A novel property of anti-Helmholz coils for in-coil syntheses of antihydrogen atoms: formation of a focused spin-polarized beam

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Abstract
We demonstrate here that cold antihydrogen beams formed and extracted from a cusp magnet (anti-Helmholtz coils) are well focused and spin-polarized. A new discovery was the fact that the antihydrogen beam follows the well-known lens formula of optical lenses with its focal length properly scaled with the initial kinetic energy, the magnetic field strength and the magnetic moment. Furthermore, the simulation revealed that for a certain kinetic energy region of antihydrogen atoms, the optimum production position is upstream of the center of the cusp magnet, where a well-known nested potential configuration can be applied.

Keywords: atomic and molecular beam sources and techniques, beam optics, exotic atoms and molecules

1. Introduction

The CPT (C: charge conjugation, P: parity operation, T: time reversal) symmetry is assumed to be the most fundamental symmetry in physics, and guarantees that atomic properties of antihydrogen (\(\bar{\text{H}}\)) and hydrogen are exactly the same. This symmetry might be violated if, for example, the gravitational interaction is taken into account, which causes the space-time to be curved [1]. The standard model extension developed by Kostelecky et al discusses physical
Quantities which are sensitive to the CPT violation [2]. High-precision comparisons of hyperfine transitions between $\bar{H}$ and hydrogen atoms are predicted to constitute stringent tests of the CPT violation [3].

Syntheses of $\bar{H}$ atoms have been extensively studied in the last few decades. The ALPHA and the ATRAP collaborations aim at $1S-2S$ high-precision laser spectroscopy of $\bar{H}$ atoms trapped in magnetic bottles [4, 5]. The ASACUSA collaboration attempts the CPT test through high-precision microwave spectroscopy of ground-state hyperfine transitions using $\bar{H}$ beams extracted in a magnetic field-free region [6–8].

Recently, the ASACUSA collaboration successfully synthesized $\bar{H}$ atoms in a so-called cusp trap, which is a unique method of preparing a spin-polarized $\bar{H}$ beam for a microwave spectroscopy of $\bar{H}$ atoms, and produced $\bar{H}$ atomic beams [9, 10]. Figure 1 shows a conceptual drawing of the experimental setup, which is composed of the cusp trap, a microwave cavity, a sextupole magnet and an $\bar{H}$ detector. The cusp trap consists of superconducting anti-Helmholtz coils and a stack of multiple ring electrodes (MRE). $\bar{H}$ atoms formed in the cusp trap are emitted in all directions under the influence of the cusp magnetic field. As discussed in detail in the next section, $\bar{H}$ atoms in low-field-seeking states (LFS) are preferentially focused along the magnet axis, and a spin-polarized $\bar{H}$ beam is automatically produced. It is noted that the magnetic bottle to trap $\bar{H}$ atoms [11, 12] employs a strong non-uniform magnetic field, which deteriorates the spectroscopic behavior of $\bar{H}$ atoms. To avoid this problem, we designed the cusp trap scheme to extract $\bar{H}$ atoms from the cusp magnet region to a magnetic field-free region where a weak uniform magnetic field is easily prepared for high-precision microwave spectroscopy. Conventionally it is necessary to place a spin selector downstream of the $\bar{H}$ synthesizer to produce polarized beams, which are well integrated into the cusp trap, realizing efficient productions of polarized beams [13]. The $\bar{H}$ beam in LFS passes through the microwave cavity and is refocused on the $\bar{H}$ detector by the sextupole magnet. If the microwave frequency matches with one of the hyperfine transition frequencies, the $\bar{H}$ atoms in LFS are converted into high-field-seeking states (HFS). Because $\bar{H}$ atoms in HFS are defocused by the sextupole magnet, most of them do not reach the $\bar{H}$ detector; i.e., the transition frequencies are precisely determined by measuring the number of $\bar{H}$ atoms reaching the $\bar{H}$ detector as a function of the microwave frequency.

