SLAC–PUB–5939
September 1992
(T/E)

PRODUCTION OF RELATIVISTIC ANTI-HYDROGEN ATOMS BY PAIR PRODUCTION WITH POSITRON CAPTURE AND MEASUREMENT OF THE LAMB SHIFT

CHARLES T. MUNGER* and STANLEY J. BRODSKY*

Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94309

and

IVAN SCHMIDT†

Universidad Federico Santa María
Casilla 110–V, Valparaíso, Chile

ABSTRACT

A beam of relativistic antihydrogen atoms–the bound state ($\bar{p}e^+$)– can be created by circulating the beam of an antiproton storage ring through an internal gas target. An antiproton which passes through the Coulomb field of a nucleus will create e^+e^- pairs, and antihydrogen will form when a positron is created in a bound instead of continuum state about the antiproton. The cross section for this process is roughly $1\,Z^2$ pb for antiproton momenta above 6 GeV/c. A sample of 200 antihydrogen atoms in a low-emittance, neutral beam will be made in 1994 as an accidental byproduct of Fermilab experiment E760. We describe a simple experiment, Fermilab Proposal P862, which can detect this beam, and outline how a sample of a few-10^4 atoms can be used to measure the antihydrogen Lamb shift to 1%.

Presented at the Antihydrogen Workshop, Münich, Germany, July 30-31, 1992

* Work supported in part by Department of Energy contract DE–AC03–76SF00515 (SLAC).
† Work supported by Fondo Nacional de Investigación Científica y Tecnológica, Chile.

Antihydrogen, the simplest atomic bound state of antimatter, $\bar{H} \equiv (\bar{p}e^+)$, has never been observed. While the development of sources is the major topic of this conference, ironically it seems a working source already exists. A relativistic antiproton passing through the Coulomb field of a nucleus of charge Z will create electron-positron pairs; occasionally the positron will appear in a bound instead of a continuum state about the antiproton and form antihydrogen. This process has a cross section of roughly 1 Z^2 pb for antiproton momenta above 2 GeV/c. Fermilab experiment E760 has studied $\bar{p}p$ annihilation at the Fermilab accumulator using an internal hydrogen gas target; roughly 10 antihydrogen atoms have already been produced but left undetected, and roughly 200 will be produced in an extended run at higher luminosity scheduled for 1994. A proposal for the experiment outlined here to detect this antihydrogen, with we believe greater than 90% efficiency and zero background, has been submitted to Fermilab as Fermilab Proposal E862 [1]. A sample of only $\sim 3 \cdot 10^4$ antihydrogen atoms would suffice for a future atomic-beam experiment to check the equivalence of the hydrogen and antihydrogen $2s - 2p$ splittings to $\sim 1\%$ and so check for anomalous, CPT-violating $\bar{p}e^+$ interactions causing level shifts equal to a fraction of roughly 10^{-8} of the antihydrogen binding energy. Greater precision will not be achievable because of the short time ($\sim 10^{-7}$ seconds) taken by the relativistic antihydrogen to pass through our apparatus.

The calculation of the cross section for forming antihydrogen will appear in a subsequent paper [2] and only an outline will be presented here. Within the equivalent photon approximation [3] the cross section $\sigma_{\bar{p}Z \to \bar{H}(1s)\, Ze^-}$ can be written as an integral over the virtual cross section for photoproduction of antihydrogen, $\sigma_{\gamma^* \bar{p} \to \bar{H}(1s)\, e^-}(s, q^2)$:

$$\sigma_{\bar{p}Z \to \bar{H}(1s)\, e^- Z} = \frac{Z^2\alpha}{\pi} \times$$

$$\int_0^1 \frac{dx}{x} \int_0^{q^2_{\perp max}} dq^2_\perp \frac{q^2_\perp}{(q^2_\perp + x^2 M^2)^2} \left(\frac{1+(1-x)^2}{2}\right) \sigma_{\gamma^* \bar{p} \to \bar{H}(1s)\, e^-}(\omega, q^2).$$

Here $x = \omega/E = \omega/(M\gamma)$ is the photon energy fraction evaluated in the antiproton rest frame, where $\omega > 2m_e$, $q_\perp$ is the photon's transverse momentum, and M is the antiproton mass. Because the photoabsorption cross section falls off as $(Q^2 + 4m_e^2)^{-1}$ at large photon virtuality $Q^2 = -q^2$, $q_\perp$ is typically of order $2m_e$. The antihydrogen atom is formed when the positron and antiproton have very small relative velocity; thus the $\bar{H}$ only receives a small momentum transfer of order the Bohr momentum αm_e. Thus the scattered nucleus recoils with a transverse momentum $-q_\perp$, which is balanced almost completely by the outgoing electron.

