Pulsed Sisyphus Scheme for Laser Cooling of Atomic (Anti)Hydrogen

Saijun Wu, Roger C. Brown, William D. Phillips, and J. V. Porto
Joint Quantum Institute, NIST and University of Maryland, Gaithersburg, Maryland 20899, USA
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We propose a laser cooling technique in which atoms are selectively excited to a dressed metastable state whose light shift and decay rate are spatially correlated for Sisyphus cooling. The case of cooling magnetically trapped (anti)hydrogen with the $1S$-$2S$-$3P$ transitions by using pulsed ultraviolet and continuous-wave visible lasers is numerically simulated. We find a number of appealing features including rapid three-dimensional cooling from $\sim$1 K to recoil-limited, millikelvin temperatures, as well as suppressed spin-flip loss and manageable photoionization loss.

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Recent progress [1,2] in producing antihydrogen ($\bar{\mathrm{H}}$) improves the prospects for precision spectroscopy and de Broglie wave interferometry of $\bar{\mathrm{H}}$ that may uncover new physics in low-energy experiments [3,4]. Antihydrogen atoms are made [1–5] in such small numbers that trapping appears crucial for precision measurements, e.g., for *CPT* tests. Cooling to the lowest possible temperatures is essential in order to reduce inhomogeneous broadening in a magnetic trap and may also be important for transferring $\bar{\mathrm{H}}$ to a (possibly magic-wavelength) optical dipole trap. In contrast to H, which may be cooled by collisions with a buffer gas [6] or by selecting low-energy atoms from an intense beam, the cooling of $\bar{\mathrm{H}}$ will likely rely on laser cooling techniques [7].

Despite the significant impact effective laser cooling would have on precision $\bar{\mathrm{H}}$ studies, laser cooling of H (or $\bar{\mathrm{H}}$) has remained a challenge for many years due to the unavailability of powerful 121.6 nm Lyman-α (Ly-α) lasers. The only experimental work so far [8] used a pulsed Ly-α laser with an average power of 160 nW (2.5 nW at the location of atoms) to cool magnetically trapped H, precooled to 80 mK via evaporation, and it took more than 15 min to reach just 8 mK. The generation of even $\sim$10 nW of cw Ly-α radiation is technically difficult [9]. Laser cooling of magnetically trapped $\bar{\mathrm{H}}$ (produced at or possibly precooled [10] to kelvin temperatures) faces several interrelated difficulties. The need to avoid spin-flip losses, combined with the limited fraction of phase space addressable with a low intensity, single-frequency laser, implies that the cooling will be slow, particularly since 3D cooling aided by collisional mixing [8] will be absent in dilute samples of $\bar{\mathrm{H}}$. Instead of relying on Ly-α radiation, several proposed cooling schemes use more readily available lasers to drive Doppler-sensitive two-photon transitions [11–13]. However, in addition to limited phase-space addressability similar to Ly-α cooling, these schemes have the difficulty of losses due to photoionization. Since $\bar{\mathrm{H}}$ is produced in such small quantities, it is important to mitigate such losses.

Motivated by previous work [14] using cooling transitions between excited states, we propose a 3-level cooling scheme (Fig. 1), applicable to magnetically trapped H: A metastable state $|e\rangle$ is coupled to a short-lived state $|e'\rangle$ by a blue-detuned standing wave coupling $\Omega_{ee'}$. Atoms in the ground state $|g\rangle$ are repeatedly excited to the bottom of the dissipative $|e\rangle$-$|e'\rangle$ optical lattice by a pulsed, Doppler-sensitive two-photon coupling Ω_{ge}. The cooling process arises from two effects: two-photon Doppler cooling [11–13], associated with $|g\rangle \rightarrow |e\rangle$ excitation, and Sisyphus cooling [15], associated with the lattice.

For magnetically trapped H, $|g\rangle$, $|e\rangle$, and $|e'\rangle$ are the maximally Zeeman-shifted states in the $1S$, $2S$, and $3P$ manifolds, respectively. We show that the cooling scheme provides both a large capture velocity (100 m/s) and a low final temperature (near the Ly-β single-photon recoil temperature of 1.8 mK) and allows for large volume 3D cooling. Advantages include the technical feasibility of generating both the nanosecond-pulsed UV two-photon $1S$-$2S$ radiation [16] and the cw radiation at 656 nm, reduction of UV photoionization losses, and a suppressed