Figure 1. Schematic diagram for the ground-state hyperfine transition measurements of $\bar{H}$ atoms using the cusp trap, the microwave cavity, the sextupole magnet and the $\bar{H}$ detector.
We report here novel properties of the cusp magnet in transporting $\bar{\text{H}}$ beams; namely that the $\bar{\text{H}}$ atoms in LFS produced in the cusp trap are extracted along the magnet axis following a well-known lens formula for a broad range of experimental conditions.

2. Trajectory calculations of $\bar{\text{H}}$ beams

The force acting on an $\bar{\text{H}}$ atom in a magnetic field $\mathbf{B}$ is given by $\nabla \cdot (\mathbf{\mu} \cdot \mathbf{B})$, where $\mathbf{\mu}$ is the magnetic moment of the $\bar{\text{H}}$ atom. In the magnetic field, the energy level of the $\bar{\text{H}}$ atom in the ground state splits into four sub-states. For a strong magnetic field, $\mathbf{\mu}$ is approximately constant for all the four hyperfine states, and the forces are given by $\pm \mathbf{\mu} \nabla |\mathbf{B}|$ depending on whether $\mathbf{\mu}$ is parallel (HFS) or antiparallel (LFS) to $\mathbf{B}$, respectively. In the following discussions, this strong magnetic field condition is assumed for the sake of simplicity.

The above consideration is valid as far as the magnetic moment $\mathbf{\mu}$ of the $\bar{\text{H}}$ atom adiabatically follows $\mathbf{B}$. Such an adiabatic condition might not be satisfied near the center of the cusp magnet where $\mathbf{B} = 0$, and $\mathbf{\mu}$ of the $\bar{\text{H}}$ atom makes a transition, which is called the Majorana spin-flip [15]. The criterion for the Majorana spin-flip can be obtained carefully as follows. The axial and radial magnetic fields of the cusp magnet near the center are given by $B_z = -\eta z$ and $B_r = \eta r/2$, respectively, where $\eta$ is around 36 [T/m] in the case of the cusp magnet of the ASACUSA collaboration. The direction of $\mathbf{B}$ acting on the $\bar{\text{H}}$ atom is shown along the trajectory passing near $z = 0$ at $r = r_0$ in figure 2. The time necessary to vary the direction by 1 radian would be evaluated by $\sim r_0/v_z$, where $v_z$ is the axial velocity of the $\bar{\text{H}}$ atom. Because the Larmor frequency is $\omega_L = \mu B/\hbar$, if $\left( \mu B/\hbar \right) (r_0/v_z) \gg 1$, $\mathbf{\mu}$ is expected to follow the direction of $\mathbf{B}$ adiabatically. For example, when $v_z = 1000$ [m/s] ($\sim 50$ K), $r_0$ is estimated to be $\sim 20 \mu$m for the ground state adopting the minimum $B = B_\perp$. Considering that the maximum radial position of the $\bar{\text{H}}$ atoms at $z = 0$ reaching the cavity is about 5 mm (see the next paragraph), the fraction to make the Majorana spin-flip is about $10^{-4}$ or less, which is negligibly small.

![Figure 2](image.png)

Figure 2. Magnetic field lines of the cusp magnet around the center where the $\bar{\text{H}}$ atom passes through the position $z = 0$. 

We report here novel properties of the cusp magnet in transporting $\bar{\text{H}}$ beams; namely that the $\bar{\text{H}}$ atoms in LFS produced in the cusp trap are extracted along the magnet axis following a well-known lens formula for a broad range of experimental conditions.
Trajectories of \( \bar{H} \) atoms in the cusp magnetic field are calculated solving the Newtonian equations of motion numerically. Initial emission directions of \( \bar{H} \) atoms are assumed to be isotropic. The \( z \) component of the magnetic field, \( B_z \), of the model cusp magnet is drawn in figure 3(a). Figures 3(b) and (c) show examples of trajectories of \( \bar{H} \) atoms in ground states having the initial kinetic energy of \( K_0 = 10 \text{ K} \) synthesized at the maximum magnetic field, \( B_m = 3.0 \text{ T} \), for LFS and HFS, respectively (\( K_0 \) is given as a temperature unit, i.e., the kinetic energy divided by Boltzmann’s constant). It is seen that the number of \( \bar{H} \) atoms in LFS traveling along the magnet axis is much larger than that in HFS; i.e., one can obtain an intensified and spin-polarized \( \bar{H} \) beam automatically. The 10 cm disk 1.5 m downstream from the cusp magnet center actually corresponds to the size and the position of the entrance of the ASACUSA microwave cavity (see figure 1). Initial emission directions are assumed to be isotropic, and the lines are drawn every 1 degree from the beam axis. (c) The same as (b) but for \( \bar{H} \) atoms in HFS.

