First Laser-Controlled Antihydrogen Production

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Lasers are used for the first time to control the production of antihydrogen ($\overline{H}$). Sequential, resonant charge exchange collisions are involved in a method that is very different than the only other method used so far—producing slow $\overline{H}$ during positron cooling of antiprotons in a nested Penning trap. Two attractive features are that the laser frequencies determine the $\overline{H}$ binding energy, and that the production of extremely cold $\overline{H}$ should be possible in principle—likely close to what is needed for confinement in a trap, as needed for precise laser spectroscopy.

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All slow antihydrogen ($\overline{H}$) atoms to date have been produced in the same way—during positron cooling of antiprotons [1] in a nested Penning trap [2], with the $\overline{H}$ detected using two techniques [3–5]. The high production rate and the observation of highly excited states suggests that the $\overline{H}$ is produced by a three body mechanism involving two e^+ and one $\overline{p}$—the expected high-rate formation process at low temperature [2,6,7]. The coldest possible $\overline{H}$ are required for the intriguing goal of achieving $\overline{H}$ that is cold enough to be trapped for precise spectroscopic comparisons with hydrogen [8], building upon highly accurate hydrogen spectroscopy [9,10]. Hopes for three-body formation of $\overline{H}$ that is colder than the 200_meV observed in the only $\overline{H}$ velocity measurement so far [11] remain to be realized.

This Letter reports a very different way to produce $\overline{H}$. Lasers determine the binding energy of $\overline{H}$ atoms that are most likely as cold as the $\overline{p}$ from which they form. The lasers directly excite Cs atoms to high Rydberg states, Cs*. Two resonant charge exchange collisions [12],

$$Cs^* + e^+ \rightarrow Ps^* + Cs^+, \qquad (1)$$

$$Ps^* + \overline{p} \rightarrow \overline{H}^* + e^-, \qquad (2)$$
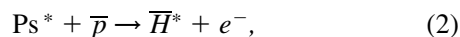
transfer the laser-selected Cs* binding energy to an excited positronium atom (Ps*) [13] and then to an excited $\overline{H}^*$. Both processes have large cross sections because of the large size of the Cs* and Ps* [14], whereas $\overline{H}$ formation using ground state Ps [15] has a rate too small to be observed. Very slow $\overline{H}$ are expected because a Ps* transfers little kinetic energy to a $\overline{p}$ as $\overline{H}$ forms. The $\overline{p}$ can be no colder than 4 K here, but the $\overline{p}$ could be made much

colder in principle—using techniques that cooled a trapped electron to 300 mK [16], for example.

The schematic in Fig. 1 shows three coaxial Penning traps (yellow regions)—for e^+ (left), for $\overline{p}$ (center), along with an initially empty trap for $\overline{H}$ detection (right). Cs from an oven is excited with two lasers. The Cs* collide with trapped e^+ to form Ps* atoms [Eq. (1)]. A small fraction of the Ps* collides with trapped $\overline{p}$ to produce $\overline{H}^*$ [Eq. (2)]. A small fraction of the $\overline{H}^*$ enters the detection trap, is ionized by the electric field in this trap, and deposits $\overline{p}$ in the trap to be counted later. Three close traps are realized with potentials [Fig. 3(b)] applied to cylindrical ring electrodes that are 6 mm long and 12 mm diameter [Figs. 2 and 3(a)]. The close traps maximize the solid angles which nonetheless remain small enough that many more $\overline{H}$ will be produced than can be detected.
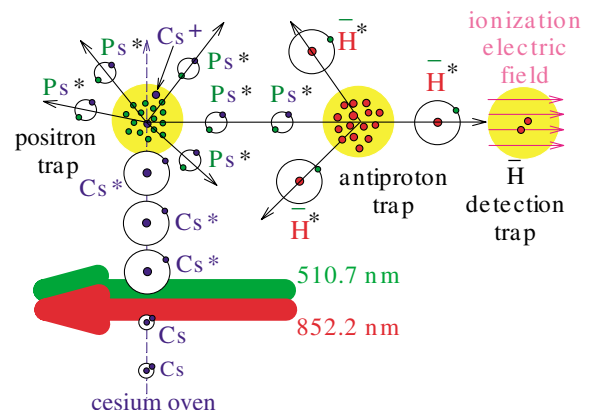

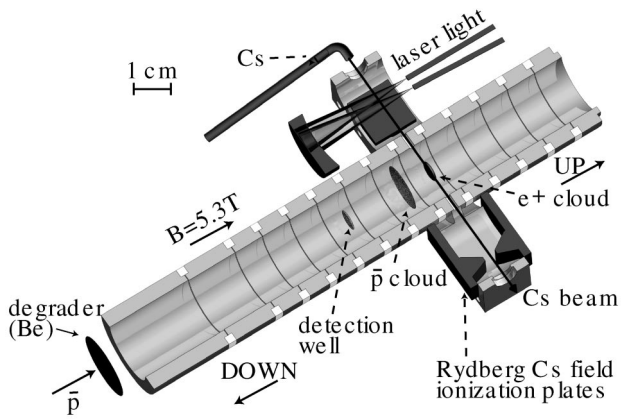FIG. 1 (color). Schematic of laser-controlled $\overline{H}$ production.

