Antihydrogen Formation and Level Population Evolution During Passage Through a Positron Plasma

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Antihydrogen formation and level population evolution during passage through a positron plasma

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Antihydrogen is at the focus of antimatter research. One of the main aims is to perform a direct test of the fundamental CPT symmetry by comparing the spectroscopic properties of the ground-state antihydrogen atom with those of the hydrogen atom. In current experiments synthetized antihydrogen is formed mainly via the three-body recombination process after mixing positron and antiproton clouds together in a cryogenic trap. The major three-body formation process populates mainly highly excited Rydberg states, therefore before the antihydrogen atoms reach the ground-state additional processes may take place, such as collisional (de)excitation, ionization and spontaneous or stimulated radiative transitions. We have used a classical-trajectory Monte Carlo (CTMC) code along with regular atomic codes to generate a scattering database of rate coefficients in various experimentally achievable magnetic field strengths and in low temperature positron plasma conditions. We used these rates to calculate the evolution of level population of antihydrogen during formation, scattering and flight within our experimental conditions [1]. The model and the results are presented.

KEYWORDS: antihydrogen, positron, Monte Carlo, CPT

1. Introduction

Antihydrogen production has reached such a level that precision spectroscopic measurements of its properties are within reach. In particular, the ground-state level population is of central interest for experiments aiming at antihydrogen spectroscopy, the ultimate goal of which is testing the CPT-symmetry. Antihydrogen production is a result of the interplay between recombination, collisional and radiative processes in magnetic fields. A list of the various relevant atomic scattering processes are shown in Table I.

Antihydrogen atoms with principal quantum number $n = 15$ or lower quickly cascade down to

Table I. Atomic scattering processes between antiprotons ($\bar{p}$), positrons (e^+) and antihydrogen atoms ($\bar{H}$) taking place during antihydrogen formation.

Process name	Process
Three-body recombination	$\bar{p} + e^+ + e^+ \rightarrow \bar{H}^* + e^+$
Radiative recombination	$\bar{p} + e^+ \rightarrow \bar{H}^* + h\nu$
Collisional (de)excitation	$\bar{H}^* + e^+ \leftrightarrow \bar{H}^{**} + e^+$
Collisional Ionisation	$\bar{H}^* + e^+ \rightarrow \bar{p} + e^+ + e^+$
Spontaneous radiative decay	$\bar{H}^{**} \rightarrow \bar{H}^* + h\nu$
Stimulated radiative transition	$\bar{H}^* + h\nu \rightarrow \bar{H}^{**}(+2h\nu)$

the ground state within $\simeq$ 1 ms, therefore in this work the number of such states is adopted as a measure of experimentally useful antihydrogen atoms. In this work the level population evolution is studied using classical-trajectory Monte Carlo based scattering rate coefficients [1].

2. Level population evolution model

For a particular bound state $N(i)$ (where i is any quantum number), the scattering processes either populate or depopulate a given state. Therefore the evolution of level population of each state and the loss of antiprotons over time can be described by a system of coupled differential equations,

$$\begin{aligned} \frac{dN(i)}{dt} &= [C_{rr}(i) + C_{tbr}(i)n_e]n_e N_p - C_{ion}(i)n_e N(i) \\ &+ \sum_{j\neq i}[C_{col}(j,i)n_e + C_{str}(j,i)]N(j) \\ &- N(i)\sum_{j\neq i}[C_{col}(i,j)n_e + C_{str}(i,j)], \end{aligned} \tag{1}$$

while the number of bare antiprotons fulfills the relation given by,

$$\frac{dN_p}{dt} = \sum_i \Big(C_{ion}(i)n_e N(i) - [C_{rr}(i) + C_{tbr}(i)n_e]n_e N_p\Big). \tag{2}$$

Here N_p is the number of antiprotons, n_e is the density of positrons, C_x denote rate coefficients for atomic process, $C_{rr}(i)$ and $C_{tbr}(i)$ for radiative and three-body recombination to state i, $C_{ion}(i)$ for ionisation by positron impact from bound state i, $C_{col}(i, j)$ for collisional (de)excitation by positron impact and $C_{str}(i, j)$ for spontaneous or stimulated transitions due to presence of a radiation field. The initial conditions used for the system is a completely empty antihydrogen level population and a given number of antiprotons.

