

Two-stage Rydberg charge exchange: An efficient method for production of antihydrogen

E. A. Hessels

Department of Physics and Astronomy, York University, Toronto, Ontario, Canada M3J 1P3

D. M. Homan and M. J. Cavagnero

Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506-0055

(Received 12 September 1997)

An efficient method for production of cold antihydrogen (\bar{H}) is proposed. Alkali-metal atoms laser excited to a Rydberg state are charge exchanged with cold trapped positrons, producing Rydberg states of positronium. In a second Rydberg-state charge exchange, the positronium atoms give up their Rydberg positrons to cold trapped antiprotons, producing Rydberg states of \bar{H} . These \bar{H} atoms soon decay down to the ground state, and, because they are cold, could be trapped in a magnetic trap. The efficiency of the process results from the extremely large cross sections for Rydberg charge exchange. Classical trajectory Monte Carlo calculations indicate an \bar{H} instantaneous production rate of $10^6/s$. [S1050-2947(98)07602-1]

PACS number(s): 36.10.-k, 34.60.+z, 34.70.+e

Recent successes in trapping large numbers of cold antiprotons (10^5 at 4.2 K) [1], and even larger numbers of cold positrons (10^6 , also at 4.2 K) [1,2], provide the building blocks for the production of cold antihydrogen \bar{H} . Several methods for production of cold \bar{H} from these building blocks have been proposed [3], but none has a very high efficiency. Cold \bar{H} production would allow for trapping \bar{H} in a magnetic trap, similar to that used to trap neutral hydrogen atoms [4]. Spectroscopy on such trapped \bar{H} could provide a strong test of *CPT*, as well as allowing for many precision tests of the physics of antimatter [5]. We propose here an efficient method using two stages of Rydberg-state charge exchange to produce cold \bar{H} atoms from the cold trapped components.

Charge-exchange processes between slow ions and Rydberg atoms have extremely large cross sections. For a Rydberg state with principal quantum number n , the radius of the atomic wave function is approximately $n^2 a_0$, leading to a geometric area of $n^4 \pi a_0^2$. Here $a_0 = 0.529 \times 10^{-10}$ m is the Bohr radius. For slow ions, charge-exchange cross sections σ_{CE} are predicted to be approximately an order of magnitude larger than these already large geometric areas [6]. Here “slow” refers to ion speeds v less than $v_e = \alpha c/n$, which is the characteristic speed of the electron in its Rydberg orbit, where α is the fine-structure constant and c is the speed of light. The Rydberg charge-exchange process has been studied extensively [6–9]. These experiments show large charge-exchange cross sections at low reduced velocity v/v_e , with cross sections dropping off very quickly for $v/v_e > 1$. The experiments also show that the ion captures the electron into states that have a similar binding energy to that of the electron in the Rydberg target.

Calculations of Rydberg charge exchange have been done [10,11] using the classical trajectory Monte Carlo (CTMC) methods. In these calculations, the incoming ion, the ion at the core of the Rydberg atom, and the Rydberg electron are all treated as classical particles and their trajectories are obtained by integrating the Newtonian equations of motion.

The initial trajectory of the electron is taken to be a trajectory consistent with the energy, total orbital angular momentum, and the z component of orbital angular momentum of the Rydberg state of the target atom. The final trajectory of the electron is analyzed to determine whether it has been captured by the ion, and to determine its state from its final energy and angular momentum. The main features of the CTMC predictions agree quite well with experimental results [7,8].

The present proposal is to create \bar{H} via two sequential Rydberg charge-exchange collisions as shown schematically in Fig. 1. The first charge exchange is between a thermal beam of cesium (or other alkali) atom, which is laser excited to a high- n Rydberg state and positrons that are trapped and cooled to 4 K. The product of this charge exchange is Rydberg states of positronium (Ps). When these Rydberg Ps atoms collide with 4-K trapped antiprotons, a second charge exchange occurs, producing Rydberg states of \bar{H} . The following paragraphs provide some details about the proposed scheme and present the CTMC calculations for the two charge-exchange processes.

