Comment on "Driven Production of Cold Antihydrogen and the First Measured Distribution of Antihydrogen States"

The recent production of antihydrogen by the ATHENA [1] and ATRAP [2,3] Collaborations represents important steps in antihydrogen experimentation. However, the desired recombination to atomic ground states was apparently interrupted, since weakly bound atoms escape the trap and are detected. Here, we argue that the ATRAP analysis data [3] determines these atoms to be in the long-lived "guiding center drift" regime. Moreover, application of the classical theory of (interrupted) 3-body recombination in strong magnetic fields [4] gives similar binding energy spectra, and predicts production rates with unexpected temperature and density scalings.

The experiments repeatedly propel $\bar{p}$'s through e^+ plasmas to allow recombination. The e^+ plasmas in ATRAP had density $n \sim 10^7\,\mathrm{cm}^{-3}$ and length $L \sim 1$ mm in a field $B_z = 5$ Tesla. The *estimated* temperature $T_e \sim 4$ K gives collision time $\tau_c \equiv (n\bar{v}b^2)^{-1} \sim 0.7\ \mu$s. A transiting $\bar{p}$ with 10 meV (estimated) kinetic energy remains in the plasma for a time $\Delta t \sim \tau_c$. Marginally bound $e^+\bar{p}$ pairs may occur immediately, and collisions cause the binding energy $(-E)$ to increase or decrease.

Pairs with $E \sim 2$ meV have separations $\rho = e^2/E \sim 0.7\ \mu$m, and are well described by classical $\mathbf{E} \times \mathbf{B}$ drift dynamics [4]. The e^+ guiding center oscillates (ω_z) along B_z, and executes slower drift orbits $(\omega_{\mathbf{E}\times\mathbf{B}})$ around the $\bar{p}$ [Fig. 1(a)]; or the pair may drift together across B_z; or perpendicular $\bar{p}$ velocity $(v_{p\perp})$ may separate the pair.

Out of the plasma, these "guiding center atoms" do not readily relax to deeper binding [4,5], since the (quantized) e^+ cyclotron dynamics (Ω_c) is isolated, with $\Omega_c \sim 30\omega_z \sim 10^3\omega_{\mathbf{E}\times\mathbf{B}}$. This ordering breaks down at $E \sim 20$ meV, where $\Omega_c \sim \omega_z \sim \omega_{\mathbf{E}\times\mathbf{B}}$; the orbits become chaotic, and radiative relaxation may occur.

These pairs are destroyed by weak electric fields $F = \alpha e/\rho^2$, with $\alpha \lesssim 1$ depending somewhat on field direction, e^+ energy, and $\bar{p}$ velocity. ATRAP counted the number $N(F_{\mathrm{lo}} \rightarrow F_{\mathrm{hi}})$ of bound pairs leaving the plasma axially which survive a field F_{lo} but which are pulled apart by F_{hi}. This was reported as a *relative* number $\mathrm{N}(F_a) \equiv N(F_a \rightarrow 140)/N(20 \rightarrow 80)$, with "analysis" field $23 < F_a < 84$ [V/cm], per Fig. 2 of Ref. [3]. Figure 1(b) replots this data [3] versus estimated binding energy, taking $E_a = 0.38\ \mathrm{meV}\,F_a^{1/2}$ from $\alpha = 1$ [6].

The theory and simulations of Ref. [4] describe a stationary $\bar{p}$, with bound state distribution W temporally relaxing towards the thermal equilibrium $W_{\mathrm{th}}(\varepsilon) = (5\pi^{3/2}/4)\,nb^3\varepsilon^{-7/2}\exp(\varepsilon)$, with scaled energy $\varepsilon \equiv E/T_e$. Collisions *fill* the bound states to a progressively increasing depth $\varepsilon_0 = (\Delta t/\tau_c)^{1/2} \sim 1$, limited by the "kinetic bottleneck" to $\varepsilon_0 \lesssim 5$. Also, a low probability *tail* is observed for $\varepsilon > \varepsilon_0$, empirically described by $W(\varepsilon) \approx (\varepsilon/\varepsilon_0)^{-8}W_{\mathrm{th}}$. Integrating this tail over the ATRAP detection range gives the probability spectrum $P(E_a) \equiv \int_{\varepsilon_a}^{\varepsilon_{140}} d\varepsilon' W(\varepsilon')$ shown in Fig. 1(b). Each $\bar{p}$ has probability $P \sim 0.5 \times 10^{-8}$ of binding with $E \sim 2 \rightarrow 4$ meV on each transit; and ATRAP "drives" the $\bar{p}$'s at 0.8 MHz for up to 250 sec.

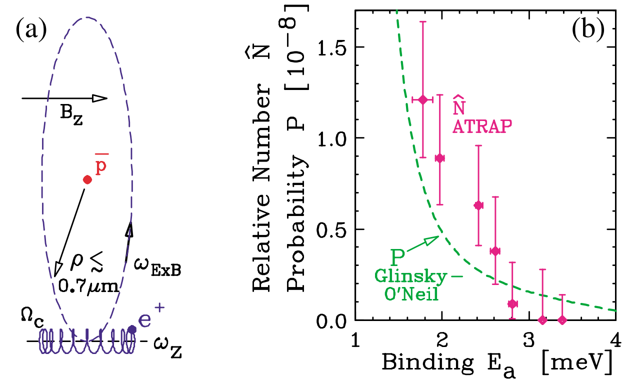

FIG. 1 (color online). (a) $\mathbf{E} \times \mathbf{B}$ drift orbit of e^+–$\bar{p}$ pair; (b) observed and predicted binding energy spectra.

Surprisingly, the density and temperature scalings for these weak bindings differ markedly from the full recombination rate $R \propto n^2T_e^{-9/2}$. The tail probability gives $W(E) \propto \Delta t^4 n^5 T_e^{5/2}$ for $E/T_e \lesssim 1$; so detected pair production may actually *increase* with T_e, if $v_{p\perp}$ remains small. For larger E/T_e, the exponential factor becomes important, so knowledge of T_e is crucial. Moreover, at *high* T_e (e.g., 300 K), even "plasma-weak" bindings $(\varepsilon \sim 1)$ could be deep enough $(E \sim 25$ meV) for chaotic relaxation to occur.

Thus, there may be several possible routes to the desired ground state of $\bar{H}$. Measurements of bound state formation rates *per $\bar{p}$ transit*, with well-characterized T_e and $\bar{p}$ velocities, could clarify the picture substantially.

C. F. Driscoll
Physics Department
University of California, San Diego
La Jolla, California 92093-0319, USA

Received 30 May 2003; published 9 April 2004
DOI: 10.1103/PhysRevLett.92.149303
PACS numbers: 36.10.–k, 34.80.Lx, 52.27.Jt

[1] M. Amoretti *et al.*, Nature (London) **419**, 456 (2002).
[2] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 213401 (2002).
[3] G. Gabrielse *et al.*, Phys. Rev. Lett. **89**, 233401 (2002).
[4] M. E. Glinsky and T. M. O'Neil, Phys. Fluids B **3**, 1279 (1991).
[5] G. J. Ackerman *et al.*, Phys. Rev. Lett. **78**, 199 (1997).
[6] J. Estrada *et al.*, Phys. Rev. Lett. **84**, 859 (2000).