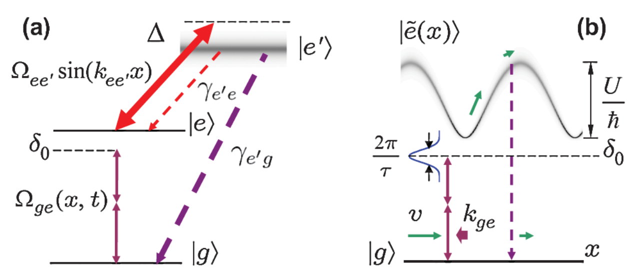

FIG. 1 (color). Level diagram (a) and simplified dressed-state picture (b) for the proposed cooling scheme. Pulsed two-photon excitation with bandwidth $1/\tau$ is detuned from the bottom of the lattice of depth U by δ_0 and cools by transferring momentum $\hbar k_{ge}$ to an atom with velocity v. The decay rate $\Gamma(x)$ of the dressed excited state $|\tilde{e}(x)\rangle$ is indicated by the width of the gray curve. As the atom climbs the hill, the velocity (green arrow) decreases while the decay probability increases, leading to Sisyphus cooling. [Not shown in (b) is the other, detuned dressed state $|\tilde{e}'(x)\rangle$.]

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spin-flip transition from the $3P$ level in a high field. In the following, we first discuss the pulsed Sisyphus cooling scheme in a 1D, semiclassical model. After justifying the model with a 1D quantum simulation [17,18], we present a 3D semiclassical simulation for magnetically trapped H.

The proposed cooling scheme involves repeated pulsed excitations, each followed by spontaneous decay [19]. The propagation direction of the two-photon excitation pulses alternates between $\pm\hat{x}$. The Rabi frequency $\Omega_{ge}(x,t)$ is $(\theta/\tau)f(t/\tau)e^{\pm ik_{ge}x}$, where θ is the pulse area, k_{ge} is the sum of the wave vectors of the two photons, and $f(t/\tau)$ is a normalized pulse-shape function with characteristic duration τ and excitation bandwidth $\sim 1/\tau$. The interval $T_{\rm rep}$ between pulses is long enough so that excited atoms, moving in the $|e\rangle$-$|e'\rangle$ lattice, decay to $|g\rangle$ with high probability. In the effective 2-level system [Fig. 1(b)], the spatially dependent detuning $\delta(x)$ and linewidth $\Gamma(x)$ [see Eq. (1)] produce spatial selectivity in both pulsed excitation and subsequent decay. The $|e\rangle$-$|e'\rangle$ transition is driven by a standing wave coupling $\Omega_{ee'}(x)$ with a positive detuning Δ, resulting in two dressed states $|\tilde{e}(x)\rangle$ and $|\tilde{e}'(x)\rangle$, which are spatially dependent superpositions of $|e\rangle$ and $|e'\rangle$ and connect to those states, respectively, as $\Omega_{ee'}\to 0$. The two-photon $|g\rangle$-$|e\rangle$ detuning from the unshifted metastable state $|e\rangle$ (decay rate $\gamma_{eg}\approx 0$) is δ_0, and $\gamma_{e'g}$ and $\gamma_{e'e}$ are the decay rates from $|e'\rangle$ [Fig. 1(a)]. We assume $\Delta \gg \delta_0, \gamma_{e'g}$ and $\gamma_{e'g}\gg\gamma_{e'e}$. Atoms are predominantly excited to, and adiabatically follow, the dressed state $|\tilde{e}(x)\rangle$ [and not $|\tilde{e}'(x)\rangle$] [20], and

$$\delta(x) = \delta_0 - \left[\sqrt{\Omega_{ee'}^2(x)+\Delta^2}-\Delta\right]/2,$$
$$\Gamma(x) = \frac{\delta_0-\delta(x)}{\sqrt{\Omega_{ee'}^2(x)+\Delta^2}}\gamma_{e'g}. \tag{1}$$

In Eq. (1), we have ignored $\gamma_{e'e}$ and γ_{eg}, but their inclusion has little influence on the results described below. The depth U of the resulting $|e\rangle$-$|e'\rangle$ optical lattice is given by the maximum of $\delta_0-\delta(x)$, and its period is determined by $k_{ee'}$. We define k_{ij} as the wave vector of the i-j transition for $i, j = g, e, e'$, with the associated recoil velocities and frequencies defined as $v_{ij}=\hbar k_{ij}/m$ and $\omega_{r,ij}=\hbar k_{ij}^2/(2m)$, where m is the atomic mass.