The rate coefficient of an atomic scattering process depends on the energy distribution of the impact particle, $C = \int \sigma(E)f(E)vdE$, where $f(E)dE$ is the energy distribution function with positron temperature T_e, $\sigma(E)$ cross section, v velocity of the impact particle. Collisional and ionisation rate coefficient can be computed by Monte Carlo methods [3]. From the ionisation rate the three-body recombination rate can be derived by the detailed balance principle and assuming thermodynamical equilibrium

$$C_{tbr}(i) = C_{ion}(i)g_i n_e \Lambda^3 e^{\frac{E(i)}{k_B T_e}}, \tag{3}$$

where $g_i = n_i^2$ is the statistical weight of state i with principal quantum number n_i, $\Lambda = h/\sqrt{2\pi m_e k_B T_e}$ is the thermal de Broglie wavelength of the positron, m_e is the positron mass, $E(i)$ is the binding energy of state i. The radiative recombination, spontaneous and stimulated radiative transition rates and black-body radiation calculation is detailed in [1].

3. Results

The coupled system of differential equations are solved for 150 bound states, corresponding to principal quantum numbers $n_i = 1\ldots150$, a number chosen sufficiently large to represent thermal equilibrium level population for highly excited Rydberg states. The initial conditions for the solution are an empty level population for the bound states of antihydrogen atoms, with conditions of $N_p = 10^6$ antiprotons, a positron density of $n_e = 10^{14}$ m^{-3}, a positron temperature of $T_e = 50$ K, a magnetic field strength of $B = 2$ T and a $T_r = 300$ K black-body radiation field. A resulting level population is shown for a range of evolution times in (Fig 1) and plasma lengths (Fig 2). A typical experimental time scale of one bouncing cycle is 10 μs, which is the average time an antiproton spends in the positron plasma. Also, on Fig 1 the thermal equilibrium distribution of bound state population, given by the Saha-Boltzmann relation, $N_{th}(i) = N_p n_e n_i^2 \Lambda^3 e^{\frac{E(i)}{k_B T_e}}$, is shown for the same temperature of $T_e = 50$ K.

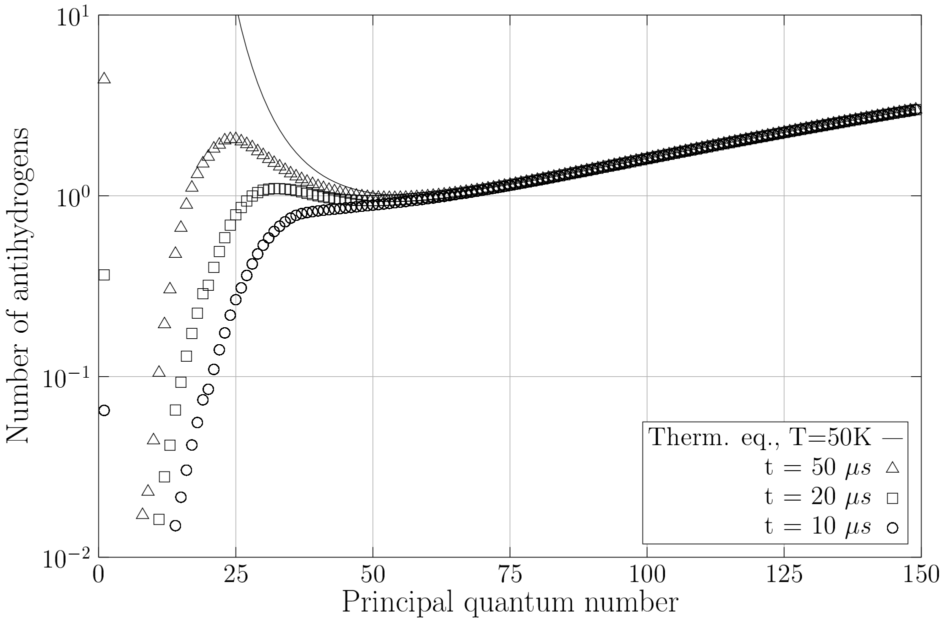

Fig. 1. Level population (number of antihydrogen atoms) as a function of the principal quantum number for various time scales allowed for evolution, ranging from $t = 10\mu$s to $t = 50\mu$s at positron temperature $T = 50$ K. The thermal equilibrium level population is shown with solid line.

The main result of the study, the positron plasma parameter scan, is illustrated in Fig 3 and Fig 4, represented as a contour plot where each contour line corresponds to the same ground-state antihydrogen yield. The rate of increase in the number of antihydrogens does not follow any simple scaling law. The power law scaling dependence of the number of ground-state antihydrogen atoms, $N(1)$, on positron temperature and density is illustrated in the left and right of Fig 4 for 10 μs of plasma interaction. Also, the expected scaling behaviour is shown for three-body recombination (solid line), $R_{tbr} \propto n_e^2 T_e^{-4.5}$, as well as a lower limit scaling which is fitted to the shape dependence found in this work (dashed line).

