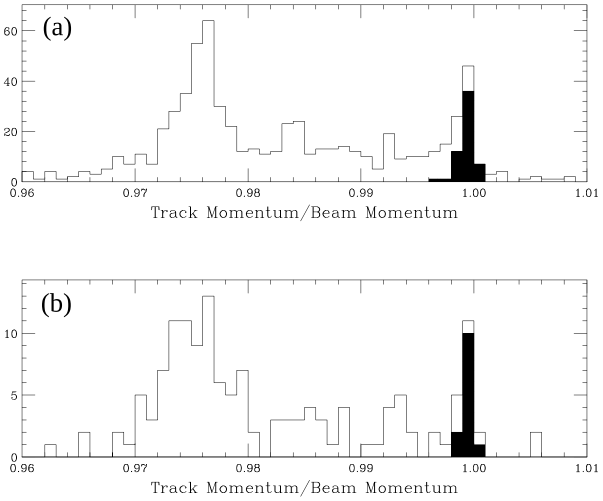

FIG. 2. (a) Momentum of antiproton candidate tracks for foil-in data. Three-way coincidence events are shaded. (b) Momentum of antiproton candidate tracks for foil-out data. Events with a spectator track are shaded.

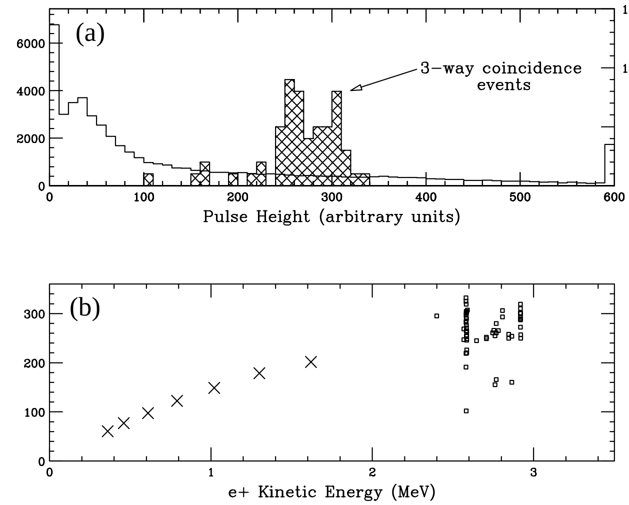

FIG. 3. (a) CE pulse height for foil-in data. (b) CE pulse height as a function of expected e^+ kinetic energy. The crosses show the average response to a ^{68}Ge calibration source.

counter. The response to 47 three-way coincidence events [11] is shown in the main part of the figure, and the response to a ^{68}Ge calibration source is shown in the inset. For the calibration events, 20.5% have both counter halves within 45 of 511 keV and 52.9% have at least one of the two counter halves within 45 of 511 keV. For the 47 signal events, 14 (30%) have both counter halves within 45 of 511 keV, and 25 (53%) have at least one counter half within 45 of 511 keV.

All features of the three-way coincidence events are consistent with antihydrogen. The requirement of a three-way coincidence, independent of any cut on the pulse height in counter CE, or the existence of information in either half of the NaI(Tl) counter, selected only events containing beam-momentum tracks. This demonstrates that there is no background due to a continuum of off-momentum $\overline{p}$'s. The fact that no three-way coincidence event was recorded with the ionization foil removed from the beam line demonstrates that these events are caused by an interaction in the foil. Data were taken with two ionization foil thicknesses, 437 and 777 μg/cm^2. The data, given in Table I, favor the hypothesis (likelihood ratio = 2.1) that the event rate is independent of foil thickness, as expected for the ionization of $\overline{H}$, rather than proportional to the thickness, as expected for scattering in the foil. Finally, in the absence of the ionization foil, $\overline{H}$ events were observed with a second signature and a consistent cross section.