Cesium atoms can easily be excited to high- n Rydberg states via a two- or three-step laser excitation. For example, efficient three-step CW excitation is possible via diode-laser

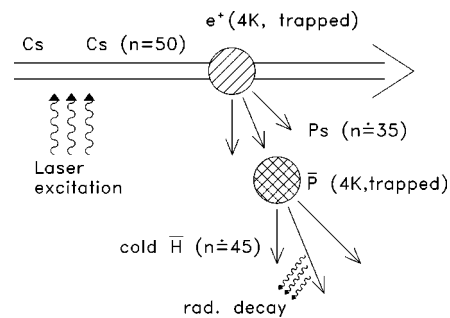


FIG. 1. A schematic of the dual-charge-exchange scheme for creating cold \bar{H} .

excitation to $6p$, followed by dye-laser excitation to $13d$, followed by a Stark-tuned CO_2 laser excitation up to a high- n Rydberg state. Other excitation schemes are also possible, both in Cs and in other alkali-metal atoms. Rydberg states can easily be created in large densities. However, because of their large cross sections, collisional and radiative effects become important if the density is too high [12]. For $n=50$ atoms, densities of up to 10^5 Rydberg atoms per cm^3 should lead to sufficiently small collisional effects, while still allowing for a very fast rate of charge exchange.

The radiative lifetimes of Rydberg atoms are very long, especially for states with large orbital angular momentum ℓ . Rydberg atoms are extremely sensitive to electric and magnetic fields [12], and the fields present near the traps will mix the ℓ and m states within a particular n manifold. An n state that is an equal mixture of all ℓ and m states has a radiative decay rate [13] of

$$1/\tau_{\text{rad}} \approx \frac{4}{3} n^{-5} \alpha^5 \frac{\mu c^2}{\hbar} [\ln(2n-1) - 0.365], \quad (1)$$

where μ is the reduced mass of the Rydberg electron. Transitions induced by blackbody radiation, which are usually important contributions to the lifetimes of Rydberg states, are not a major concern here since the ambient temperature near the Rydberg atoms would be 4 K, leading to a blackbody-radiation-induced transition rate [12] of $1/\tau_{\text{BB}} = \frac{4}{3} n^{-2} \alpha^3 k_{\text{B}} T / h = n^{-2} 4 \times 10^4 \text{ s}^{-1}$. This rate is smaller than the radiative decay rate for n 's of less than 100. For Cs with a principal quantum number $n_{\text{Cs}}=50$, the radiative lifetime of the statistically mixed state is 3.5 ms. During these 3.5 ms, the thermal Cs atoms travel a distance of approximately 1 m. It is therefore possible to laser excite the Rydberg atoms at a location well separated from the trapped positrons.

Because of the weak binding of the Rydberg electron to the core of the atom, relatively small electric fields of

$$E_{\text{SI}} = n^{-4} \left(\frac{\mu}{m_e} \right)^2 3 \times 10^8 \text{ V/cm} \quad (2)$$

are sufficient [12] to Stark ionize the atom. Thus the fields along the Cs beam for an $n_{\text{Cs}}=50$ state must be smaller than 50 V/cm.

The scaling of E_{SI} , τ_{rad} , and σ_{CE} with n are the main considerations for the choice of n_{Cs} . A plot showing these scalings is given in Fig. 2.

The Cs atoms are traveling at a speed v_{Cs} of approximately 300 m/s, the e^+ has a speed v of approximately 11 000 m/s as given by the Maxwellian distribution for 4 K, and an $n=50$ electron has a characteristic speed v_e of $(\mu/m_e)\alpha c/50 = 44\,000$ m/s. Thus, the collision between the Cs Rydberg atom and the cold trapped e^+ has a reduced velocity v/v_e of less than 1. Our CTMC calculations show that the charge-exchange cross section $\sigma_{\text{Cs}e^+}$ for this process (averaged over the Maxwellian distribution speed distribution for the 4-K positrons) is $9.7n_{\text{Cs}}^4 \pi a_0^2$, or $5 \times 10^{-9} \text{ cm}^2$ for $n_{\text{Cs}}=50$. This calculation assumes the Cs atom is in an $\ell=2, m=1$ state. Both experiment and CTMC theory [7] show that cross sections do not vary by more than factors of about 2 for different ℓ 's and m 's, so any other $n=50$ state

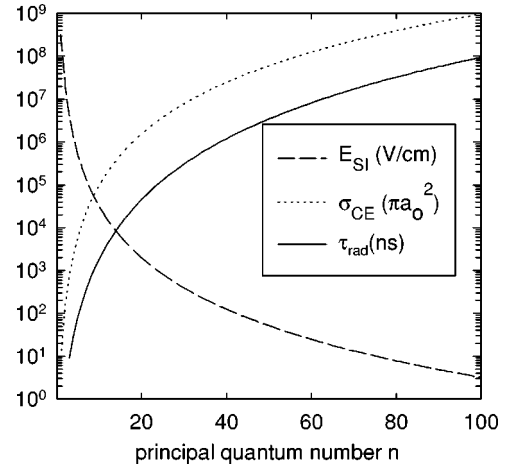


FIG. 2. Parameters of importance for choice of n for the dual-charge-exchange process. The charge-exchange cross section (dotted line) increases quickly with n , however, the higher- n states Stark ionize at smaller fields (dashed line), putting an upper limit on the usable n 's. The lifetime in the presence of fields (solid line) is important since it determines how far an atom travels in an n state. Note the y axis covers 9 decades.

could also be used. Because the e^+ is in a trap, the charge exchange is likely to occur in electric and magnetic fields. Theory and experiment [9,10,14] show that the presence of fields does not greatly affect charge-exchange cross sections.

