Efficient two-dimensional subrecoil Raman cooling of atoms in a tripod configuration

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We present an efficient method for subrecoil cooling of neutral atoms by applying Raman cooling in two dimensions to a four-level tripod system. The atoms can be cooled simultaneously in two directions using only three laser beams. We describe the cooling process with a simple model showing that the momentum distribution can be rapidly narrowed to velocity spread down to $0.1v_{\mathrm{rec}}$, corresponding to effective temperature equal to $0.01T_{\mathrm{rec}}$. This method opens new possibilities for cooling of neutral atoms.

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I. INTRODUCTION

Cold atoms are multipurpose tools for both fundamental observations and technological innovations. Cooling and trapping of neutral atoms has led to many discoveries such as Bose-Einstein condensation [1], atom interferometry [2], atomic nanofabrication [3,4], and improved atomic clocks [5,6]. Evaporative cooling in magnetic traps is an efficient tool for reaching high densities at low temperatures [7], necessary for the observation of quantum many-body effects in dilute gases. It has been applied with success also to optically trapped gases [8], as well as to the cooling of fermionic atoms via sympathetic cooling [9]. However, for many applications it is not necessary or even desirable to reach quantum degeneracy. The external fields and atomic interactions can be harmful for ultraprecise measurements and atomic clocks, for which low temperatures coupled to low densities but large numbers of atoms are needed for a good signal-to-noise ratio and unperturbed atomic transition frequencies. Evaporative cooling is rather wasteful on atoms, and it requires also a large cross-section of elastic collisions and strongly confining traps with velocity-selective output coupling. For quantum-information purposes one has to target single atoms, and then cooling without collisional thermalization is needed. Finally, the current interest in nanomechanics has stirred renewed interest in laser cooling [10,11]. We present an efficient Raman cooling method, which allows one to reach subrecoil temperatures rapidly with purely optical means in two dimensions (2D), with a simple pulse setup. The method is applicable to all densities and even single atoms, and can be combined with sympathetic cooling if necessary.

The original Raman cooling idea was presented and verified experimentally by Kasevich and Chu in 1992 at Stanford for Na atoms in one dimension (1D) [12]. The setup consists of a three-level Λ-type atom. A Raman pulse (two contrapropagating beams) moves an atom from one state to another and at the same time gives it a velocity change of $2v_{\mathrm{rec}} = 2\hbar k/m$. The pulse duration and detunings are selected so that the two-photon Raman process is suppressed for atoms with velocity near $v = 0$. The central frequency and duration of the subsequent pulses is adjusted to target different velocity groups while still avoiding $v = 0$. As atoms are optically pumped back to the original state after each pulse, they eventually accumulate at velocities near $v = 0$. The original work was later extended to 2D and three-dimensional (3D) cooling [13], without reaching subrecoil temperatures. The 1D scheme has been used in attempts to reach high 3D phase-space densities in optical traps [14,15]. The use of a dipole trap allowed subrecoil 3D cooling by ergodicity of the motion in the inverted pyramidal trap [14] or the simple anisotropy of a 3D harmonic trap [14,17] while applying the Raman cooling only in 1D. Similar work with Cs atoms has been done at the École Normale Supérieure, Paris [16–18]. Whereas the original scheme used Blackman pulses of finite spectral width, it was actually shown with Levy flight simulations that for 2D and 3D the square pulses are quite efficient [18].

The key issue is that in the original scheme the direct Raman cooling in 2D requires four Raman beam pairs and can be quite cumbersome. The 2D scheme with square pulses was applied to Cs atoms at NIST, Gaithersburg, MD, giving temperatures down to $0.15T_{\mathrm{rec}}$ [19], where T_{rec} is the atomic recoil temperature. This is actually the only demonstrated case of reaching subrecoil temperatures with true 2D Raman cooling. We show that in the tripod system, one can go down in theory by an order of magnitude or even more, which means going down to $\frac{1}{100}T_{\mathrm{rec}}$. The scheme can also be used in transversal cooling of atomic beams, for example Ne* [20,21].

The structure of this presentation is such that we first derive the basic equations for the velocity changes induced by one cycle of Raman pulses in the 2D tripod configuration. We show that in the limit of small effective interaction between ground states one can obtain simple solutions for the equations. Then we extend the treatment to arbitrary interaction strength. Finally, we demonstrate the efficiency of the method by solving the model numerically for an appropriate initial momentum distribution, including both the Raman cycles as well as the optical pumping between them.

