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Antihydrogen Beam Formation by Transporting an Antiproton Beam Through an Electron-Positron Plasma That Produces Magnetobound Positronium

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Abstract

The formation of an antihydrogen beam by transporting an antiproton beam through an electron-positron plasma that produces magnetobound positronium is studied using a classical trajectory simulation. Through simulation, it is found that antihydrogen can be synthesized via three body recombination involving magnetobound positronium. It has previously been reported that giant cross-magnetic-field particle drifts can occur as a result of binary collisions between charged matter particles and their antimatter counterparts. An electron-positron pair collision can result in a correlated drift of the two particles, perpendicular to a magnetic field. While the two particles remain in their correlated drift, they are referred to as magnetobound positronium. This study was conducted to determine what would happen if a magnetobound positronium system encountered an antiproton. The simulation shows that a positron can be captured into a bound state with an antiproton. This study also considers the effect that the electron-positron collision pitch angle has on antihydrogen production via magnetobound positronium.

Keywords: antihydrogen;positronium; plasma; beam; magnetobound

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1. Introduction

Previous simulations have predicted that within a low temperature plasma that contains electrons and positrons, binary collisions involving electron-positron pairs can cause them to become temporarily correlated and experience giant cross-magnetic field drifts (Aguirre and Ordonez, 2015). Those particle pairs have been referred to as being in a magnetobound state (Correa et al. 2014). It has been previously proposed that magnetobound states may be a useful intermediate state in the production of antihydrogen (Correa et al. 2014). Although various possibilities were discussed in (Correa et al. 2014) concerning possible scenarios in which antihydrogen synthesis could occur via magnetobound states, a simulation of the phenomenon was not reported. This phenomenon occurs at low temperatures and in strong magnetic fields similar to the ones used inside Penning traps that produce antihydrogen. Several collaborations including ALPHA (Charman et al. 2013, Amole et al. 2013, Andersen et al. 2011), ATRAP (Gabrielse et al. 2011-2012, Richerme et al. 2013), ASACUSA (Kuroda et al. 2014), AEgIS (Krasnick et al. 2013), and GBAR (Perez et al. 2012) have achieved or are working towards producing and studying antihydrogen. For example, techniques are being developed to measure the gravitational properties of antihydrogen that could lead to better tests of the gravitational interaction between matter and antimatter (Charman et al. 2013). Furthermore, cooling methods have also been studied that aim to capture cold antihydrogen in strong magnetic fields for precise spectroscopic measurements (Gabrielse et al. 2011). Various alternatives to primary methods that are being used by the CERN collaborations are also being explored (Lane et al. 2014-2016, Ordonez et al. 2012, Rocha et al. 2013). Antihydrogen synthesis via magnetobound states of positronium involves a process that is similar to antihydrogen synthesis via a charge exchange reaction between an excited (e.g., Rydberg) positronium atom and an antiproton. Unlike Rydberg positronium, magnetobound positronium isn’t an energetically bound state, because a magnetobound state can dissociated spontaneously and adiabatically. Also, a magnetobound state forms spontaneously and adiabatically from two otherwise free particles that become spatially correlated temporarily as a result of undergoing a collision in the presence of a magnetic field. It is possible that antihydrogen synthesis via magnetobound positronium has previously been simulated but not identified, provided that a free electron, a free positron, and a free antiproton were made available or became available during the simulation so that the phenomenon could occur.

In the work presented here, three body recombination resulting in bound state antihydrogen is studied by computer simulation when a magnetobound positronium system encounters an antiproton. Sec. II discusses the governing equations for the simulation. Sec. III describes the results of the simulation and shows a sample trajectory for a positron captured by the antiproton. Sec. IV contains concluding remarks.

2. Governing Equations

In the simulation, the positron, electron, and antiproton interact classically. The antiproton is approximated as being fixed in space. Beginning with the electric force, Coulomb’s law states that the electric force exerted on the positron (particle 1) by the electron (particle 2) is given by $\boldsymbol{F}_{on\ 1\ by\ 2} = k_c q_1 q_2 \boldsymbol{r}_{12}/r_{12}^3$, where k_c is the Coulomb force constant, q_1 and q_2 are the charges of the positron and electron, $r_{12} = |\boldsymbol{r}_{12}|$ is the distance between particles, and $\boldsymbol{r}_{12} = \boldsymbol{r}_1 - \boldsymbol{r}_2$ is the separation vector between the particles. The Coulomb force constant is $k_c = 1/(4\pi\epsilon_0)$ in SI units, and ϵ_0 is the permittivity of free space. Similarly, the force acting on the positron by the antiproton (particle 3) is $\boldsymbol{F}_{on\ 1\ by\ 3} = k_c q_1 q_3 \boldsymbol{r}_{13}/r_{13}^3$. These steps are repeated to find the forces acting on the electron. The electric force acting on the electron by the positron is$\boldsymbol{F}_{on\ 2\ by\ 1} = k_c q_1 q_2 \boldsymbol{r}_{21}/r_{21}^3$, and the electric force acting on the electron by the antiproton is $\boldsymbol{F}_{on\ 2\ by\ 3} = k_c q_2 q_3 \boldsymbol{r}_{23}/r_{23}^3$.

A magnetic force, $\boldsymbol{F}_B = k_L q(\boldsymbol{v} \times \boldsymbol{B})$, is experienced by each particle. The Lorentz force constant is $k_L = 1$ in SI units, q is the charge of the particle, $\boldsymbol{v}$ is the velocity of the particle, and $\boldsymbol{B}$ is the magnetic field parallel to the unit vector $\hat{\boldsymbol{k}}$. The magnetic force acting on the positron is $\boldsymbol{F}_{on1byB} = k_L q_1 B(v_{1y}\hat{\boldsymbol{\imath}} - v_{1x}\hat{\boldsymbol{\jmath}})$. The unit vectors in a Cartesian coordinate system are $(\hat{\boldsymbol{\imath}}, \hat{\boldsymbol{\jmath}}, \hat{\boldsymbol{k}})$, and v_{1x}, v_{1y}, v_{1z} are the velocity components of the positron. For the electron, $\boldsymbol{F}_{on2byB} = k_L q_2 B\big(v_{2y}\hat{\boldsymbol{\imath}} - v_{2x}\hat{\boldsymbol{\jmath}}\big)$, where v_{2x}, v_{2y}, v_{2z} are its velocity components. Newton’s second law governs the classical motion of the particles. For the positron and electron, $\Sigma\boldsymbol{F} = m\boldsymbol{a}$.

Newton’s second law for the positron is $\boldsymbol{F}_{on1by2} + \boldsymbol{F}_{on1by3} + \boldsymbol{F}_{on1byB} = m_1\boldsymbol{a}_1$, where m_1 and $\boldsymbol{a_1}$are the mass and acceleration of the positron. Newton’s second law for the electron is $\boldsymbol{F}_{on2by1} + \boldsymbol{F}_{on2by3} + \boldsymbol{F}_{on2byB} = m_2\boldsymbol{a}_2$, where