The large predicted cross section, along with a Cs Rydberg beam of density ρ_{Ryd} of $10^5/\text{cm}^3$ leads to a characteristic time $(\rho_{\text{Ryd}}\sigma_{\text{Cs}e^+}v)^{-1} = 2$ ms for a e^+ to capture an $n_{\text{Cs}}=50$ Rydberg electron. (Note that since the positrons are moving much faster than the cesium atoms, it is the positron speed, rather than the cesium speed that determines the characteristic time.) The small value of this characteristic time indicates the fast rate of this process, but the time is long enough to make a second charge-exchange collision unlikely before the neutral Ps exits the trap. For a trap with $N_{e^+} = 10^6$ positrons, if the cross-sectional area A of the trap volume is 0.1 cm^2 , there will be $v_{\text{Cs}}\rho_{\text{Ryd}}A = 3 \times 10^8$ Rydberg atoms entering the trap per s, or the required 10^6 Rydberg atoms every 3 ms. Thus, after approximately 3 ms, the trap will be emptied of its positrons, all of them having captured a Rydberg electron. In addition, almost every Rydberg atom that passed through the trap lost its electron to a positron, indicating a surprising result of a very high efficiency for charge exchange. The net result is that only about 10^6 Rydberg atoms need to be released into the e^+ trap, a very small quantity even in the extremely high vacuum ($< 5 \times 10^{-17}$ Torr) used [15] in e^+ and antiproton traps. Annihilation of the positrons by the incident Cs atoms is not a concern for this small quantity of Cs.

The Rydberg Ps atoms exit the e^+ trap isotropically since the initial momenta of both the positrons and Cs Rydberg electrons are nearly isotropically distributed. The distribution of Ps speeds v_{Ps} obtained from our CTMC calculations is shown in Fig. 3(a).

The final n states populated in the charge exchange (as calculated using CTMC) is shown in Fig. 3(b). Note that the final-state distribution is sharply peaked near $n_{\text{Ps}} = n_{\text{Cs}}/\sqrt{2}$. Since the Ps binding energy is $E_{\text{Ps}} = -\text{Ry}/2n_{\text{Ps}}^2$, whereas the

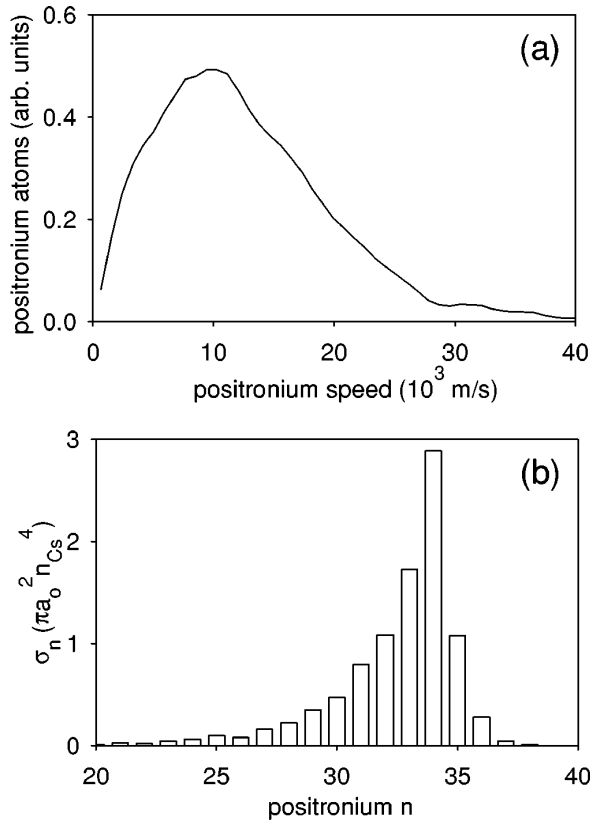


FIG. 3. The final Ps speeds (a) and n states (b) created in a charge exchange between $n=50$ Cs atoms and 4-K positrons.