The photon virtuality is small so one may take $q^2 \approx 0$. Typically $x << 1$, so performing the integral over $q^2_\perp$ we find for large γ that

$$\sigma_{\bar{p}Z \to \bar{H}(1s)\, e^- Z}(\gamma) = \frac{2Z^2\alpha}{\pi} \int_{2m_e}^{E} \frac{d\omega}{\omega} \left[\ell n \left(\gamma \frac{q_\perp^{max}}{\omega}\right) - \frac{1}{2}\right] \sigma_{\gamma \bar{p} \to \bar{H}(1s)\, e^-}(\omega)$$

The matrix element for the cross section to photoproduce antihydrogen in the $1s$ state we obtain by applying crossing symmetry to the well-known matrix element for the photo-ionization of the $1s$ state of hydrogen. After a numerical integration we find the result shown in Table 1, that $\sigma_{\bar{p}Z \to \bar{H}(1s)\, e^- Z}$ is roughly 1 Z^2 pb for antiproton momenta above 6 Gev/c.

Because the momentum transferred to the antihydrogen is tiny, $\sim 5 \cdot 10^{-6}$ GeV/c, the antihydrogen emerges from a gas target as a neutral beam with the same tiny momentum spread $\delta p/p \sim 2 \cdot 10^{-4}$ as the accumulator's circulating (and stochastically cooled) antiproton beam. Even after 40 meters flight the $\pm 1\sigma$ spread of the antihydrogen beam spot grows from 0.50 cm in the gas target [5] to only to 2 cm. Being neutral the antihydrogen emerges from the antiproton storage ring at the first bend magnet, 14.5 meters from the gas target, and can be detected by a separate apparatus.

Antihydrogen does not ionize in laboratory magnets. Even at the maximum accumulator momentum of 8.83 GeV/c and dipole strength of 16.7 kgauss, the rest ionization rate of the $1s$ state in the electric field induced in the antihydrogen rest frame is only $4.3 \cdot 10^{-13}\,\mathrm{sec}^{-1}$ [6]. It also does not disassociate in the gas target. Data for the disassociation cross sections for monatomic hydrogen beams [7], extrapolated to a beam momentum of 3 GeV/c, yield disassociation cross sections of $2.5 \cdot 10^{-20}\,\mathrm{cm}^2$, $2.7 \cdot 10^{-19}\,\mathrm{cm}^2$, and $3.3 \cdot 10^{-19}\,\mathrm{cm}^2$ per H_2, N_2, and CH_4 target molecule, respectively. Consequently the probability that an antihydrogen atom will disassociate before exiting the E760 H_2 gas target, of column density 10^{14} atoms/cm^2, is less than 10^{-4} even if the target consists entirely of microdroplets of $\sim 10^5 - 10^6$ molecules per droplet [8], and if all the antihydrogen is created inside a droplet. Antihydrogen however disassociates with a probability > 0.99 in a membrane only 400 microgram/cm^2 thick, while the probability a photon converts or a hadron interacts in such a thin membrane are respectively only $\sim 2.7 \cdot 10^{-5}$ and $6.6 \cdot 10^{-7}$ [9]. The momentum transfer which disassociates antihydrogen is small, and so an antihydrogen atom escaping the accumulator ring will generate, in coincidence, and from some point in a known, few-square-centimeter area of a thin membrane possibly tens of meters from the gas target, a positron and an antiproton with a common and tightly constrained velocity equal to the velocity of the circulating antiprotons in the ring. For a model momentum and momentum spread of 6.0000(12) GeV/c for the antiproton circulating in the ring, one finds that the antiproton from antihydrogen disassociation will have a momentum of 6.0000(12) GeV/c and the positron will have a kinetic energy of 2.797(14) MeV. The 14 keV smear of the positron energy comes from the Fermi momentum of the $1s$ state. Multiple scattering of the positron in a 400 microgram/cm^2 membrane is small enough that more than 99% of the positrons will escape within a ± 0.10 radian cone about the antiproton direction and can be focussed into a special detector.

We propose [1] to detect the antihydrogen after its extraction from the accumulator ring is as follows. An antihydrogen atom hits a membrane and disassociate into its component positron and antiproton. The monoenergetic positrons are focussed by a weak magnetic field onto a small scintillator. The scintillator is backed by a sodium iodide detector both to veto the passage of penetrating particles and to catch one of the 511 keV xrays from the positron annihilation. The antiproton continues down a special 30-meter beamline laid which will parallel the accumulator ring. A pair of multiwire proportional chambers sandwiching a 5^0 bend magnet measure the antiproton momentum to 2%. A pair of scintillator paddles 30 meters apart and with individual timing resolution of 150 ps provide both a trigger and seven standard deviations of $\bar{p} - \pi^-$ separation even at a common momentum as high as 6 GeV/c. The antiproton's flight ends in a high-pressure ring-imaging Čerenkov detector of DISC type [10], which will count only particles within a velocity window $\delta\beta/\beta = 10^{-4}$ and within $\pm$ 1 milliradian of the nominal antiproton trajectory. The passage of an antiproton from antihydrogen is indicated by the timing of the hits in all the scintillators, chamber hits consistent with a particle of the correct momentum, a count in the Čerenkov detector indicating the passage of a particle with the correct velocity and range. To signal the passage of an antihydrogen atom a candidate antiproton must come in coincidence with a hit in the positron scintillator of roughly the right energy deposit but no hit in the veto. Catching a 511 keV annihilation photon will provide extra confirmation for about half the events.

