On the temperature of antihydrogen formed in magnetic trap

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Abstract. Kinetic processes taking place after injection of antiprotons in cold positron cloud are discussed. Mixture of antiparticles is considered as low temperature non neutral weakly coupled plasma. Simple estimations of energy of antihydrogen atoms that may be formed due to three body recombination in the system are made. Dependence of atom energy on initial particles temperatures and influence of strong confining magnetic field are discussed.

1. Introduction
In the experiments in CERN antihydrogen is formed during mixing of antiprotons and ultracold positrons in Penning-Malmberg trap. The charged particles are confined in the trap using strong uniform magnetic field applied along the axis of the experimental setup. The mixture of antiparticles is formed after injection of tens of thousands of antiprotons to the cloud of positrons with density of about \( n_e \sim 10^8 \text{ cm}^{-3} \). Initial energies of antiprotons were about tens of eV in the first experiments [1] and later initial antiproton energies were lowered to \( \sim 100 \text{ K} \) [2] and may reach \( \sim 1 \text{ K} \). Initial temperature of the positron cloud is estimated in the range of 15–50 K [3] and research work is performed to make initial positron temperature lower [4].

During mixing particles collide with each other and exchange their energies. Due to collisions with positrons injected antiproton is cooled (or heated) during mixing cycle and after a while it recombines with a positron forming atom of antihydrogen. The new formed atom has kinetic energy of antiproton. The main process of recombination in the experimental conditions is three body recombination (initial atom binding energy is carried away by third body—another positron). Both kinetic processes of interest—energy relaxation and recombination are strongly influenced by the presence of the confining magnetic field.

One of the main goals of these experiments is trapping of large number of antihydrogen atoms in atomic trap. To effectively trap atoms their energy must be as low as possible because of low energy depth of the trap—about 1 K. In the present work we focused on study of kinetic processes in antiparticles plasma and an attempt was made to estimate the dependence of atoms temperature on initial particles energies.

2. Zero magnetic field
First we made rough analytical estimation of antihydrogen temperature with zero magnetic field. We considered the positron-antiproton mixture as non neutral two temperature plasma.
Figure 1. Antihydrogen atoms temperature, zero magnetic field: $T_H$—atoms temperature, $T_p(0)$—initial antiproton temperature, full line—positron temperature 5 K, dashed line—positron temperature 50 K, dotted line—atom temperature equal to antiproton temperature (as if there is no energy exchange between positrons and antiprotons).

To describe relaxation process we used Landau kinetic equation for plasma [5]

$$\frac{dT_p}{dt} = \frac{T_e - T_p}{\tau_e}, \quad (1)$$

where $T_e$ is positron temperature, $T_p = 2E_p/3N_p$ is antiproton temperature, $\tau_e^{-1}$ is antiproton-positron energy exchange rate. When thermal velocity of positrons is much higher than velocity of antiproton $\tau_e$ according to [5] is:

$$\tau_e = \frac{T_e^{3/2}m_p}{4n_e e^4 L_e (2\pi m_e)^{1/2}}, \quad (2)$$

where $m_p, m_e$—proton and electron masses, $L_e$—Coulomb logarithm. $L_e$ for weakly coupled plasma considered here is determined by

$$L_e = \ln \sqrt{\frac{T_e}{4\pi n_e e^2}} \frac{e^2}{e^2/T_e}. \quad (3)$$

In the simplest case when $T_e$ is constant (since the number of positrons is significantly higher than the number of antiprotons and radiative cooling of positrons is negligible on the time scale of collisional kinetics) Landau equation has simple analytical solution:

$$T_p = T_e - (T_e - T_p(0)) e^{-t/\tau_e}. \quad (4)$$

If we substitute to this solution inverse three body recombination rate from Thomson formula [6]

$$\frac{1}{\tau_R} \approx 2 \frac{n^2 e^{10}}{\sqrt{m_e L_e^{9/2}}} \quad (5)$$
Figure 2. Antihydrogen atoms axial temperature, magnetic field \( H = 10^4 \) Gauss: \( T_{p,\parallel} \)—atoms temperature, \( T_{p}(0) \)—initial antiproton temperature, full line—positron temperature 5 K, dashed line—positron temperature 50 K.

For \( t \), we will get estimation of antiproton temperature in the moment of recombination or rough estimation of antihydrogen atom temperature.

In figure 1 we present estimations of atoms temperature depending on initial antiproton temperature for two values of possible positron temperature. Results show how atoms temperature is influenced by antiproton initial temperature despite the fact that relaxation and recombination rates are independent of antiproton temperature. For \( T_e = 5 \) K recombination rate is close to relaxation rate and antiprotons do not have enough time in positrons cloud to cool down (or heat up) to positrons temperature before recombination occurs. By contrast, for \( T_e = 50 \) K relaxation is much faster process and atom is formed having temperature equal to the positrons temperature.

3. Nonzero magnetic field

In real experiments presence of strong magnetic field complicates analytical approach. Existing theory for electron cooling of proton [7] is valid for magnetic field not so strong as used in the experiments on antihydrogen. In [7] classical distance of minimal approach \( r_T \sim e^2/T \) was considered smaller than electron Larmor radius \( r_L = m_e c^2 v_e / e H \). But in the experiments considered here for typical magnetic field values of \( H = 10^4 \) Gauss and positron temperature \( T_e = 5 \) K, positron subsystem is strongly magnetized and \( r_T \) is many times greater than Larmor radius. To study relaxation of kinetic energy of antiproton in strongly magnetized positron gas we used molecular dynamics simulation (for simulation details see [8]). From the molecular dynamics data we derived relaxation rates for transverse \( T_{\perp} \) and axial \( T_{\parallel} \) antiproton temperatures.

As for three body recombination rate in strong magnetic field there are several different estimations (see e. g. [9–11]), all of them show that recombination rate is suppressed in magnetic field. We used Thomson formula for three body recombination rate in the sense of upper limit
Figure 3. Antihydrogen atoms transverse temperature, magnetic field $H = 10^4$ Gauss: $T_{H}^\perp$—atoms temperature, $T_p(0)$—initial antiproton temperature, full line—positron temperature 5 K, dashed line—positron temperature 50 K.

of recombination rate in strong magnetic field to make estimation of atoms transverse and axial temperature by analogy with zero field case.

After substituting to (1) recombination rate from Thomson formula and relaxation rates for transverse and axial antiproton temperatures from molecular dynamics we obtained dependencies for atom temperatures in axial and transverse directions (see figures 2 and 3). The results show the dependance of atoms temperature on antiprotons temperature and also that for $T_e = 5$ K transverse and axial atoms temperatures are not equal. The temperature difference may influence the angle between direction of atoms departure from the trap and the direction of magnetic field (or axis of experimental setup).

4. Conclusion
We made simple estimations of temperature of antihydrogen atoms formed in non neutral cold positron-antiproton plasma in strong uniform magnetic field. We used data from our molecular dynamics simulations for positron-antiproton relaxation rate. Our estimations show the dependence of atoms temperature on initial energies of charged particles. In addition to that our results show that for some initial conditions atoms temperatures along and transverse to magnetic field direction may be different.

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