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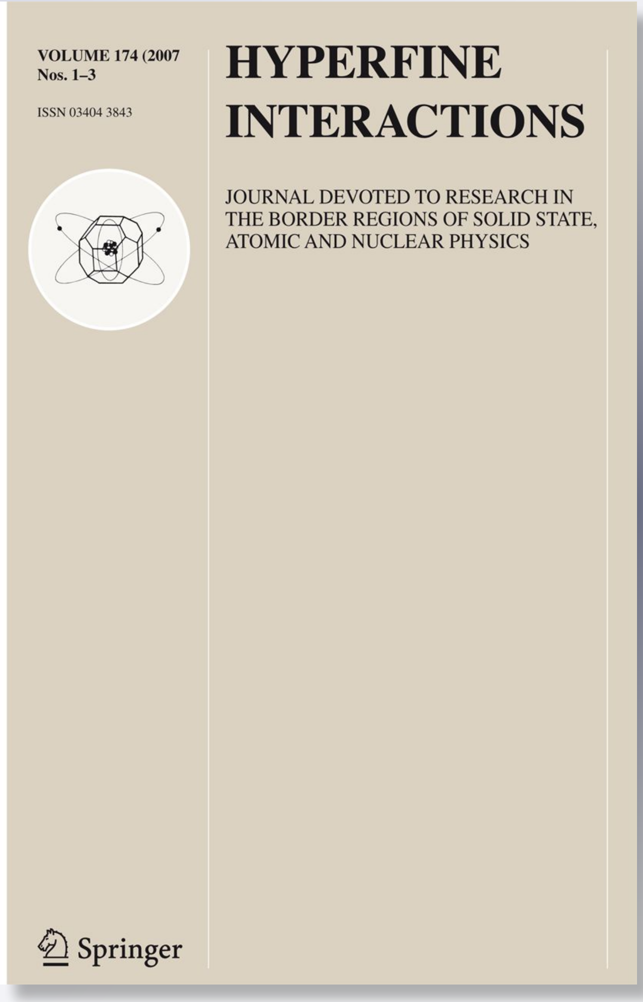

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The atomic coilgun and single-photon cooling

A method for trapping and cooling of hydrogen isotopes

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Abstract As the simplest atom, hydrogen has a unique role as a testing ground of fundamental physics. Precision measurements of the hydrogen atomic structure provide stringent tests of current theory, while tritium is an excellent candidate for studies of β-decay and possible measurement of the neutrino rest mass. Furthermore, precision measurement of antihydrogen would allow for tests of fundamental symmetries. Methods demonstrated in our lab provide an avenue by which hydrogen isotopes can be trapped and cooled to near the recoil limit. The atomic coilgun, which we have demonstrated with metastable neon and molecular oxygen, provides a general method of stopping a supersonic beam of any paramagnetic species. This tool provides a method by which hydrogen and its isotopes can be magnetically trapped at around 100 mK using a room temperature apparatus. Another tool developed in our laboratory, single-photon cooling, allows further cooling of a trapped sample to near the recoil limit. This cooling method has already been demonstrated on a trapped sample of rubidium. We report on the progress of implementing these methods to trap and cool hydrogen isotopes, and on the prospects for using cold trapped hydrogen for precision measurements.

Keywords Hydrogen · Antihydrogen · Trapping · Cooling · Coilgun

1 Introduction

Comprehensive control of atomic motion has been a long standing goal of atomic physics, which has been motivated by a desire for increased precision for spectroscopy, tests of fundamental symmetries, studies of entanglement, and many-body

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physics. Laser cooling has been an extremely successful technique and is currently the method of choice for most experiments, however it has been limited to a few species due to requirements on the atomic structure of the atoms to be cooled. Since it relies on the transfer of momentum from photons to atoms, laser cooling requires many scattering events [1], which means that a cycling transition needs to be used as the cooling transition so that the atom can scatter many photons without falling into a dark state. Additionally, a laser with sufficient power must also be available at the required frequency. Using a cold buffer gas to trap and cool paramagnetic species is quite general [2–4], but with the drawback of limited optical access and the high cost and complexity of cryogenic methods.