Doppler-sensitive $|g\rangle$-$|e\rangle$ absorption leads to two-photon Doppler cooling [11–13]. The Doppler-shifted, spatially dependent detuning $\delta(x,v)=\delta(x)\pm k_{ge}v$ allows atoms with different v to be excited to the lattice potential at different x. Atoms with velocity v are resonantly excited at positions such that $|\delta(x,v)|\tau\lesssim 1$. For $\tau > 2\pi/|\delta_0|$, strong excitation occurs only in the velocity range $v_d<|v|<v_c$, with decoupling velocity $v_d\simeq|\delta_0|/k_{ge}$ and capture velocity $v_c\simeq(|\delta_0|+U/\hbar)/k_{ge}$. Atoms with $|v|\ll v_d$ or $|v|\gg v_c$ are off resonance and not efficiently excited.

In addition to Doppler cooling, the correlation between the spatially dependent detuning $\delta(x)$ and the decay rate $\Gamma(x)$ leads to Sisyphus cooling since atoms preferentially decay from $|\tilde{e}(x)\rangle$ at the tops of the light shift potential [15]. The Sisyphus effect is particularly effective for atoms excited near the bottom of the lattice with $v\sim v_d$. If $\frac{1}{2}mv^2<U$, atoms remain within one lattice site and typically oscillate before decaying to $|g\rangle$. The decay is enhanced at the classical turning point, due to both the larger decay rate and the longer time spent there. Averaged over the position- (and velocity-) dependent decay probability, the velocity distribution after decay is centered at zero velocity, with a rms width less than $\frac{1}{2}v$ for $v\gg v_{ge}$. On average, this removes >75% of the atomic kinetic energy per two-photon excitation.

To characterize the cooling, we define the normalized position- and velocity-dependent excitation probabilities $p_e=4P_e/\theta^2$ and energy loss per two-photon pulse $\varepsilon = 4\Delta E/\theta^2$, where P_e is the two-photon excitation probability, ΔE is the energy loss per pulse, and p_e and ε are θ-independent for $\theta\ll 1$. Figures 2(a) and 2(b) ($k_{ge}/k_{ee'}=25$) and 2(d) and 2(e) ($k_{ge}/k_{ee'}=5.4$, corresponding to $k_{1S\text{-}2S}/k_{2S\text{-}3P}$ in H) show p_e and ε, determined by using 3-level optical Bloch equations for a "dragged atom" following $x(t)=x_0+vt$. For atoms that move more than $1/k_{ee'}$ during τ, the excitation is complicated by multiphoton resonances at velocities with $k_{ge}v+2nk_{ee'}v\approx\delta$ [the peaks of the black curve in Fig. 2(e) for $\bar{v}>20$] [14]. In addition, for large $k_{ee'}$, Doppleron [21] resonant coupling to $|\tilde{e}'(x)\rangle$ occurs at moderate speeds v with $(2n+1)k_{ee'}v\approx\Delta$ for integer n [the sharp dips of the black

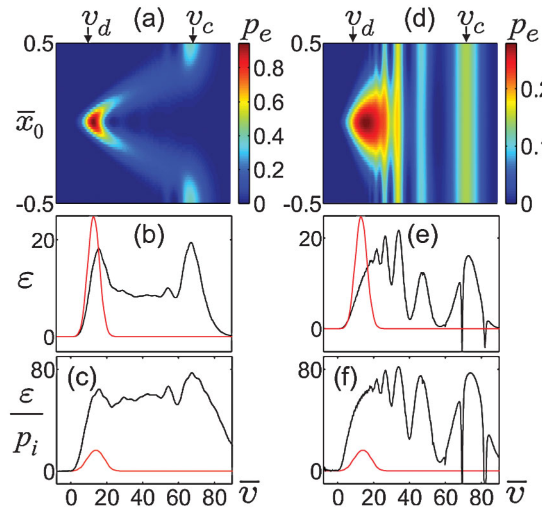

FIG. 2 (color). Optical Bloch equation simulation of cooling properties. (a),(d) Normalized excitation probability p_e vs $\bar{x}_0 = k_{ee'}x_0/\pi$ and $\bar{v}=v/v_{ge}$. (b),(e) Normalized energy loss per pulse ε vs $\bar{v}$. ε is averaged over x_0 and is in units of $\hbar\omega_{r,ge}$. (c),(f) Ratio of ε to the normalized ionization probability, ε/p_i vs $\bar{v}$. Here $\delta_0=-25\omega_{r,ge}$, $\tau=-2.5/\delta_0$, $f(t/\tau)=(1/\sqrt{\pi})e^{-t^2/\tau^2}$, $\theta=\pi/8$, $\Omega_{ee'}(x)=\Omega_{ee'}\sin(k_{ee'}x)$, $\Delta=\Omega_{ee'}/2=200\omega_{r,ge}$, and $\gamma_{e'g}=8\gamma_{e'e}=2\omega_{r,ge}$. The red curves in (b), (c), (e), and (f) correspond to $\Omega_{ee'}=0$. The left and right panels are for $k_{ge}/k_{ee'}=25$ and 5.4, respectively. The bottom axes apply for all panels.

