Metastable states in antihydrogen formation

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Abstract

At temperatures and densities relevant to current experiments antihydrogen is mainly formed through the three-body process $\bar{p} + e^+ + e^+ \to \bar{H} + e^+$ The state formed initially through this process is a Rydberg state, usually with a binding energy of only a few Kelvin. This state is fragile, and will not survive interaction with external fields or other particles, unless it is first stabilized through further collisions with positrons. Much more often, though, collisions with positrons will destroy the weakly bound antiatom, and only a very small fraction of the initially formed atoms will gain sufficient binding energy to reach a stable state. Simulations have shown that antiatoms are stable against collisional ionization once they have reached a binding energy greater than about 10 times the temperature of the positron plasma – the so called “bottleneck”[1].

Antihydrogen is formed in a static magnetic field (~1 T), so for the typical intial Rydberg antihydrogen, magnetic forces will dominate. Thus, the cyclotron energy of the positron is a conserved quantity, and the antiatom may remain bound even if its total energy (including the cyclotron energy of the positron) lies above the ionization threshold. On rare occasions, the positron passes close to the antiproton, which causes its cyclotron energy to rapidly change. The bound states with positive total energies are therefore metastable, as was pointed out by [2]. Through the inverse process, a metastable state can be formed in a positron-antiproton collision where the positron passes very close to the antiproton.

We have simulated antihydrogen formation through classical particle-in-a-box calculations, in order to investigate the importance of formation and decay of these metastable states. We compare to similar calculations using the Guiding Center Approximation (GCA), where the cyclotron energy of the positrons is not allowed to change. We find that, though the formation of the initial antihydrogen state is usually well described by the GCA, the energy transfer is usually much larger in collisions where a metastable state is formed. These states are therefore more likely to survive further collisions. We find that inclusion of this mechanism has a significant impact on the formation rate of antihydrogen with binding energy of the order of the bottleneck energy.

Theory

Three-body formation of antihydrogen starts with a single collision of the type:

$$\bar{p} + e^+ + e^+ \to \bar{H} + e^+$$

leading to an antihydrogen atom with very small binding energy (a few Kelvin). The initially formed antihydrogen is stablized (or, more usually, destroyed) by further two-body collisions: $e^+ + \bar{H}(E_B) \to e^+ + \bar{H}(E_B')$

The rate of formation of antiatoms with binding energy larger than some E_B is according to this model proportional to the positron denisty squared:

$$\lambda = C n_e^2 b^5 \bar{v} \quad \text{where} \quad b = \frac{e^2}{4\pi\epsilon_0 k_B T}$$

C describes the formation rate in “steady state”, which requires many collisions to establish.

An alternative route to formation is via metastable stated which could be formed via two-body collisions. These states exist because in strong magnetic fields the cyclotron energy of the positron is an approximately conserved quantity. Thus for a loosely bound antihydrogen the relevant binding energy is

$$E_B = -\frac{m_p v_z^2}{2} + \frac{e^2}{4\pi\epsilon_0}\frac{1}{r}$$

This binding energy can be positive, even if the usual binding energy

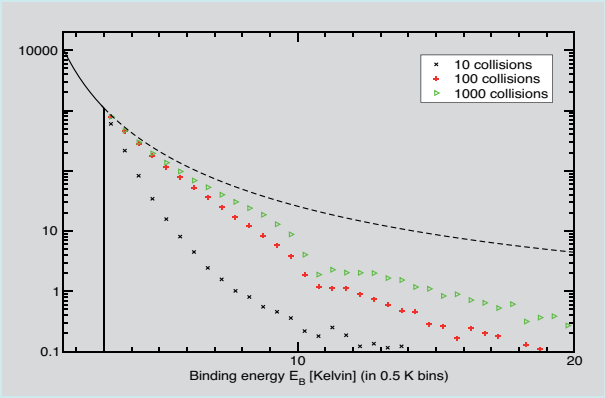
$$E_B^{\text{tot}} = -\frac{m_p v^2}{2} + \frac{e^2}{4\pi\epsilon_0}\frac{1}{r} = E_B - E_{\text{cyc}}$$

is negative. Such a state is metastable. It can be formed or decay on rare occasions when the positron passes sufficiently close to the antiproton to induce a rapid and effectively random change to the cyclotron energy. This can happen without interaction with a third body since the total energy is conserved. Since this is a two-body process, one would expect a violation of the density squared scaling of the formation rate, if this process is significant.