Cs binding energy is $E_{Cs}^- = -Ry/n_{Cs}^2$ (here $Ry = \frac{1}{2}\alpha^2 m_e c^2$ is the Rydberg constant), $n_{Ps} = n_{Cs}/\sqrt{2}$ corresponds to the same binding energy before and after the charge exchange.

The lifetime of an $n=34$ Rydberg Ps state (assuming magnetic and electric fields mix all ℓ and m states) is 1 ms as given by Eq. (1). The annihilation rate is not a concern for these Rydberg states since the overlap between the e^- electron and e^+ wave functions is small for these large-sized atoms. The Ps atoms are capable of traveling a distance of meters without decaying out of the Rydberg state or annihilating and thus can easily survive the distance between the e^+ trap and \bar{p} trap.

Both electric and magnetic fields have large effects on the Rydberg Ps atoms. From Eq. (2), dc electric fields of greater than $\frac{1}{4}n_{Ps}^{-4}3 \times 10^8$ V/cm will cause the Rydberg states to Stark ionize. For $n_{Ps}=34$, this corresponds to a field of 50 V/cm. The motional electric field due to the relativistic transform (even though v_{Ps}/c is typically 0.000 05) of a dc magnetic field that is transverse to the direction of the Ps motion can also cause Stark ionization. For 4-K Ps, a transverse magnetic field of greater than 0.3 T would lead to Stark ionization. Transverse fields of this size should be possible even in traps with magnetic fields of several T by having the Ps travel parallel to the field (i.e., having the line from the positron trap to the antiproton trap be aligned with the magnetic field [16]).

For the second Rydberg charge exchange, the Ps is traveling at speeds of approximately 15 000 m/s, and the antiprotons are moving with speeds given by a Maxwellian distribution for 4 K, typically 250 m/s. Thus, the relative speed

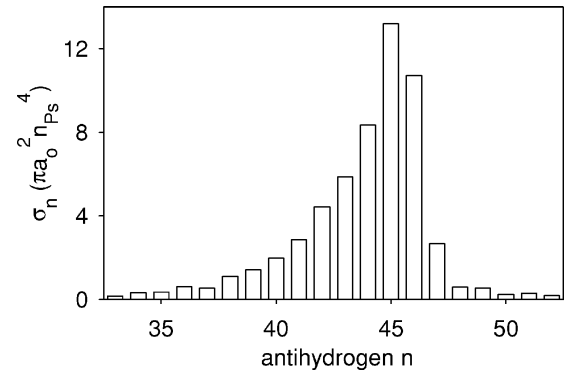


FIG. 4. Final \bar{H} n states created by the dual-charge-exchange for 4-K positrons and antiprotons and $n_{Cs}=50$.

between the two is less than $\frac{1}{2}\alpha c/34 = 30\,000$ m/s and the cross section for charge exchange is again expected to be large. Our CTMC calculations [17] give a charge-exchange cross section (averaging over the incident speeds of the Ps atoms) of $\sigma_{Ps\bar{p}} = 58n_{Ps}^4\pi a_0^2$.

Because of the 4π steradian distribution of the Rydberg Ps atoms, the efficiency of the dual-charge-exchange process is maximized when the distance between the trapped positrons and the trapped antiprotons is minimized. If the distance between the two trapped species is $d=0.2$ cm, the fraction of Ps atoms that charge exchange with $N_{\bar{p}}=10^5$ antiprotons is $N_{\bar{p}}\sigma_{Ps\bar{p}}/(4\pi d^2)$, which equals 10^{-3} for $n_{Ps}=34$. With the $N_{Ps}=10^6$ Ps atoms created in the first charge exchange, this implies a production of $N_{Ps}N_{\bar{p}}\sigma_{Ps\bar{p}}/(4\pi d^2) = 1000$ cold \bar{H} atoms. This number indicates that the two-stage Rydberg charge exchange method is an efficient way to produce \bar{H} atoms. In fact with a Rydberg Cs density of $10^5/\text{cm}^3$, these 1000 \bar{H} 's are created within a few ms, leading to an \bar{H} instantaneous production rate of almost $10^6/\text{s}$.

It should be noted that antiprotons that do not charge exchange remain trapped and so can be used again once the e^+ trap is reloaded. By repeated loadings of the e^+ trap, it is expected that a large fraction of the antiprotons can be converted into Rydberg states of \bar{H} .