curve in Fig. 2(e) near $\bar{v} = 70, 80$] and leads to heating. Nevertheless, efficient Sisyphus cooling is still possible for moderate $k_{ge}/k_{ee'}$ [see Fig. 2(e)]. Compared to regular two-photon cooling [red curves in Figs. 2(b) and 2(e)], the peak excitation probability is decreased by approximately $\frac{2\pi}{\tau} / \frac{U}{\hbar}$ due to the spatially inhomogeneous broadening of $|\tilde{e}(x)\rangle$ [Fig. 1(b)]. Because of the Sisyphus-enhanced energy removal per excitation, the average energy loss per pulse remains comparable to the Doppler-only case but with an increased velocity capture range $v_d < |v| < v_c$.

In addition to the increased velocity capture range, the decreased excitation probability to $|\tilde{e}(x)\rangle$ helps mitigate the photonionization loss from $|\tilde{e}(x)\rangle$ to the continuum. For degenerate two-photon excitation to the $2S$ level, the ionization probability per pulse is given by $P_{\rm ioni} = \int dt \gamma_{\rm ioni}(t)\rho_{2S}(t)$, where $\rho_{2S}(t)$ is the $2S$ state population and $\gamma_{\rm ioni}$ is the rate of ionization from $2S$ due to the UV radiation [22]. $P_{\rm ioni}$ scales with the pulse area as θ^3. As one measure of cooling efficiency per two-photon pulse, in Figs. 2(c) and 2(f), we compare ε/p_i, the ratio between the normalized energy loss ε and normalized ionization probability $p_i = 12P_{\rm ioni}/\theta^3$, with (black curve) and without (red curve) the Sisyphus cooling, where $\gamma_{\rm ioni} = 1.6\Omega_{ge}$ [22]. We see that the Sisyphus effect enhances the cooling efficiency by approximately $U/|\hbar\delta_0|$ near $v = v_d$, where the Doppler cooling has the best ε/p_i.

We simulate the cooling process with a semiclassical stochastic wave function (SCSW) method [17,18]. The simulation of a cooling cycle is divided into two stages: excitation ($0 < t < \tau$) and decay ($\tau < t < T_{\rm rep}$) (we ignore quantum jumps during excitation). The external motion of the atom is described by a classical trajectory $x(t)$. The internal dynamics are described by a stochastic wave function $|\psi(t)\rangle$, which, after the g-e pulse, is probabilistically projected to either $|g\rangle$ or the $\{|e\rangle, |e'\rangle\}$ manifold [typically, almost all in $|\tilde{e}(x)\rangle$] as $|\psi_p\rangle$. Because of this postselection, the optical force in the excitation stage cannot be evaluated in the usual way as $\langle\psi(t)|\hat{F}|\psi(t)\rangle$, where $\hat{F}$ is the force operator. Instead, the force is estimated as the real part of a "weak value" [23] $\langle\psi_p(t)|\hat{F}|\psi(t)\rangle/\langle\psi_p(t)|\psi(t)\rangle$, where $|\psi(t)\rangle$ is found by forward-propagating the predetermined state $|\psi(0)\rangle = |g\rangle$ and $\langle\psi_p(t)|$ is found by back-propagating the postdetermined state $\langle\psi_p(\tau)|$, both for a dragged atom. This estimation method reproduces the quantum-mechanically expected velocity change during the pulse, $\delta v_{\rm pulse}$, due to both the recoil effect and the excited-state dipole force. During the second stage, the stochastic wave function $|\psi_p(t)\rangle \in \{|e\rangle, |e'\rangle\}$ manifold and $x(t)$ are propagated in small time steps, until a quantum jump occurs [17,18]. If the quantum jump is an $|e'\rangle \rightarrow |e\rangle$ transition, we project $|\psi_p(t)\rangle$ to the dressed states $|\tilde{e}(x)\rangle$ or $|\tilde{e}'(x)\rangle$ probabilistically [24], while for an $|e'\rangle \rightarrow |g\rangle$ jump, we propagate $x(t)$ freely until the next pulse. Upon each spontaneous emission, we use random velocity jumps to account for the recoil effect.