Cooling and trapping of hydrogen isotopes offer the possibility of increased precision of fundamental tests of quantum mechanics. Furthermore, experiments with trapped antihydrogen [5–7] will benefit from a cooling method which enables increased precision in tests of fundamental symmetries. Hydrogen is already the basis of some of the most precise atomic measurements made to date [8]. Because of this importance, significant effort has been devoted to hydrogen over the years. Hydrogen has been trapped at high phase space density [9], and has even been Bose-condensed via evaporative cooling in a cryogenic apparatus [10]. This remarkable experiment was limited to H and did not enable trapping and cooling of D and T. Hydrogen has also been laser cooled, but due to the low VUV laser power available, laser cooling of hydrogen is extremely slow [11], though a Sisyphus cooling scheme has been proposed [12], as well as a scheme using ultrafast pulses [13]. Finally, cryogenic methods do not provide a path for cooling of $\bar{\mathrm{H}}$. The disadvantages in existing methods motivate the search for a more general cooling method. As such, we describe a general method for cooling and trapping which we have developed [14].

Similar to the approach taken in a coilgun for bulk projectiles, we use pulsed magnetic fields to slow and stop beams of paramagnetic atoms and molecules. Since most atomic species are paramagnetic in their ground state or an easily accessible metastable state, this approach is very general. Pulsed coils are used to generate high magnetic fields which are switched off when atoms in a beam are near the magnetic field maximum. This same approach was independently pursued [15, 16] and has succeeded in trapping hydrogen for a few milliseconds [17, 18]. Once atoms are trapped, single-photon cooling can be applied to increase the phase space density of the ensemble. This cooling process relies on an irreversible state change of the atom or molecule, which changes the potential landscape seen by the particle. If this state change happens when the atom has low kinetic energy, such as near the classical turning point of an atom in the trap, and the new potential landscape has a minimum near this location, then the atom can be trapped at lower kinetic energy. These two techniques complement each other, as the coilgun provides a general method for magnetically trapping paramagnetic species, while single-photon cooling provides cooling to near the recoil temperature, providing a general method of trapping and cooling.

2 The atomic coilgun

Before the atomic coilgun can be used to bring paramagnetic species to rest in the laboratory frame, they must be in the form of a pulsed beam. Supersonic

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expansion of gas into the vacuum system, a general and well-established method, is an ideal source for such a beam, as the adiabatic expansion cools the beam to temperatures of a few tens of millikelvin [19]. The velocity of these beams ranges from a few hundred meters per second to a few kilometers per second, depending on the mass and temperature of the carrier gas. Several methods have been used to slow supersonic beams while maintaining their temperature. Mechanical methods of slowing have included moving the source of the beam [20], crossed beam collisions [21], and reflecting the beam from a moving mirror [22]. Cold buffer gas collisions [23], interactions with pulsed laser fields [24], and pulsed electric fields [25, 26] have also been used to control supersonic beams.

The atomic coilgun takes advantage of the Zeeman effect to exert a force on the atoms in the beam. In a magnetic field, a paramagnetic atom or molecule will either gain or lose potential energy, depending on the internal state. We slow low field seeking atoms, which are atoms that gain potential energy with increasing magnetic field. We use pulsed electromagnetic coils to produce regions of high magnetic field along the atomic beam axis. When low field seeking atoms enter the coil, they lose kinetic energy equal to the Zeeman energy shift $\Delta E = g\mu_B m_j B$, where g is the Lande factor, μ_B is the Bohr magneton, m_j is the projection of the angular momentum along the direction of the magnetic field, and B is the magnitude of the magnetic field. When the atoms are near the center of the coil, we switch the magnetic field off quickly, so that they do not accelerate as they exit the coil. This process can be repeated in multiple coils, allowing the beam to be brought to rest. The switching times for each coil are calculated numerically by simulating the trajectory of an atom as it travels through the experiment. An atom following the trajectory of this simulated atom is referred to as a synchronous atom, and can generally be thought of as being at the center of the slowed bunch in phase space.

While the magnetic field is axially maximal at the center of the coil, and thus provides the greatest slowing for a synchronous atom, we switch the field off before the atom reaches the center of the coil. This provides phase stability, similar to that seen in synchrotrons. Varying the position of the synchronous atom when the coils are switched off affects both the size of the region of phase stabilty and the kinetic energy removed. In addition to the axial stabilty of the slow packet, the field profile of the coil also provides radial stability. While the field is maximal axially at the center of the coil, radially the field is at a minimum. This means that a low field seeker is pushed towards the center of the coil as it flies through, causing the coilgun to act as a waveguide.