Three of the events in the foil-out sample were collected with a beam momentum of 8815 MeV/c, and one was collected with a beam momentum of 6934 MeV/c. The balance of the data was collected at beam momenta between 5203 and 6232 MeV/c [12]. This subset of the data has been used to determine the $\overline{H}$ production cross section. To determine the cross section, we have multiplied the integrated luminosity recorded by E835 [13]

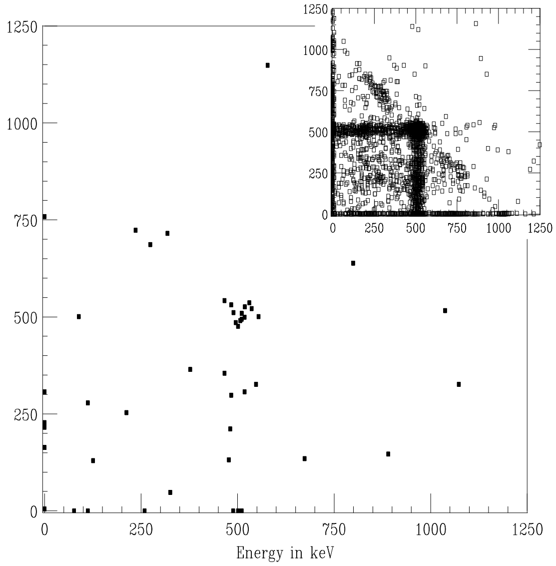

FIG. 4. Pulse heights in the NaI(Tl) counter halves for three-way coincidence events. The inset is the response to a ^{68}Ge calibration source.

by our estimated geometrical acceptance, reconstruction efficiency, and experiment live time. The geometrical acceptance was primarily a function of the beam angle and emittance, and the size of the ionization foil. The beam angle and emittance were logged by the Fermilab Operations Group. Using these numbers as input to a Monte Carlo simulation of the experiment, we have computed the geometrical acceptance as a function of time. Using PWC efficiencies determined from the $\overline{H}$ events themselves, we estimate the reconstruction efficiency to be 99%. The measured experiment live time was 97%.

The systematic error in our cross section measurement is determined by uncertainty in the luminosity measurement and acceptance corrections. The uncertainty in the luminosity measurement has been estimated to be 4% [13]. Uncertainties in acceptance due to the alignment of our apparatus or of the instruments used to measure the beam trajectory have been estimated and found to be much smaller than the uncertainty associated with the estimate of the

TABLE I. $\overline{H}$ production cross section, for three data sets taken with $5203 \leq p_{\text{beam}} \leq 6232$ MeV/c, and for the combined data set.

	437 μg/cm^2 Foil	777 μg/cm^2 Foil	Foil out	Full data set
Luminosity (pb^{-1})	34.8	29.6	10.4	74.8
Acceptance × efficiency	0.67	0.92	0.80	0.79
Sensitivity (pb^{-1})	23.3	27.2	8.3	58.8
Number of events	24	33	9	66
Background	0	0	0.16	0.16
Cross section (pb)	1.03	1.22	1.07	1.12
Statistical error (pb)	0.21	0.21	0.36	0.14
Systematic error (pb)	0.08	0.09	0.14	0.09

angular spread of the $\overline{p}$ beam, which is derived from the beam profile and the emittance. The emittances reported by the Operations group were typically $<2\pi$ mm mrad. These emittances were computed from measurements using the Accumulator lattice parameters, which are not precisely known for the range of beam momentum covered by our data [14]. Therefore, in order to estimate the systematic error, we have repeated the acceptance Monte Carlo calculations with the beam emittance increased by 50%. The result of this study is summarized in Table I. The errors associated with the acceptance correction and the luminosity measurement have been added in quadrature.

In summary, we have observed the production of atomic antihydrogen in the reaction $\overline{p}p \rightarrow \overline{H}e^- p$. The signal is unambiguous and background free. We measure the production cross section between 5203 and 6232 MeV$/c$ to be $1.12 \pm 0.14 \pm 0.09$ pb [15,16]. The relatively small systematic error in this measurement is made possible by the high quality luminosity measurement provided by E835 and by the fact that the acceptance and efficiency of our apparatus are both high. We have verified the acceptance correction by increasing the angular coverage of the apparatus part way through the data taking, and by collecting data with the ionization foil removed.