Figure 3. (a) The \( z \) component of the magnetic field, \( B_z \), of the model cusp magnet. (b) Trajectories of \( \bar{H} \) atoms in LFS synthesized on the magnet axis at the maximum magnetic field \( B_m \) having the kinetic energy of \( K_0 = 10 \text{ K} \). The open circle in (b) shows the \( \bar{H} \) production position. The disk with its diameter of 10 cm placed at \( z = 1.5 \text{ m} \) shows the size and the position of the entrance of the ASACUSA microwave cavity (see figure 1). Initial emission directions are assumed to be isotropic, and the lines are drawn every 1 degree from the beam axis. (c) The same as (b) but for \( \bar{H} \) atoms in HFS.

Trajectories of \( \bar{H} \) atoms in the cusp magnetic field are calculated solving the Newtonian equations of motion numerically. Initial emission directions of \( \bar{H} \) atoms are assumed to be isotropic. The \( z \) component of the magnetic field, \( B_z \), of the model cusp magnet is drawn in figure 3(a). Figures 3(b) and (c) show examples of trajectories of \( \bar{H} \) atoms in ground states having the initial kinetic energy of \( K_0 = 10 \text{ K} \) synthesized at the maximum magnetic field, \( B_m = 3.0 \text{ T} \), for LFS and HFS, respectively (\( K_0 \) is given as a temperature unit, i.e., the kinetic energy divided by Boltzmann’s constant). It is seen that the number of \( \bar{H} \) atoms in LFS traveling along the magnet axis is much larger than that in HFS; i.e., one can obtain an intensified and spin-polarized \( \bar{H} \) beam automatically. The 10 cm disk 1.5 m downstream from the cusp magnet center actually corresponds to the size and the position of the entrance of the microwave cavity in the ASACUSA setup (see figure 1).

Figure 4(a) again shows \( B_z \). Symbols in figures 4(b) and (c) plot the fractions of LFS \( f_{\text{LFS}} \) and HFS \( f_{\text{HFS}} \) \( \bar{H} \) atoms reaching the 10 cm disk, calculated solving the equations of motion as a function of the \( \bar{H} \) production position, \( z_o \), respectively. Different symbols correspond to different kinetic energies, \( K_0 \), from 5 K to 100 K. The thick blue solid lines in figures 4(b) and (c) show the fraction of \( \bar{H} \) atoms arriving at the disk when \( \bar{H} \) atoms are emitted isotropically following straight trajectories (the solid angle divided by \( 4\pi \) from \( z_o \) to the 10 cm disk). For all the temperatures calculated, the fractions of \( \bar{H} \) atoms in LFS transported to the disk are larger than the fraction of the straight trajectory case for \( z_o \leq 0 \text{ m} \); i.e., \( \bar{H} \) beams in LFS are focused. In the case of \( K_0 = 5 \text{ K} \) and 10 K (the red open circles and blue open diamonds, respectively), the fraction increases considerably for smaller \( z_o \). In other words, the best position to synthesize \( \bar{H} \) atoms is located upstream of the cusp magnet center, although synthesis at the center was anticipated in the original cusp trap scheme [13]. This is particularly true because the densities of antiproton and positron plasmas are higher at the higher magnetic field, resulting in a higher \( \bar{H} \) yield. Actually, the first \( \bar{H} \) production in the cusp trap was realized at the maximum magnetic field.
field region taking this optimal property into account [9, 10]. In the case of $K_0 = 5$ K, $f_{LFS}$ reaches its maximum at $z_o \sim -0.22$ m (with the intensity enhancement of $\sim 200$), because 5 K $\tilde{H}$ atoms produced at $z_o \sim -0.22$ m are focused on the disk 1.5 m downstream of the cusp magnet. For $K_0 = 30$ K, $f_{LFS}$ is almost constant, independent of $z_o$. This finding suggests that $\tilde{H}$ atoms in a certain kinetic energy range can be synthesized in a strong magnetic field region,
where a well-known nested potential configuration [14] can be applied, still optimizing the $\hat{H}$ beam intensity. For $\hat{H}$ atoms in HFS in figure 4(c), the behavior is just the opposite: the lower the kinetic energy, the lower the transport efficiency; i.e., the cusp magnetic field acts in itself as the spin filter as well as the beam intensifier of $\hat{H}$ atoms in LFS. Figure 4(d) shows the polarization of $\hat{H}$ beams calculated using the results of figures 4(b) and (c) assuming that an equal number of LFS and HFS are produced, where the polarization is defined by $(f_{LFS} - f_{HFS})/(f_{LFS} + f_{HFS})$. The polarization decreases gradually as $K_0$ increases.