Method

Collisions are simulated using classical equations of motion within a suffciently large box around the antiproton.

The initial state of the antihydrogen atom is taken from a thermal distribution (15 Kelvin) extending across the threshold down to a binding energy of 3 Kelvin.



Thermal steady-state distribution of atoms (arbitrary unit on y-axis). Our initial state is taken from the solid curve. The dashed curve is the expected steady-state distribution.Symbols show how the simulated distribution converges to the steady-state.

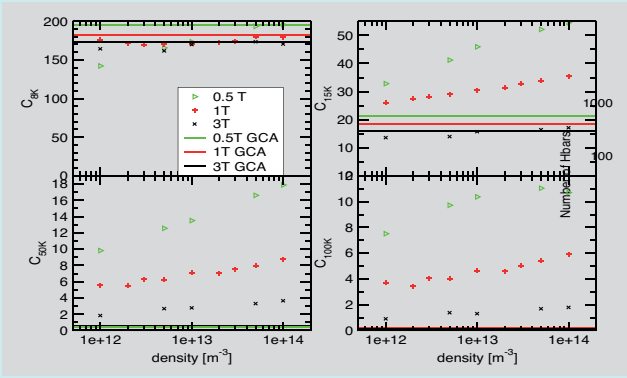
The antihydrogen is repeatedly collided with positrons from a 15 K distribution. Collisions are repeated until either (i) the antiatoms is ionized or (ii) the binding energy drops below a pre-defined value.

The different positron densities are simulated by varying the average time between collisions.

$$t_{\text{coll}} = \frac{1}{n_e \bar{v} \pi \rho^2}$$

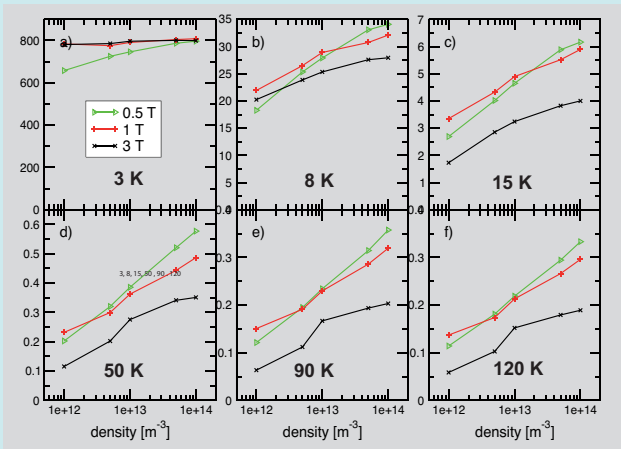
For the usual three-body mechanism involving properly bound state the results should be independent of the time between the collisions. For a metastable state there is a possibility that the atom decays during the intervening time.

Results



Formation coefficients for different magnetic fields and different binding energies defined as

$$E_B = -\frac{m_p v_z^2}{2} + \frac{e^2}{4\pi\epsilon_0}\frac{1}{r}$$



Formation coefficients for different magnetic fields and different total energies defined as

$$E_B^{\text{tot}} = -\frac{m_p v^2}{2} + \frac{e^2}{4\pi\epsilon_0}\frac{1}{r} = E_B - E_{\text{cyc}}$$

Conclusions

We do see evidence for a density-dependent rate coefficient indicative of meta-stable states.
The effect kicks in at binding energeis 8-50 K, showing that though formation through meta-stable states involves larger energy transfers than conventional three-body collisions.
The C-coefficient increases with density - indicating the decay of metastable states.

References

[1] E.M. Bass and D.H.E. Dubin, *Phys. Plasmas* **16**, 12101 (2009);M.E. Glinsky and T.M. O'Neil, *Phys. Fluids* B **3** 1279 (1991)
[2] Correa et al. *Physical Review* E **72,** 046406 (2005)