Our measured cross section is smaller than the $n = 1$ cross section of 4.0 pb computed in [6]. However, a recent calculation by Bertulani and Baur [17] gives a cross section for production of $n = 1$ $\overline{H}$ of 0.91 pb at $p_{\text{beam}} = 5700$ MeV$/c$, which is consistent with our measurement. The same calculation gives a cross section at the CERN momentum of 1940 MeV$/c$ of $0.23Z^2$ pb, which is 671 pb for $Z = 54$. CERN PS-210 [5] quotes an integrated luminosity of 5×10^{33} cm^{-2} ($\pm 50\%$) and a product of acceptance and efficiency less than 0.3. Thus, their signal of 11 events, with an estimated background of 2, corresponds to a cross section of at least 6000 pb, with a systematics-dominated uncertainty of $\sim 50\%$. This result is not consistent with the recent calculation of Bertulani and Baur [17].

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[7] T. A. Armstrong *et al.*, Report No. FERMILAB-PROPOSAL-P-835-REV, 1992; D. Allspach *et al.*, Report No. FERMILAB-Pub-97/274-E, 1997 (to be published).

[8] All $\overline{H}$ atoms which exit the Accumulator do so in the ground state. This includes atoms produced in 1 s, and 98% of atoms formed in $n = 2$, which decay radiatively to 1 s before reaching the dipole magnet (the electric field in the $\overline{H}$ rest frame, caused by the earth's magnetic field, mixes the $2s$ and $2p$ states). States with $n > 2$ field ionize before or within the storage ring dipole.

[9] D. C. Christian *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **345**, 62 (1994).

[10] This event may have been caused by a beam momentum $\overline{p}$ (exiting the Accumulator after an elastic scatter with a "heavy" nucleus such as carbon) that knocked an electron out of the titanium vacuum window, or by an $\overline{H}$ which passed through the 777 μg/cm^2 foil without ionizing. In our cross section determination, we assumed that this was not an $\overline{H}$ event.

[11] After an exposure of 34.84 pb^{-1}, the aperture of the spectrometer was increased. The 2.54 cm diameter (437 μg/cm^2) ionization foil was replaced with a 4.44 cm diameter (777 μg/cm^2) foil, the e^+ scintillator was increased from 2.54 to 5.1 cm diameter, and the central bore of the NaI(Tl) counter was increased from 3.0 to 5.1 cm. Ten of the 57 three-way events were collected while the NaI(Tl) counter was being modified.

[12] The sensitivity-weighted average beam momentum is $\sum(\text{sensitivity}) \times p_{\text{beam}} / \sum \text{sensitivity} = 5767$ MeV$/c$.

[13] S. Trokenheim *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **355**, 308 (1995).

[14] We have plotted the vertical (horizontal) slope of the $\overline{p}$ tracks from the $\overline{H}$ data verses the vertical (horizontal) position at PWC#1, and thus have directly measured vertical (and horizontal) emittance ellipses of area $<3\pi$ ($<4\pi$) mm mrad. Since these data were collected over a period of months, these areas represent extreme upper limits to the actual beam emittances.

[15] Our cross section is for all $\overline{H}$ atoms produced in the ground state, plus 98% of those produced in $n = 2$ states. The production cross section is expected to be $\propto |\Psi(0)|^2$, and thus 8/9 $n = 1$ plus 1/9 $n = 2$ atoms.

[16] We have also developed a technique for performing spectroscopic measurements of the $n = 2$ antihydrogenic levels which may be practical for use in a future experiment at Fermilab: G. Blanford *et al.*, Report No. FERMILAB-Pub-97/426-E [Phys. Rev. D (to be published)].

[17] C. A. Bertulani and G. Baur, Phys. Rev. D (to be published); available at http://xxx.lanl.gov/abs/hep-ph/9711273.