FIG. 2.   Cutaway view of the Cs beam and the three traps for e^+, $\overline{p}$, and for $\overline{H}$ detection. The trap is surrounded scintillators that detect $\overline{p}$ annihilation at high efficiency [19].
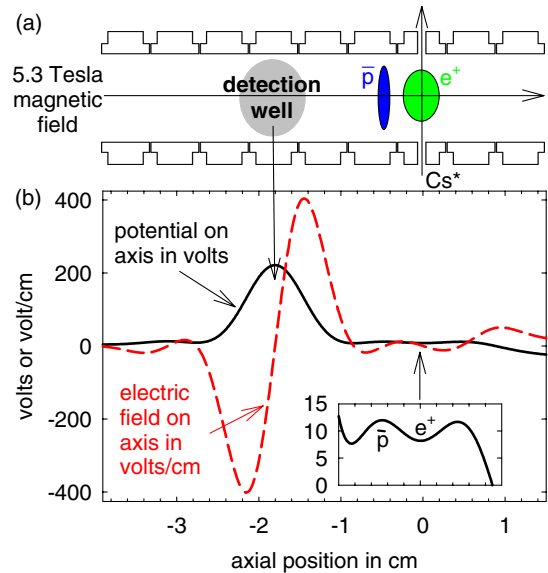

FIG. 3 (color online).   (a) Trap electrode cross section with particle locations. (b) On-axis potential and electric field used to confine the e^+ and $\overline{p}$, and to ionize and detect $\overline{H}^*$.

Positrons for $\overline{H}$ formation are transferred into the location shown in Figs. 2 and 3 from an upper accumulation region of the trap apparatus (not shown). In a well-documented accumulation method [18], e^+ from a 41 mCi ^{22}Na source slow in tungsten crystals and produce a Ps* that field ionize within a e^+ trap. The trapped e^+ radiate synchrotron radiation to come into thermal equilibrium with their 4 K environment. Their number, 1.4×10^6 on average for these trials, is deduced from the measured width of the dip that they cause in the noise-driven resonance of an attached LCR circuit [18].

Our trials use 2.4×10^5 $\overline{p}$ on average, accumulated typically in a half hour [19], and then located as shown in Figs. 2 and 3. They originate in CERN's unique antiproton decelerator (AD). We accumulate $\overline{p}$ at 4 K after reducing their energy by a factor of more than 10^{10}. The slowing, trapping, cooling, and accumulation techniques which make this possible for all experiments attempting to make and study slow $\overline{H}$ are well documented [19,20]. The number of $\overline{p}$ is measured by releasing them from the trap, and counting the annihilation pions with calibrated scintillators that have near unit efficiencies.

Cs atoms are sent towards the trapped e^+ [Figs. 2 and 3(a)] by heating to 350 K a thermally isolated, 5 mm^3 Cs oven within the cryogenic vacuum enclosure for the trap. One of 16 Cs $6S_{1/2}$ states is excited to $6P_{3/2}$ ($M_J = +1/2$ to $M_J = +3/2$, with $M_I = -5/2$). The transition is saturated with infrared (852.2 nm) light from a diode laser. About 10 mW is sent into the 4 K vacuum enclosure of the trap through a 1 mm diameter optical fiber. It illuminates the Cs beam, reflects from a spherical mirror, again illuminates the Cs, and about 55% exits the system through a second fiber. Pulses of green 510.7 nm light from a copper vapor laser (20 ns duration every 50 μs, 1250 W peak, 0.025 mJ) go through the same fiber and optics, and excite the Cs from $6P_{3/2}$ to a state that would be 37D (binding energy $\sim$10 meV) with no magnetic field. The approximately 45% of the light that does not exit the trap through the second fiber heats the trap

electrode by a couple of degrees during a typical experiment. A small electric field can tune the atoms into resonance with the fixed-frequency laser.

The Cs* beam enters the trap through a 0.3 mm aperture at the entrance of a 1 mm hole in a trap electrode, passes through the e^+ plasma, and leaves through a second 1 mm hole. The Cs* flux is measured by field ionizing these atoms and measuring the ionization current [13]. The current is proportional to and calibrates the $6P_{3/2}$ to $6S_{1/2}$ fluorescence, measured with a photodiode, whose signal then determines smaller Cs fluxes. Of order 10^{-3} of the Cs atoms are in large Rydberg orbits [13] with enormous charge exchange cross sections for producing Ps*. Typically 8×10^5 Cs*/s pass though the trapped e^+ location for 100 s.