Notwithstanding the $\sim 3 \cdot 10^{10}$ times larger cross section for $\bar{p}p$ annihilation than for antihydrogen formation, target-related backgrounds should be negligible. Relative to the target the solid angle subtended by the membrane, and the acceptance aperture for a candidate antiproton, are small ($\sim 10^{-7}$ and $\sim 10^{-8}$ of 4π, respectively); the momentum windows set by the Čerenkov detector and the positron veto are small ($\delta p/p \sim 10^{-3}$ and 10^{-1}, respectively); the probability that any stray particle which passes through the membrane interacts is small ($\sim 10^{-5}$); and kinematics dictate that a pair of particles, produced in coincidence and near the membrane, will rarely possess a momentum both as high as the original $\bar{p}$ momentum and as low as a few Mev/c. Random coincidences are suppressed by requiring few-nanosecond coincidences between small and widely separated detectors. There are also two potent experimental check for false signal: if another membrane is inserted upstream of the original, none of the antihydrogen will survive intact to disassociate in the original membrane to give a signal, but all the particle and electronic backgrounds will remain the unchanged. Also the accumulator ring can circulate protons in the same sense as antiprotons. The cross section for the radiative recombination of protons and electrons at 3 GeV/c to form fast hydrogen is 1.7 nanobarns [11]. Thus there will be available a neutral hydrogen beam, with the same optics and momentum spread as the antihydrogen beam but ~ 340 times as intense, which to test an apparatus.

Future antihydrogen experiments and the Lamb Shift

The process of pair creation with capture has itself never been seen and its measurement is of interest. The first observation of the analogous process in the collision of ordinary nuclei, $Z_1 + Z_2 \rightarrow (Z_1 e^-) + e^+ + Z_2$, is the subject of an experiment soon to run at the Lawrence Berkeley Laboratory BEVALAC [12], and the process is predicted to be a major source of beam loss at the Relativistic Heavy Ion Collider [13]. However the primary motivation for experiments studying antihydrogen is to test the CPT theorem.

We outline two experiments which seem practical with samples of order 10^3 and 10^4 antihydrogen atoms. The first is a measurement of the rate of field ionization of the $n = 2$ states in an electric field provided by the Lorentz transform of a laboratory magnetic field. Perhaps 10% of a 3 GeV/c beam of antihydrogen atoms in the $1s$ state can be collisionally excited into states with $n = 2$ by passing the beam through a thin membrane. If the membrane sits in a 20 kgauss transverse magnetic field, states with $n > 2$ will ionize instantly, the states with $n = 2$ will ionize with $1/e$ decay lengths of order 10 cm, and the $1s$ state will not ionize at all. The distance a states with $n = 2$ flies before ionizing is marked by the a deflection of the freed antiproton by the magnetic field by an amount between the zero deflection of the surviving $1s$ component of the beam and the large deflection of the antihydrogen which ionizes instantly or disassociates in the membrane. Ten centimeters of flight before disassociation changes the deflection of the antiproton seen 3 meters away by 6.7 cm–many times the antiproton spot size of $\lesssim 1$ cm. The distance a state flies is also marked by the freed positron, whose orbit radius is only 2 mm in the transverse field and which can be directed into some sort of position-sensitive detector. The positron and antiproton have of course their usual unique energy. A flux of a few thousand $\bar{H}$'s may be sufficient to measure the three distinct field ionization rates of the $n = 2$ states to $\sim 10\%$. Because the ionization rate is a tunneling process it is surprisingly sensitive to details of the antihydrogen wavefunction; a 10% shift would require for example a change in $\langle r \rangle$ for the $n = 2$ states of only 0.24%.