3. Lens formula and the scaling law

Having observed that the cusp magnet has the ability to enhance the beam intensity of $\hat{H}$ atoms in LFS, the next step is to quantitatively study the transport property. In doing so, the image point, $z_l$, is evaluated calculating trajectories with different ejection angles, $\theta_i$, from the axis at a fixed object point ($\hat{H}$ production position $z_o$). Then, the thin lens formula, $1/a + 1/b = 1/l$, is applied to get the focal length $l$, where $a$ and $b$ are given by $z_l - z_o$ and $z_i - z_o$, respectively, and $z_l$ is an effective lens position. Figure 5(a) shows the example of $l$ evaluated using $\left(\frac{1}{a} + \frac{1}{b}\right)^{-1}$ for 10 K $\hat{H}$ atoms in LFS produced at $z_o = -0.14$ m assuming $z_l = 0$ m for $\theta_i \ll 3^\circ$. It is observed that for different ejection angles, $l$ is distributed in a narrow region for a fixed $z_o$; i.e., the concept of the focal length is well satisfied. In the following, the central value of $l$ for $\hat{H}$ atoms arriving at the disk is re-defined as the focal length $l$. Figure 5(b) shows $l$ evaluated as a function of $z_l$ for 10 K $\hat{H}$ atoms ($z_o = -0.10, -0.14$ and $-0.18$ m). Figures 5(c) and (d) are the same as figure 5(b) but for $K_0 = 30$ K and 70 K, respectively. It is observed that $l$ can be determined consistently independent of $z_o$ for each $K_0$ if $z_l$ is chosen to be $\sim 0.05$ m; i.e., the cusp magnet acts practically as a converging lens for $\hat{H}$ beams in LFS, fulfilling the lens formula with a small aberration. Figure 5(e) shows $l$ as a function of $z_o$ for $5 \leq K_0 \leq 100$ K, setting $z_l = 0.05$ m. $l$ is almost constant for $z_o \leq -0.1$ m for each $K_0$. Figure 5(f) shows $l$ as a function of $K_0$ for five different $B_m$ with $z_l = 0.05$ m, where $l$ is evaluated, e.g., from figure 5(e) for $z_o \leq -0.1$ m in the case of $B_m = 3.0$ T, and the lines are drawn employing the linear least square method. It is seen that $l$ increases linearly with $K_0$, having a steeper slope for a lower $B_m$. Furthermore, all lines merge at the same point when $K_0$ is extrapolated to 0 with a finite intercept, $l_0 \sim 0.09$ m. Figure 5(g) plots $(l - l_0) \times B_m$ as a function of $K_0$. All the lines overlap with each other; i.e., $l$ has an excellent scaling property with respect both to $K_0$ and to $B_m$:

$$l_{LFS} [m] = 0.085 \left( K_0 \left[ K \right] + 1.1 B_m \left[ T \right] \right) / B_m \left[ T \right]$$