4. Conclusions

The calculation results indicate that the number of ground-state antihydrogen atoms, if measured experimentally, should not follow simple power-law scaling. For example, our simulation predicts that a measurement of the ground-state antihydrogen atom yield as a function of the positron plasma temperature at a positron plasma density $n_e \simeq 10^{14}$ m^{-3} would show a weaker power-law scaling behaviour than that of three-body recombination. It is noted that the positron temperature dependence of antihydrogen formation was measured at positron density $n_e \simeq 10^{14}$ m^{-3}, and an observed scaling behaviour of $T_e^{-1.1\pm0.5}$ was reported [4] by the ATHENA collaboration, which is consistent with the direction of our prediction qualitatively.

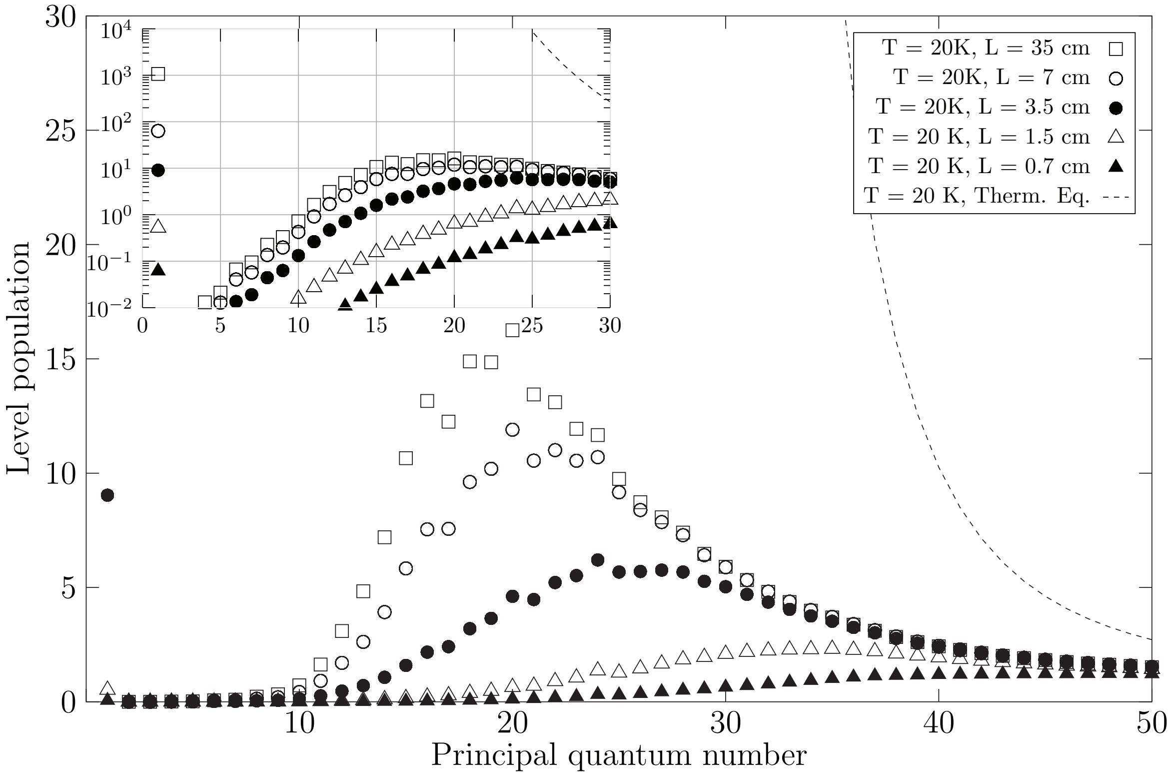

Fig. 2. Level population (number of antihydrogen atoms) as a function of the principal quantum number for various positron plasma lengths, ranging from $L = 0.7$ cm to $L = 35$ cm with positron plasma temperature $T = 20$ K. The thermal equilibrium level population is shown with dashed line. The inset plot shows a zoom into the principal quantum number $n \leq 30$ cases with logarithmic scale of the level population.