To produce our supersonic beam, we use an Even-Lavie supersonic valve [27, 28]. This valve has an opening time of only 10 μs FWHM, with fluxes of 10^{24} atoms/sr/s. The nozzle can be cooled to cryogenic temperatures, which reduces the initial beam speed and lowers the number of magnetic stages required to stop the beam. While we do cool the nozzle, no other part of the experiment is cryogenic.

Stopping of supersonic beams of both metastable neon and ground state molecular oxygen has been demonstrated [29, 30]. We produce metastable neon using a pulsed dc discharge at the exit of the supersonic nozzle, and observe beam speeds of 446.5 m/s. Final beam speeds of 55.8 m/s are produced by the coilgun, which corresponds to a removal of over 98% of the energy. For our experiments with molecular oxygen, the initial velocity of the beam is 389 m/s and we slowed to 83 m/s, removing over 95% of the initial energy.

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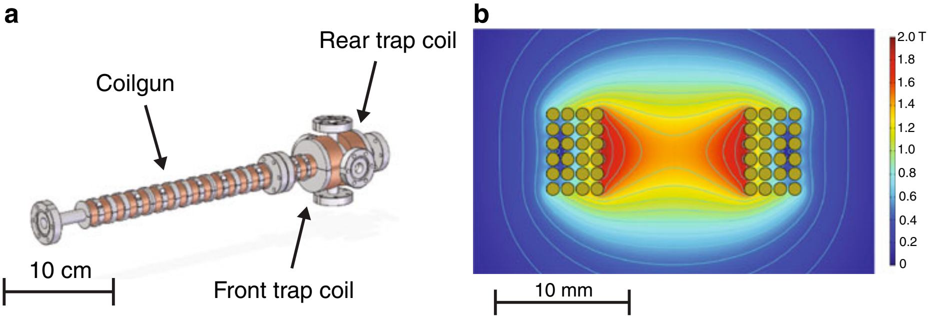

Fig. 1 (**a**) A drawing of the hydgrogen trapping apparatus. (**b**) The numerically calculated magnetic field profile of the hydrogen specific coilgun coil. Peak fields on axis are 1.4 T

The coilgun is an excellent means by which hydrogen may be stopped and trapped. Supersonic expansion provides the cold pulsed beam the coilgun requires, and molecular hydrogen in the beam can be dissociated via a discharge. Since the energy removed per stage depends only on the Zeeman splitting and the magnetic field, the behavior of a particle in the coilgun is determined by its magnetic moment to mass ratio. Hydrogen has a magnetic moment of $1\mu_B$ and a mass of 1 amu, while the metastable neon we slowed has a magnetic moment of $3\mu_B$ and a mass of 20 amu. As such, the magnetic moment to mass ratio is extremely favorable for using the coilgun to stop and trap hydrogen isotopes.

Due to this favorable ratio, the hydrogen apparatus we have built has only 18 slowing coils, compared to 64 coils in the neon and oxygen apparatus. A CAD drawing of this apparatus is shown in Fig. 1a. Additionally, these 18 coils are significantly larger than those in the neon apparatus since the peak magnetic field does not need to be as great to achieve effective slowing. This larger bore provides an increased slowed flux. The larger coil size also allows us to move the coils outside of vacuum. The slowing coils consist of 24 windings of 1 mm copper magnet wire (4 layers of 6 windings). The coil bore is 11.5 mm while the outside diameter is 19.5 mm. We pass approximately 825 A of current in up to 200 μs pulses, which produces peak fields on axis of 1.4 T, with switch off times of less than 10 μs. We characterize our coils using the Faraday effect, as previously reported [30]. The field profile produced by this coil is calculated numerically and can be seen in Fig. 1b.