Excited Ps* form when e^+ capture e^- from Cs* [Eq. (1)]. The Ps* formed in such resonant charge exchange collisions have approximately the $\sim$10 meV binding energy of the Cs*, as initially determined by the laser frequencies. An initial study [13] revealed an enormous cross section estimated to be 8×10^{-10} cm^2 —the area of a disc with a radius of nearly 0.2 μm—and approximately one in four of the trapped e^+ formed Ps* [13] assuming that the Ps* distribution was isotropic. The Ps* production also saturated when Cs* passed through the e^+ plasma for about 35 s, a time that should be much shorter here because of a much higher Cs* flux.

To minimize possible $\overline{p}$ heating the potential wells (Fig. 3) ensure that any Cs$^+$ ion with enough energy to escape the e^+ well will make no more than one pass back and forth through the $\overline{p}$ before escaping to the right in Fig. 3. This precaution halves the number of $\overline{H}$ we detect. We must forgo a second detection trap to the right of the e^+ well in Fig. 3(b) since Cs$^+$ could be confined between

the potentials of two detection traps and make many passes through the $\bar{p}$.

Ps* that enter the small solid angle presented by the trapped $\bar{p}$ can collide with the $\bar{p}$ to form $\bar{H}^*$ with essentially the ~ 10 meV binding energy of the Cs*, via the second resonant charge exchange [Eq. (2)]. The large size of the Ps* ensures a large (though yet unknown for a strong B) cross section, but a large fraction of Ps* still go through the e^+ plasma without forming $\bar{H}^*$.

The effective solid angle for $\bar{H}^*$ to be detected in the detection trap is also very small. The axial electric field exceeds 400 V/cm for all radii in the detection trap, more than enough to ionize the $\bar{H}^*$ which should ionize by about 200 V/cm. The ionized $\bar{H}$ deposit their $\bar{p}$ in this trap to be counted later. This electric field is also more than enough to ionize Ps* which arrive at the detection trap, and we can observe electrons that ionized Ps* deposit in this same trap. These electrons cool $\bar{p}$ captured from $\bar{H}^*$ ionization to the bottom of the detection trap well. The electric field is so strong off the axis in the detection trap region that it can ionize $\bar{H}^*$ before they enter the potential well of the detection trap. There is also a large radial component of the electric field off axis, whose effect upon $\bar{H}$ ionization is not well understood. These two effects prevent the detection of $\bar{H}$ that are more than some 3 to 5 mm away from the trap axis, but this radius and hence the effective detection solid angle is not precisely known.

To calibrate the detection time window we place $\bar{p}$ in the detection trap, then reduce the well depth through zero [solid curve in Fig. 4(b)] while counting $\bar{p}$ annihilations in scintillation detectors that surround the trap. The right edge of the peak in the histogram in Fig. 4(b) is used to select a 700 μs time window that contains annihilation signals from $\bar{p}$ released from the very bottom of the detection trap.

The $\bar{p}$ captured from $\bar{H}$ are released in the same way. A count in Fig. 4(a) indicates a coincidence of signals from at least two scintillating fibers, from different layers of a three layer fiber hodoscope, located just outside the trap's vacuum enclosure. When we sum 6 trials, 13 counts in the expected channel form a peak. This corresponds to 14 $\bar{H}$ ionized in the detection trap when the $94 \pm 6\%$ detection

efficiency is factored in. The detection efficiency is measured *in situ* by slowly ejecting $\bar{p}$ from the trap and comparing the number of annihilations detected in coincidences between fibers in the hodoscope and a double layer of scintillators that surrounds the trap, outside of the superconducting solenoid and its Dewar.

On average 2.2 background counts are expected in the 40 ms width of Fig. 4(a), and we see 3 counts outside of the peak. Statistically there is about a 4% chance that a background count is in the peak. The 3 counts outside the peak are not present in a coincidence of the described signals and the signals from large plastic scintillators that surrounds the superconducting solenoid around our trap. About half the counts in the peak survive this background free detection, as expected.

Owing to small solid angles and few trials, only 14 ± 4 $\bar{H}$ are detected in this proof-of-principle experiment. However, these correspond to between 100 to 200 $\bar{H}$ produced if the production is isotropic (with uncertainty coming from the mentioned uncertainty in the effective detection solid angle). Moreover, more atoms are expected for larger numbers of $\bar{p}$ and e^+. This demonstration came in several hours at the end of the 2003 $\bar{p}$ run at the CERN AD so the method has yet to be optimized.