We use a 1D full quantum stochastic wave function (QSW) simulation [17,18], which includes both internal and external degrees of freedom of a 3-level atom, to confirm that the SCSW method correctly predicts the cooling dynamics and the final temperature. In Fig. 3, typical results for smoothed square pulses [25] are compared, for the appropriate hydrogen $1S$-$2S$-$3P$ parameters, $\{\gamma_{e'g}, \gamma_{e'e}\}/(2\pi) = \{26.6, 3.6\}$ MHz and $\{v_{ge}, v_{ee'}, v_{ge'}\} = \{3.3, 0.6, 3.9\}$ m/s, which are also used in Figs. 2(d)–2(f). We find good agreement between the SCSW and QSW methods as long as the dragged atom picture is valid during the pulse, i.e., if the optical force during the short excitation does not significantly displace the trajectory compared to the wavelength ($k_{ee'}\delta v_{\rm pulse}\tau \ll 1$) [Fig. 3(b)]. The 1D temperature predicted by the quantum simulation decreases with $1/\tau$ and is remarkably low (~ 3 mK) even with $\tau = 5$ ns.

Having verified the semiclassical approach for our parameters, we use SCSW to simulate 3D cooling of magnetically trapped H, including all ten electronic levels in the $1S$-$2S$-$3P$ manifold (ignoring hyperfine structure). In a high magnetic field, the cooling process is dominated by the three maximally Zeeman-shifted states of the $1S$, $2S$, and $3P$ levels (corresponding to $|g\rangle$, $|e\rangle$, and $|e'\rangle$), which would form a closed system under $1S$-$2S$ two-photon coupling Ω_{ge} and perfect σ^+ $2S$-$3P$ coupling $\Omega_{ee'}$. We consider a magnetic trap with $\mathbf{B} = \{B_x, B_y, B_z\} = \{B_1 y - B_2 zx/2, B_1 x - B_2 zy/2, B_0 + B_2(2z^2 - x^2 - y^2)/4\}$, $B_0 = 0.75$ T, $B_1 = 0.8$ T/cm, and $B_2 = 12$ mT/cm^2, similar to those for an existing $\bar{\rm H}$ apparatus [5]. Both $|g\rangle$ and $|e\rangle$ feel a trapping potential $V \approx \mu_B|\mathbf{B}|$ (μ_B is the Bohr magneton), so the $|g\rangle$-$|e\rangle$ detuning δ_0 is nearly free from Zeeman shifts [26]. The $|e\rangle$-$|e'\rangle$ detuning $\Delta(B) \approx \Delta - \mu_B B/\hbar$, on the other hand, is field-sensitive and has a position-dependent shift.

We consider a $2S$-$3P$ lattice composed of three pairs of standing wave Gaussian beams, each with $1/e^2$ diameter d, arranged symmetrically with equal intersection angles α to $\hat{z}$. The choice of relative phases between standing waves is

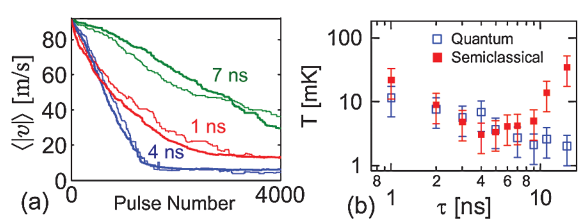

FIG. 3 (color). Comparison of 1D SCSW and QSW simulations. Here $\Omega_{ee'}/(4\pi) = \Delta/(2\pi) = 2.7$ GHz as in Fig. 2, $\delta_0 = -2\pi/\tau$, $\theta = \pi/4$. (a) Average speed $\langle|v|\rangle$ vs pulse number for three different τ. 4 ns is a compromise between large bandwidth with little spatial selectivity (1 ns) and small bandwidth with a small total excitation fraction (7 ns). Thick (thin) lines are an average of 30 QSW (20 SCSW) trajectories, respectively. (b) Equilibrium temperature T vs pulse duration τ. At small v the SCSW method becomes less accurate for $\tau > 9$ ns, roughly set by half the oscillation period in a $|e\rangle$-$|e'\rangle$ lattice site.