Once the hydrogen has been slowed by the coilgun, the next step is to trap the ensemble. To preserve phase space density, we must mode-match the trap to the coilgun. An anti-Helmholtz trap configuration enables this. To improve the mode-matching between the coilgun and the trap, we will use the first trapping coil that atoms see as a final slowing coil. This serves to confine the slowed atoms both axially and radially due to the phase stability and waveguide effects of the coil respectively. After the atoms pass through the front trapping coil, they will enter the trapping region, where they will be brought to rest by the rear trapping coil. The velocity of the atoms will be tuned by the coilgun such that the atoms come to rest in the center of the trap. At this point in the sequence, the front trapping coil will be turned back on, though with the opposite polarity, forming an anti-Helmholtz trap with the atoms near rest in the center of the trap. This sequence is illustrated in Fig. 2. Since the temperature of the slowed atoms will be a few hundred mK, the trap must be at least

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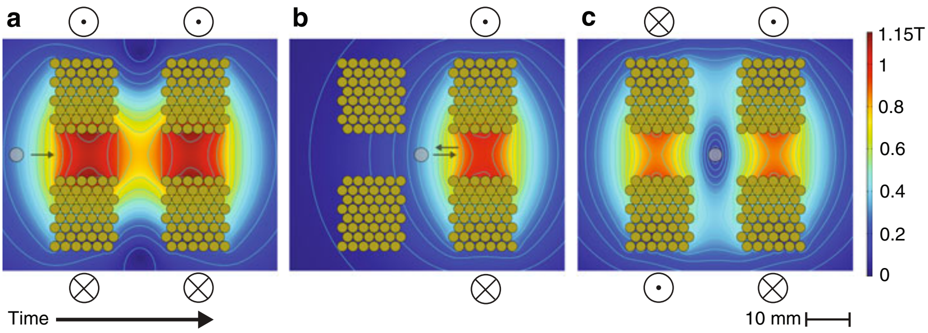

Fig. 2 Numerically calculated magnetic field profiles of the trapping coils at different stages of the trapping sequence. In **a** the cloud is approaching the trap from the coilgun and the front trap coil is used as a final slowing coil. The cloud then enters the trapping region and is stopped by the rear trapping coil as shown in **b**. Lastly, the front trapping coil is switched on, trapping the cloud in a 100 mK deep trap as illustrated in **c**

this deep to prevent losses. Additionally, the trapping coils will need to remain on for up to a few seconds, and the trapping coils must be able to withstand the high currents used for at least this long. As such, we use hollow wires and run water through the coils to remove excess heat. The wires have a 2.4 mm outer diameter and a 1.2 mm inner diameter. The coils consist of 48 windings (8 layers of 6 windings) with an inner diameter of 10 mm and an outer diameter of 47 mm, and are spaced 27 mm apart. With 500 A in each coil this produces a trap depth of 100 mK for hydrogen. Our simulations predict that using this sequence should result in a trapping effeciency of 4–5% of the atoms that enter the slower. Recently, a moving magnetic trap was used to decelerate atoms [31], and this technique may provide for even larger trapped phase space densities.

While a supersonic beam of hydrogen is relatively simple to produce, this is not the case for antihydrogen. However, the physics of the coilgun should be the same for antihydrogen, which suggests uses of the coilgun in an antihydrogen experiment. If the antihydrogen were produced in a beam, by launching antiprotons through a cloud of positrons, for example, the coilgun could be used to stop and trap the antihydrogen.

3 Single-photon cooling

Magnetic deceleration by an atomic coilgun can bring a sample of atoms to rest in the laboratory frame with a temperature of tens of millikelvin. However, it is desirable to produce even colder samples for applications such as precision measurement and evaporative cooling to quantum degeneracy. In this section we present a promising and relatively simple technique for further cooling called single-photon cooling, which has the potential to cool a sample of nearly any atomic species to its recoil limit [32–36]. Indeed, the technique has been shown to be applicable to many molecules as well [37].

Single-photon cooling relies on a one-way wall for atoms, a barrier that is permeable to atoms approaching it from one side but not from the other. Assuming,

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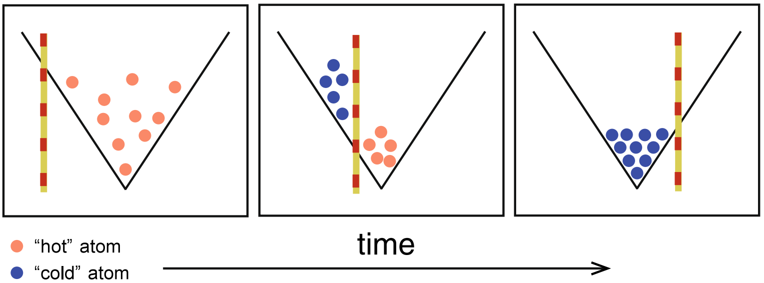