The most convincing evidence that the counts in Fig. 4(a) are from $\bar{H}$ atoms is that the potential wells [Fig. 3(b)] are carefully arranged so that the only way to get a $\bar{p}$ in the detection trap is by ionizing an $\bar{H}$ within it, as discussed [4]. If a $\bar{p}$ does manage to escape its trap and pass through the detection trap, it cannot be captured unless a collision within this well lowers the $\bar{p}$ energy by more than an eV. This is the amount that the left side of the detection well is kept lower than the right in Fig. 3(b) (though the offset is too small to see in the figure). No counts are observed in the signal channel for two trials with the red laser detuned (so that only ground state Cs and no Cs* pass through the trapped e^+), nor for two trials without trapped e^+.

The lowest possible $\bar{H}$ velocities and temperatures are required if $\bar{H}$ atoms are to be confined in 0.5 K deep magnetic traps. A very important feature of this new $\bar{H}$ production mechanism is that it seems likely to produce $\bar{H}^*$ with the velocity distribution of the trapped $\bar{p}$ from which they form. Measuring the $\bar{H}^*$ velocity distribution (using the demonstrated oscillating field method [11], or perhaps by correlating pulsed laser and $\bar{H}$ detection timing) requires more atoms than detected so far. The current $\bar{p}$ velocity distribution is determined initially by the 4 K electrons that cool the $\bar{p}$, which are then moved into the desired location. Subsequent $\bar{p}$ collisions with the much lower mass Ps* should not substantially change the velocity of the $\bar{p}$ when these collide to form $\bar{H}^*$. Dilution refrigerator and feedback cooling methods to cool a trapped electron below several hundred mK [16] could likely be adapted to trapped $\bar{p}$.

The strong 5.3 T magnetic field is an essential part of the three traps, but it also complicates this experiment
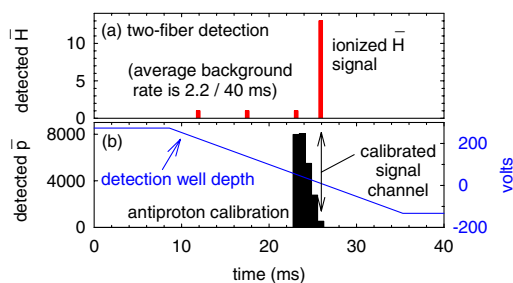

FIG. 4 (color online). (a) Antihydrogen detected (peak) as the potential well containing the ionized $\bar{H}$ is ramped down. (b) $\bar{p}$ annihilation signals (histogram and left axis) as the axial well depth is reduced through zero (solid curve and right axis).

P H Y S I C A L   R E V I E W   L E T T E R S

and its theoretical interpretation. First, exciting the Cs atoms from the $6P_{3/2}$ state to the Rydberg state requires empirically varying an electric field to tune the atoms into resonance with the fixed-frequency copper vapor laser since the states have not been calculated. Second, internal orbits of both the Cs* and $\overline{H}$* atoms formed are significantly modified by B since the magnetic force is comparable to the Coulomb force. Third, the binding energies of Rydberg atoms moving across a strong magnetic field are not even conserved, but are instead coupled to the center of mass energy of the atoms [21]. A calculation of this double charge exchange process which neglects the magnetic field [12] gives a guide about what to expect, but a formation calculation that includes the crucial role of the magnetic field is needed.

Which of the two $\overline{H}$ production methods is more useful in producing extremely cold, ground state $\overline{H}$ that can be trapped for precise spectroscopic comparisons with hydrogen and for gravitational studies? Laser-controlled charge exchange has the advantages of naturally producing both colder atoms and a much narrower, laser-selected distribution of excited states. However, a method to deexcite them to the ground state has yet to be demonstrated. $\overline{H}$ produced during e^+ cooling of $\overline{p}$ in a nested Penning trap produces atoms more easily and at a much higher rate, and it may be possible to collisionally deexcite them. However, now that the velocity of these $\overline{H}$* can be measured [11], it remains to be seen if ATRAP's method for driving $\overline{H}$ production [5] or some variant can produce very cold atoms as hoped. Other production methods, such as using a CO_2 laser to stimulate $\overline{H}$ formation in a trap [2], are yet to be tried. The best method for producing useful $\overline{H}$ is not yet clear.

In conclusion, this proof-of-principle experiment demonstrates the first laser-controlled $\overline{H}$ production. The atoms revealed by essentially back-ground-free detection are a small fraction of what is produced because the detection solid angle and the number of trials are small. Many more $\overline{H}$ are expected when more e^+ and $\overline{p}$ are used, and when the method is optimized. The produced $\overline{H}$ are expected to have the velocity distribution of the $\overline{p}$ from which they form, which can be made extremely low in principle. If measurements confirm a low $\overline{H}$ energy, and if the highly excited states can be deexcited, this laser-controlled charge exchange method could become the method of choice for producing cold $\overline{H}$ to be trapped for precise spectroscopic comparisons with hydrogen to test fundamental symmetries.

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