(1)

for $\hat{H}$ atoms in LFS ($z_o \lesssim -0.1$ m). Because we know the lens position, $z_l$, as well as $l$, $z_o$ and $z_i$, the transport fraction of $\hat{H}$ atoms to the 10 cm disk is easily calculated, and is shown by the lines in figure 4(b). These lines are in good agreement with results obtained by numerical simulations (symbols in figure 4(b)).
Figure 5. (a) The focal length distribution of $\bar{H}$ atoms in LFS evaluated using the relation $\frac{1}{l} = \frac{1}{l_0} + \frac{1}{l_1}$ for the ejection angle of $0^\circ < \theta < 3^\circ$. (b), (c) and (d) The focal length $l$ for $\bar{H}$ atoms in LFS as a function of $z_l$ for three different $z_o$ for $K_0 = 10$, 30 and 70 K. (e) The focal length $l$ as a function of $z_o$ for $\bar{H}$ atoms in LFS with $z_l = 0.05$ m. (f) The focal length $l$ as a function of $K_0$ for $\bar{H}$ atoms in LFS with $z_l = 0.05$ m for five different $B_m$. (g) $(l - l_0)B_m$ as a function of $K_0$ for $\bar{H}$ atoms in LFS with $z_l = 0.05$ m.
4. Qualitative analysis of the property of the cusp magnet

To understand why the lens formula is applicable to the cusp magnet, which is quadrupolar in its nature but not sextupolar, the behavior of the magnetic field of the cusp magnet is studied in detail. The focusing property is primarily determined by the radial force acting on the beam; i.e. \( F_r = -\mu \partial |B|/\partial r \) for \( H^- \) atoms in LFS. Figure 6(a) shows \( \partial |B|/\partial r \), and figure 6(b) is a closeup for \( 0 \leq z < 0.2 \) m. When \( z \neq 0 \), \( \partial |B|/\partial r \) is 0 at \( r = 0 \) and increases monotonically with \( r \) for \( r \leq 0.05 \) m (actually the inner radius of the MRE in the ASACUSA setup is 0.04 m). Although \( \partial |B|/\partial r \) is almost constant with respect to \( r \) at \( z = 0 \), this is just a singular point. Taking e.g. \( \partial |B|/\partial r \) at \( z = 0.004 \) m (the curve closest to \( z = 0 \) in figure 6(b)), it increases more or less linearly for \( r \leq 0.02 \) m. As a whole, \( \partial |B|/\partial r \) can be practically approximated as \( \alpha (z) B_m r \), where \( \alpha (z) \) is a coefficient of the field gradient as a function of \( z \). Accordingly, the radial force acting on the \( H^- \) atom is given by \( F_r \sim -\alpha (z) \mu B_m r \); i.e., the cusp magnet here behaves like a sextupole magnet \( (F \propto r) \).

The change of the deflection angle, \( \theta_o \), due to the radial momentum transfer from the magnetic field to the \( H^- \) atom is given by

\[
\theta_o \sim \frac{\delta p_r}{mv_c} = \frac{\int F_r dt}{mv_c} \approx -\frac{\int \alpha (z) dz \mu B_m r}{mv_c^2} \sim -\frac{\alpha \mu B_m}{2K_0} r,
\]