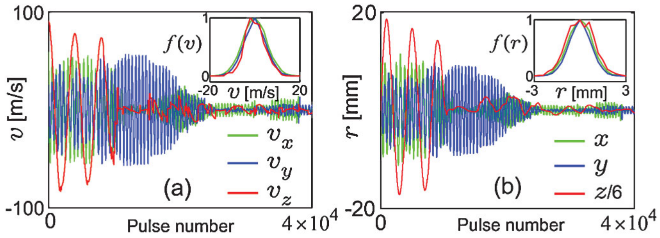

FIG. 4 (color). Evolution of atomic velocity (a) and position (b) for a typical classical trajectory during the simulated cooling of magnetically trapped H. The insets give the quasiequilibrium distributions.

not critical to the cooling scheme. The beams are circularly polarized to maximize the σ^+ components (relative to $\hat{B}$). In the Paschen-Back regime considered here, with $\mu_B B \gg \hbar\Delta_{3P,\text{fine}}$ [$\Delta_{3P,\text{fine}}/(2\pi) = 3.25$ GHz], the π coupling induces spin-flip losses after $2S$ excitation with a branching ratio of $r_{\text{sf}} = \frac{2}{9}\Delta^2_{3P,\text{fine}}/(\Delta + \mu_B B/\hbar)^2$ (similar for σ^- coupling). Even for $2S$-$3P$ light that is purely π or σ^- polarized, the spin-flip probability per $2S$ excitation is still less than 0.3% in a field of 1 T.

Figure 4 plots a typical classical trajectory of H during cooling. The simulation starts with H in $|g\rangle$ at the trap bottom ($B = 0.75$ T), with an initial longitudinal (z) and transverse (x and y) kinetic energy of $E_l = 0.5$ K and $E_t = 0.25$ K, respectively. The two-photon excitation beam overlaps with the $2S$-$3P$ beams in a 12 cm long and 1.8 cm wide cooling zone, approximately covering the trap up to the 0.2 K equipotential surface. We choose $d = 3$ cm and $\alpha = 0.1$ for the $2S$-$3P$ beams, with a peak intensity of 0.46 kW/cm^2 per beam corresponding to $\Omega_{ee'}/(2\pi) = 1.3$ GHz. $\Delta(0.75\text{ T})/(2\pi) = 5.3$ GHz is chosen so that $\Delta(B) \gg \gamma_{e'g}$ within the cooling zone. In a flatter octopole trap [1] the detuning constraint is reduced, allowing for a reduced $\Omega_{ee'}$ and less 656 nm power. The 656 nm power requirements can also be lessened with a moderate finesse optical cavity. For the UV pulses we choose $\theta = \pi/8$, $\tau = 4$ ns, and $T_{\text{rep}} = 2$ μs [27]. We choose $\delta_0 = -\pi/\tau$ to increase scattering for longitudinally hot but transversely cold atoms.

The rapid cooling trajectory shown in Fig. 4 is typical for atoms with $E_l < 0.5$ K and $E_t < 0.25$ K, which are cooled with $N_{\text{total}} = 4 \times 10^4$ pulses in just 80 ms. While some atoms with E_t larger than 0.2 K may orbit around the cooling zone and not be efficiently cooled, the final velocity distribution for most atoms is remarkably isotropic with 5 m/s width [Fig. 4(a), inset], which can be further reduced by increasing τ [Fig. 3(b)]. The total spin-flip loss is found to be less than 0.1%. As with other hydrogen cooling proposals [11–13], one must consider limitations imposed by photoionization losses. We perturbatively calculate photoionization from state populations determined by ignoring photoionization. For a two-color two-photon excitation scheme where the stronger laser beam cannot ionize H from the $2S$ state in a single step [16], we found ionization losses of less than 25% [28]. If a one-color, 243 nm scheme is used [22], photoionization loss could be less than 25% if $\theta \simeq 2.5$ mrad and $N_{\text{total}} \simeq 10^9$, requiring 2000 s.

We have proposed and analyzed a pulsed Sisyphus laser cooling scheme applicable to magnetically trapped H or $\bar{\text{H}}$. The approach features rapid 3D cooling to <10 mK in a magnetic trap over a large volume with small spin-flip and photoionization losses. Efficient 3D cooling of $\bar{\text{H}}$ would be an essential step toward precision spectroscopy of magnetically trapped $\bar{\text{H}}$ [1]. The proposed cooling method should be applicable to hydrogenlike atomic species such as deuterium or tritium, the precision spectroscopy of which is important for understanding nuclear forces.

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