Fig. 3 Cooling of atoms using a one-way wall. For simplicity, we assume a one-dimensional central potential. The wall is swept from the edge of the potential toward the center, slowly enough that each atom is near its classical turning point when it encounters the wall. Thus the atoms have very low kinetic energy when they pass through the wall and are trapped. Once the wall has swept through the entire sample, every atom has had its total mechanical energy dramatically reduced

for simplicity, a 1D central potential, cooling with a one-way wall may be done in the following way, as illustrated in Fig. 3. The wall begins at the edge of the trap, at which point no atom is influenced by the wall. The wall is then swept towards the center slowly enough that each atom encounters the wall only when it is very close to the classical limit of its trajectory in the trap, at which point it has nearly zero kinetic energy. When the atom encounters the one-way wall, it passes through and is trapped in the minimum of the potential defined by the original trap and the one-way wall, resulting in nearly zero potential energy, as well. In a real trap, the atom moves in three dimensions, but trap ergodicity may mix these degrees of freedom sufficiently for one dimensional cooling to be effective. The physical realization of the one-way wall for atoms is a laser that switches the internal state of the atom, spatially overlapped with a new trap in which the atom is confined if and only if its state has been changed. Spontaneous emission must be involved in the trap-switching to make the process irreversible, and thus produce a genuine one-way wall. Single-photon cooling takes its name from the fact that each atom must scatter, on average, just one photon. A closed two-level system, such as is required for standard laser cooling, is not required. This is the source of the very broad applicability of the technique.

Single-photon cooling has been demonstrated on a trapped sample of rubidium atoms [38, 39], resulting in an increase of phase space density of the sample by a factor of 350. That implementation of single-photon cooling used transfer between a magnetic trap and a gravito-optical trap. The transfer was mediated by excitation and spontaneous emission, which served as the irreversible step essential to forming a one-way wall. An alternative method is to transfer population between two rf-dressed states of a magnetic trap [37]. A major advantage of this approach is that it has the potential to be a genuinely three-dimensional cooling method and does not rely on trap ergodicity. The operation of a one-way wall using rf-dressed states in atomic hydrogen is presented in Fig. 4. Essentially, a hydrogen atom at its classical turning point in the lower dressed level of the $1S$ manifold can be excited to the $2S$ manifold. The excitation is done using a two-photon transition with photons at 243 nm, a standard method in spectroscopy of hydrogen [8]. The $2S$ state has an impractically long natural lifetime of 0.122 s, but mixing it with the $2P$ state using an electric field results in rapid decay, with some probability, to the upper dressed

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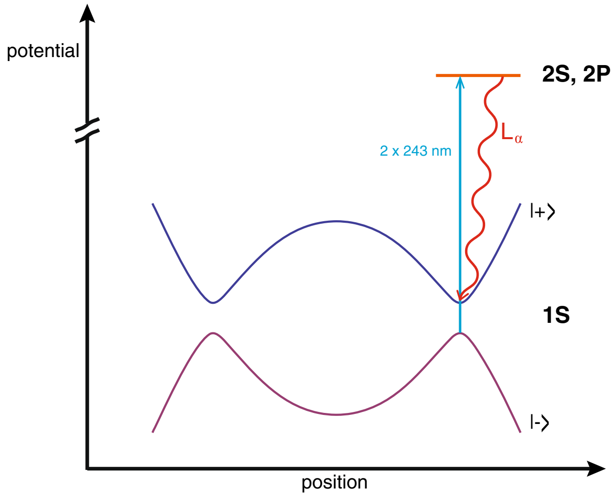

Fig. 4 A scheme for implementing single-photon cooling of hydrogen in the high-field limit. The figure depicts two of the four levels in the $1S$ manifold of the hydrogen atom, labeled $|+\rangle$ and $|-\rangle$; these are coupled by rf radiation, resulting in two avoided crossings. Atoms trapped in state $|-\rangle$ are pumped, at their classical turning point, to the $2S$ excited state using a two-photon transition at 243 nm. The $2S$ state is mixed with the $2P$ state using an electric field, and the atom rapidly decays back to the $1S$ manifold, with some probability landing in state $|+\rangle$ with nearly zero kinetic energy

level in the $1S$ manifold, where the potential is at a minimum. This scheme applies to the cooling of hydrogen in the limit of high magnetic field (in which the nuclear and electronic angular momenta are decoupled), and requires spatial localization of the 243 nm laser.