Because the antiprotons are more massive than the Ps atoms, the \bar{H} continues to move in the direction and speed of the antiprotons. Thus, they exit the trap in an isotropic 4-K Maxwellian distribution. The final n states for these \bar{H} atoms is calculated using CTMC, averaging over the distribution of incoming Ps speeds given in Fig. 3(b). The results of these calculations are shown in Fig. 4. Note that the distribution is very narrow and is centered near $n=45$ for $n_{Cs}=50$.

These Rydberg states will cascade back down to the ground state. The time for this cascade in the presence of electric and magnetic fields is given by Eq. (1), and the \bar{H} will decay out of the $n=45$ state in approximately 2 ms. In this time, the \bar{H} atoms travel a distance of about 50 cm. Those \bar{H} atoms that are on the cold end of the Maxwellian distribution will be the most probable for magnetic trapping, and these will have traveled a shorter distance. Note that if

the trapped antiprotons were colder than 4 K this distance would also be shorter. Rydberg states have very large diamagnetism, and it might be possible to set up magnetic fields that trap the Rydberg \bar{H} atoms, or guide them towards a ground-state magnetic trap.

With the large number of cold \bar{H} atoms predicted for this two-stage Rydberg charge exchange method, it seems likely that it will be possible to magnetically trap some of them.

This would allow for precise spectroscopic studies of \bar{H} and could lead to precise tests of the physics of antimatter.

We are indebted to Keith MacAdam for helpful discussions during the course of this work. This research was supported by the Natural Sciences and Engineering Research Council of Canada, and by the Division of Chemical Sciences, Offices of Basic Energy Sciences, Office of Energy Research, and U.S. Department of Energy.

-
- [1] D. S. Hall and G. Gabrielse, *Phys. Rev. Lett.* **77**, 1962 (1996), and references therein.
- [2] L. Haarsma, K. Abdullah, and G. Gabrielse, *Phys. Rev. Lett.* **75**, 806 (1995).
- [3] C. Zimmermann and T. W. Hänsch, *Nucl. Phys. A* **558**, 625c (1993).
- [4] H. F. Hess, G. P. Kochanski, J. M. Doyle, N. Masuhara, D. Kleppner, and T. J. Greytak, *Phys. Rev. Lett.* **59**, 672 (1987); C. Cesar, D. Fried, T. Killian, A. Polcyn, J. Sandberg, I. Yu, T. Greytak, D. Kleppner, and J. Doyle, *ibid.* **77**, 255 (1996).
- [5] R. J. Hughes, *Nucl. Phys. A* **558**, 605 (1993).
- [6] K. B. MacAdam, N. L. S. Martin, D. B. Smith, R. Rolfes, and D. Richards, *Phys. Rev. A* **34**, 4661 (1986).
- [7] K. B. MacAdam, J. C. Day, J. C. Aguilar, D. M. Homan, A. D. MacKellar, and M. J. Cavagnero, *Phys. Rev. Lett.* **75**, 1723 (1995).
- [8] B. D. DePaola, M.-T. Huang, S. Winecki, M. P. Stöckli, and Y. Kanai, *Phys. Rev. A* **52**, 2136 (1995).
- [9] S. B. Hansen, T. Ehrenreich, E. Horsdal-Petersen, K. B. MacAdam, and L. J. Dubé, *Phys. Rev. Lett.* **71**, 1522 (1993).
- [10] J. Wang and R. E. Olson, *Phys. Rev. Lett.* **72**, 332 (1993); D. M. Homan, M. J. Cavagnero, and D. A. Harmin, *Phys. Rev. A* **50**, R1965 (1994).
- [11] S. Bradenbrink, E. Y. Sidky, Z. Roller-Lutz, H. Reihl, and H. O. Lutz, *J. Phys. B* **30**, L161 (1997).
- [12] T. F. Gallagher, *Rydberg Atoms* (Cambridge University Press, New York, 1994).
- [13] E. S. Chang, *Phys. Rev. A* **31**, 495 (1985).
- [14] K. B. MacAdam, D. M. Homan, O. P. Makarov, and O. P. Sorokina, in *Proceedings of the 14th International Conference on the Application of Accelerators in Research and Industry* (AIP Press, New York, 1997).
- [15] G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, T. A. Trainor, and W. Kells, *Phys. Rev. Lett.* **65**, 1317 (1990).
- [16] This is the configuration of the antiproton-positron trap developed at Harvard [Gerald Gabrielse (private communication)].
- [17] The $\ell=2, m=1$ state is used in our calculations. Again, neither the ℓ and m state used [7] nor the fields present in the trap [9,10,14] are expected to have a large effect.