Ionization in a magnetic field can be efficiently used to count $n = 2$ states without counting states of different principal quantum number. (No laser for example has sufficient continuous power to photo-ionize efficiently the relativistic antihydrogen beam.) The second experiment is to drive the 1000 Mhz $2s - 2p$ transition and to monitor the surviving $2s$ population as a function of frequency to measure the antihydrogen Lamb shift. For a beam with $\gamma = 3$ the $1/e$ decay length of the $2p$ states is 1.35 meters, so a few meters from an excitation membrane only the metastable $2s$ population survives. One can conveniently drive the Doppler-shifted transition by chasing the beam with 6.1 GHz radiation aimed down a roughly 10 meter long, 4-by-2 cm cross section waveguide; this guide may also serve as a beam pipe. Modest laboratory powers [14] of roughly 10 Watt/ cm^2 will mix the $2s$ state completely with the $2p$ and to make the $2s$ decay with a $1/e$ distance of $\gtrsim 2.7$ m. To prevent Stark mixing of the $2s$ and $2p$ states, transverse magnetic fields must be less than 0.1 gauss from the excitation membrane down the length of the guide until the sharp rise of the transverse magnetic field used to ionize the $n = 2$ state. Little of the $2s$ state will decay radiatively in the rise if the rise occurs over less than the fully mixed $2s$ decay length of 2.7 meters. A sample of a few hundred antihydrogen atoms in the $2s$ state would suffice to determine the antihydrogen Lamb shift to $\sim 1\%$. Such a sample would be provided by a flux of roughly 10^4 antihydrogen atoms if the excitation target yields as expected ~ 0.01 $2s$ states per incident $1s$. Some of the required increase in intensity may come from using a high-Z target gas, thus using the $\sim Z^2$ scaling of the production cross section; however rate of heating of the transverse motion of the circulating antiproton beam by multiple Coulomb scattering also scales as $\sim Z^2$ and will limit the increase achievable. Performed in the same apparatus on hydrogen and antihydrogen, this experiment would be sensitive to a differential shift of the $2s$ and $2p$ states of hydrogen and antihydrogen equal to a fraction $\sim 2 \cdot 10^{-8}$ of the states' binding energy.

Acknowledgements

The authors thank H. Gould, A. Belkacem, M. Mandelkern and M. Peskin for many helpful conversations.

REFERENCES

[1] C. T. Munger, M. Mandelkern, J. Schultz, G. Zioulas, T. A. Armstrong, M. A. Hasan, R. A. Lewis, and G. A. Smith, Fermilab National Laboratory Proposal E862.

[2] I. A. Schmidt, S. J. Brodsky, and C. T. Munger, to be submitted to Physical Review D.

[3] V. B. Berestetskii, E. M. Lifshitz and L.P. Pitaevskii, Relativistic Quantum Theory, Part 1 (Second Edition), Pergamon Press, p. 212.

[4] G. Bertulani and C. A. Baur, Z. Phys. A 330 (1988) 777; Phys. Rep. 163 (1988) 299. See also: J. Eichler, Phys. Rep. 193 (1990) 255.

[5] John Peoples, Jr., in Proceedings of the Workshop on the Design of a Low Energy Antimatter Facility, ed. David B. Cline, World Scientific, 1986.

[6] T. Yamabe, A. Tachibana, and H. J. Silverstone, Phys. Rev. A 16 (1977) 877; R. Haydock and D. R. Kingham, J. Phys. B 14 (1981) 385.

[7] E. Acerbi, C. Birattari, B. Candoni, M. Castiglioni, D. Cutrupi and C. Succi, Lettre al Nuovo Cimento 10 (1974) 598; G. H. Gillespie and M. Inokuti, Phys. Rev. A. 22 (1980) 2430.

[8] M. Macri, in Proceedings of CERN Accelerator School, Geneva, 1983.

[9] K. Hikasa et. al., Phys. Lett. B 239 (1990), Table III.5

[10] J. Litt and R. Meunier, in Annual Review of Nuclear Science 23 (1973).

[11] G. Raisbeck and F. Yiou, Phys. Rev. A 4 (1958) 1971; W. Heitler, The Quantum Theory of Radiation, Oxford, 1954, equation V.22.45; F. Sauter, Ann. d. Phys. 9 (1931) 454, equation 39.

[12] A. Belkacem and H. Gould, Lawrence Berkeley Laboratory BEVALAC proposal 954H.

[13] RHIC Conceptual Design Report, Brookhaven National Laboratory Report BNL 52195, table IV.3-10 and pp.118-120; M. Fatyga, R. J. Rhoades-Brown, and M. J. Tannenbaum, in Brookhaven National Laboratory Report BNL 52247.

[14] W. E. Lamb, Jr., and R. C. Retherford, Phys. Rev. 60 (1941) 817.

γ	σ (pbarn)
3	0.34
6	0.64
10	1.04
50	2.0
100	2.5
200	2.8

Table I

Cross section (σ) for the production of anti-hydrogen in the $1s$ state by antiprotons incident on a proton target, as a function of the Lorentz factor γ of the antiproton. For other targets the cross section scales as Z^2.