Single-photon cooling is a physical realization of the famed "Maxwell's Demon" thought experiment, in which a being, who is able to observe the motion of each atom in an ensemble, is able to reduce the entropy of the ensemble without doing work on it, in apparent violation of the Second Law of Thermodynamics. In the classic example, the demon operates a trap door separating two chambers. By opening the door when an atom approaches from the right side, say, but not the left, it creates a one-way wall, increasing phase space density without doing work on the gas. The most widely-accepted resolution to this paradox is that by making measurements on the atoms, the Demon stores information which must be erased, in accordance with Landauer's erasure principle [40], thereby increasing the entropy of the universe. In the case of single-photon cooling, the scattering of the photon from each atom reveals information about the atom's position and/or velocity, making measurement of these quantities possible, while the entropy removed from the atomic ensemble is accounted for by the increased entropy of the radiation field [36].

Single-photon cooling is a promising method for cooling magnetically trapped hydrogen and antihydrogen. However, there are two limitations of which one should be aware: branching ratio losses and the recoil limit. Branching ratio losses occur because the atom will decay to some other, possibly untrapped, state with a certain probability. Therefore, some fraction of the atoms will be lost during the cooling process. However, since each atom only scatters a photon once, the losses are tolerable. Such losses, by contrast, would be intolerable in a process such as laser

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cooling in which many photons must be scattered. Having a low loss rate is important for experiments involving antihydrogen, in which only relatively small numbers of atoms are likely to be available. The fundamental limit of the cooling process arises from the fact that the atom scatters one photon, gaining momentum in a random direction equal to the momentum of the scattered photon. For hydrogen, the recoil limit of 1.3 mK is quite high, since the scattered photon at 121.6 nm is high in momentum and hydrogen is the lightest atom. Nevertheless, previous experiments have shown evaporative cooling of hydrogen to quantum degeneracy starting at temperatures around 40 mK [10].

4 Conclusion

The atomic coilgun and single-photon cooling together provide a general means for trapping and cooling that is well suited to hydrogen isotopes. In contrast to laser cooling, these techniques present few requirements on internal atomic structure. Magnetic slowing via the coilgun requires only that the species of interest have a magnetic moment in a long-living state. Hydrogen isotopes offer the most favorable ratios of mass to magnetic moment, simplifying the design of the apparatus. We require smaller peak magnetic fields and fewer stages in order to efficiently trap H, D, T, and $\bar{\mathrm{H}}$. Single-photon cooling likewise demands only a suitable irreversible transition in order to achieve higher phase space density. With a laser at 243 nm for driving the two-photon transition, the $1S-2S$ transition in hydrogen is well-suited for single-photon cooling.

Unlike other general techniques, the coilgun and single-photon cooling allow for experiments in an accessible, room-temperature apparatus. The high inital flux provided by a supersonic beam enables the possibility of trapping and cooling large numbers of atoms. A challenge in these experiments is thus engineering coils that produce magnetic field profiles that can translate the largest possible subset of the beam's initial phase space to rest. Numerical methods, however, allow for quickly simulating and characterizing designs for a species of interest in order to maximize the efficiency of trapping. Single-photon cooling should then allow for cooling to near the recoil limit.

With the simplest atomic structure in the periodic table, measurements of hydrogen isotopes have provided tests of theory. To date, spectroscopy of H and D present some of the highest precision measurements [41], but spectroscopic measurements of T are lacking. For instance, while the $1S-2S$ isotope shift between H and D was recently measured with an uncertainty of 15 Hz, the corresponding measurement of the $1S-2S$ transition in tritium has an uncertainty of several MHz [42]. As such, a need exists for more precise tritium spectroscopy data which we believe could be attained using the methods described here.

Another future goal includes trapping and cooling of $\bar{\mathrm{H}}$. At present a suitable beam of $\bar{\mathrm{H}}$ for trapping via the coilgun does not exist, but $\bar{\mathrm{H}}$ has been trapped in an octopole magnetic trap [7]. Substantial cooling of the trapped $\bar{\mathrm{H}}$ will be necessary for precision measurements. The large volume of the trap together with the small quantity of trapped $\bar{\mathrm{H}}$ suggests low phase space density, which can be increased using single-photon cooling.

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