where \( m \) is the \( H^- \) mass, \( \alpha = \int \alpha (z) dz \) and \( K_0 = mv_c^2/2 \). In contrast to the direction, the radial position of \( H^- \) atoms does not vary very much during the deflection; therefore the trajectory of \( H^- \) atoms can be approximated as in figure 7. In this case, the radial position of the \( H^- \) atom produced at \( z_o \), with its ejection angle \( \theta_o \) with respect to the axis is given by \( r_c \sim a \theta_o \) at \( z = z_r \), and the angle at the image point, \( \theta_i = -\theta_o - \theta_o \), is given by \( \left( \frac{\alpha B_m}{2K_0} - a^{-1} \right) r_c \). In this case, all the trajectories meet at the same point at \( b = \left( \frac{\alpha B_m}{2K_0} - a^{-1} \right)^{-1} \), independent of \( \theta_o \). Using \( a \) and \( b \)
above, one can immediately obtain the focal length \( l \) as 
\[
\frac{2}{\mu B m} = \frac{2K_B}{\mu_0 B m} \left( K_0 \left[ K \right] + \frac{\mu_0 \mu B m}{k_B} B m \left[ T \right] \right) 
\]
\[
0.09 \left( \frac{K_0 \left[ K \right] + 0.7 \frac{\mu_0 B m}{k_B} B m \left[ T \right]}{\frac{\mu_0 B m}{k_B} B m \left[ T \right]} \right),
\]
where \( \mu_0 \) and \( k_B \) are the Bohr magneton and Boltzmann’s constant, respectively. The third equation is obtained considering the size of the magnet \((\sim 0.4 \text{ m})\) and \( \alpha \left( z \right) \sim 80 \text{ m}^{-2} \) assuming \( \partial B / \partial r \sim 10 \text{ T/m} \) at \( r = 0.04 \text{ m} \) (figure 6(b)). For the ground state \((\mu = \mu_0)\), equation (4) is semi-quantitatively consistent with equation (1); \( \mu \) is a characteristic magnetic field. As shown in equation (3), \( l_{LFS} \) also has the scaling property with respect to \( \mu \).

In the case of \( \tilde{H} \) atoms in HFS, the direction of the force is just the opposite; \( \tilde{H} \) atoms are axially decelerated and radially defocused. Accordingly, by replacing \( K_0 \) by \( K_0 - \mu B_m \) and \( F_r \) by \( -F_r \), and employing more correct coefficients obtained in equation (1), one gets
\[
l_{HFS} \left[ m \right] = -0.085 \left( K_0 \left[ K \right] - 1.1 B_m \left[ T \right] \right) / B_m \left[ T \right].
\]
The transport fraction of \( \tilde{H} \) atoms in HFS can be evaluated in a similar way as in LFS, employing equation (5), which is shown by the lines in figure 4(c). It is seen that these lines reproduce the results of numerical simulations quite well. The polarization using \( l_{LFS} \) and \( l_{HFS} \) is also shown by the lines in figure 4(d), which again reproduces the numerical simulations quite well; \( \mu \), the cusp magnet works as a magnetic lens for LFS and also for HFS \( \tilde{H} \) beams. It is also noted that the cusp magnet can be used as a good spin-selector for molecular beam experiments.

5. Conclusion

Here, we study the transport properties of cold \( \tilde{H} \) atoms produced in the cusp magnet. Although the cusp magnet (anti-Helmholtz coils) has in principle a quadrupolar field distribution, it is found that the \( \tilde{H} \) beams prepared upstream of the center of the cusp magnet are well
characterized and follow the lens formula of optical lenses. The focal length satisfies a scaling
law on the initial kinetic energy \( (K_0) \), the maximum magnetic field strength \( (B_m) \) and the
magnetic moment \( (\mu) \) of \( \bar{\text{H}} \) atoms. Because the cusp magnet focuses \( \bar{\text{H}} \) atoms in LFS along the
magnet axis and defocuses those in HFS, one gets a spin-polarized intensified \( \bar{\text{H}} \) beam automatically.

Furthermore, it is found that the best position to produce \( \bar{\text{H}} \) atoms for a stronger \( \bar{\text{H}} \) beam
with higher polarization is upstream of the center of the cusp magnet for a broad range of \( \bar{\text{H}} \)
kinetic energy. This allows the use of the so-called nested trap configuration, which greatly
simplifies the \( \bar{\text{H}} \) production procedures.

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