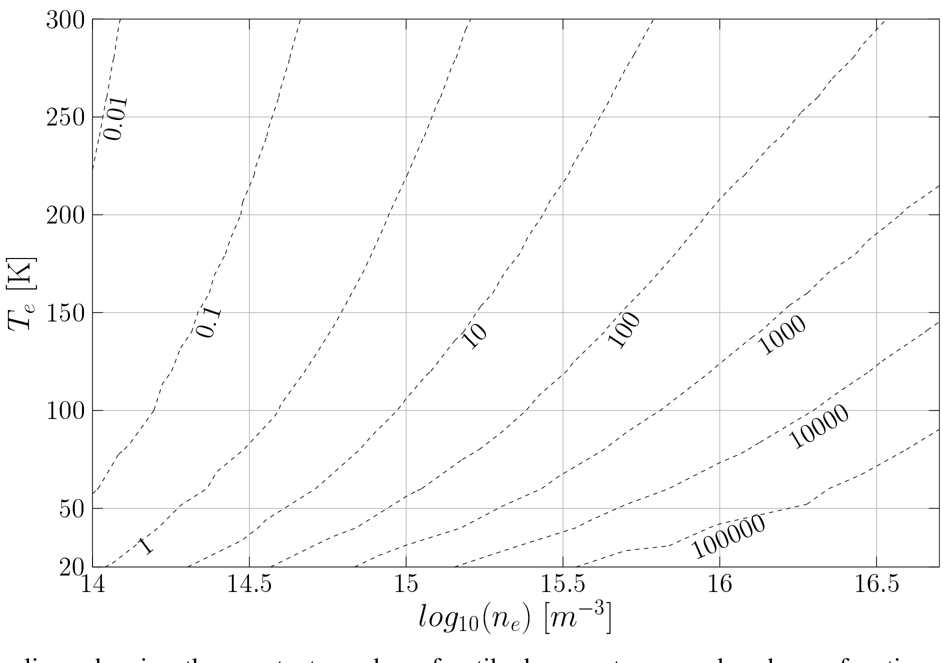

Fig. 3. Isolines showing the constant number of antihydrogen atoms produced as a function of positron density and temperature.

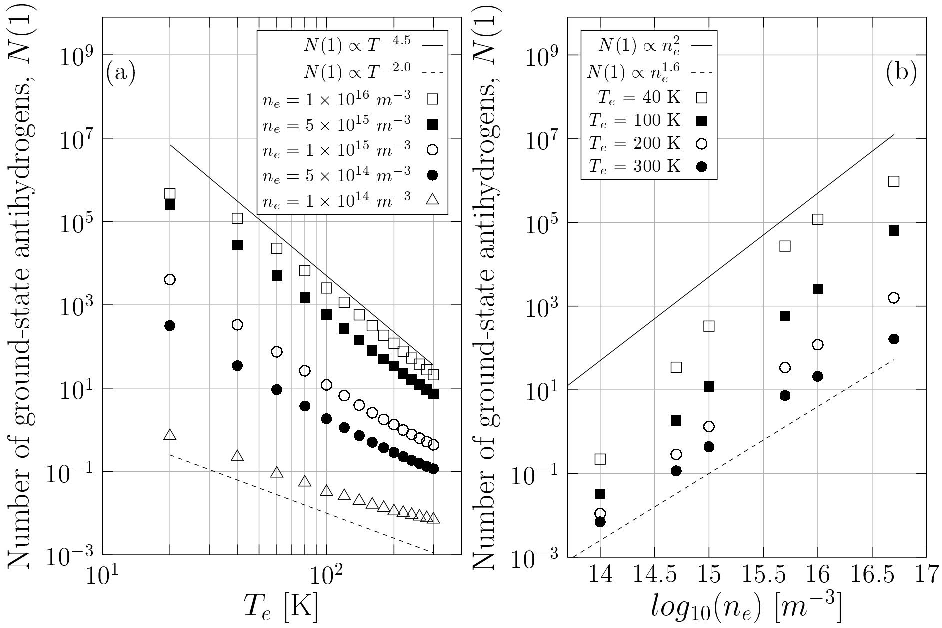

Fig. 4. Left: temperature dependence of the number of ground-state antihydrogen atoms, $N(1)$, for various positron density values. The $N(1) \propto T^{-4.5}$ (solid line) and $N(1) \propto T^{-2.0}$ (dashed line) behaviours are also shown. Right: Positron density dependence of the number of ground-state antihydrogen atoms, $N(1)$, for various positron temperature values. The $N(1) \propto n_e^2$ (solid line) and $N(1) \propto n_e^{1.6}$ (dashed line) behaviours are also shown.

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