II. 2D RAMAN COOLING IN A TRIPOD CONFIGURATION

A. Basic equations

Consider an atomic ensemble in the region of interaction with laser configuration that consists of three running optical waves shown in Fig. 1(a). Two contrapropagating σ_+ and σ_-

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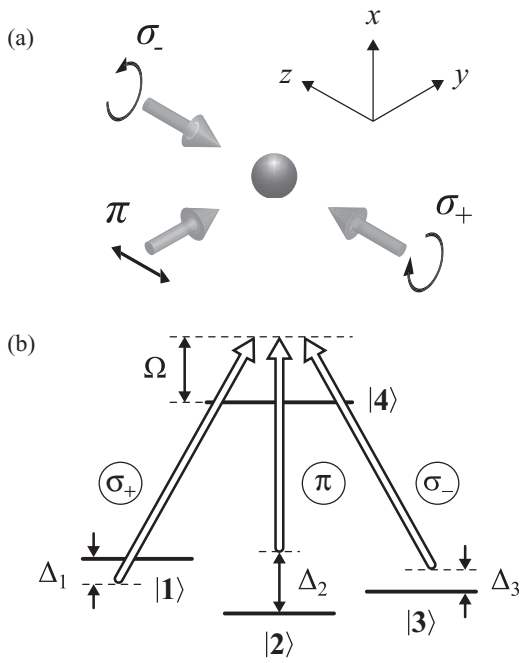

FIG. 1. (a) An atomic ensemble interacts with three running optical waves. (b) The level diagram of a four-level tripod-type atom. The σ_+ and σ_- circularly polarized contrapropagating waves couple transitions $|1\rangle \leftrightarrow |4\rangle$ and $|3\rangle \leftrightarrow |4\rangle$, respectively, and the π-polarized wave couples the $|2\rangle \leftrightarrow |4\rangle$ transition.

circularly polarized waves are directed along the z direction; a π-polarized optical wave propagates along the y direction. The positive frequency part of the electric field can be written as

$$\vec{E}^{(+)}(\vec{r},t) = \vec{E}_1 e^{-i\omega_1 t + ikz} + \vec{E}_2 e^{-i\omega_2 t + iky} + \vec{E}_3 e^{-i\omega_3 t - ikz},$$

where k is the same wave number for each optical wave. The first term corresponds to a σ_+ circularly polarized wave of frequency ω_1 and the third one corresponds to a σ_- circularly polarized wave of frequency ω_3. The second term describes a π-polarized wave of frequency ω_2.

The interaction of a four-level tripod-type atom with the laser beams is described by the Schrödinger equation

$$i\hbar\frac{\partial\Psi}{\partial t} + \frac{\hbar^2}{2M}\nabla^2\Psi = \hat{H}\Psi. \tag{1}$$

The atomic Hamiltonian and the probability function in the rotating-wave approximation (RWA) and in the resonant approximation are given by

$$\hat{H} = -\hbar\begin{pmatrix} -\Delta_1 & 0 & 0 & Ge^{-ikz} \\ 0 & -\Delta_2 & 0 & Ge^{-iky} \\ 0 & 0 & -\Delta_3 & Ge^{ikz} \\ Ge^{ikz} & Ge^{iky} & Ge^{-ikz} & \Omega \end{pmatrix}, \quad \Psi = \begin{pmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{pmatrix}, \tag{2}$$

where Ω is the detuning of driving fields from the upper state, and $\Delta_m = \omega_m - \omega_{4m} - \Omega$ $(m = 1,2,3)$ are detunings from ground states $|m\rangle$ [see Fig. 1(b)]. Without losing generality we have assumed that the Rabi frequencies $G_j = |\vec{d}_{4j}\cdot\vec{E}_j/\hbar|$ $(j = 1,2,3)$ equal a real magnitude G.

The probability amplitudes in the momentum-space approach are obtained by using the Fourier transform

$$a_m(p_z,p_y,t) = \frac{1}{2\pi}\iint_{-\infty}^{\infty} a_m(z,y,t)e^{-ik(p_z z + p_y y)}dz\,dy,$$

where p_z, p_y are projections of the atomic momentum on the axes Oz, Oy in units of $\hbar k$. For variables

$$\begin{aligned} b_1 &= a_1(p_z - 1, p_y), \quad b_2 = a_2(p_z, p_y - 1), \\ b_3 &= a_3(p_z + 1, p_y), \quad b_4 = a_4(p_z, p_y), \end{aligned} \tag{3}$$

the Schrödinger equation (1) can be written as

$$i\dot{b}_1 = \left[(p_z - 1)^2 + p_y^2 + \delta_1\right]b_1 - gb_4, \tag{4a}$$
$$i\dot{b}_2 = \left[p_z^2 + (p_y - 1)^2 + \delta_2\right]b_2 - gb_4, \tag{4b}$$
$$i\dot{b}_3 = \left[(p_z + 1)^2 + p_y^2 + \delta_3\right]b_3 - gb_4, \tag{4c}$$
$$i\dot{b}_4 = \left(p_z^2 + p_y^2 - \Delta\right)b_4 - gb_1 - gb_2 - gb_3, \tag{4d}$$

where the dimensionless time, detunings, and Rabi frequency are given by

$$\tau = \omega_R t, \quad \delta_m = \frac{\Delta_m}{\omega_R}, \quad \Delta = \frac{\Omega}{\omega_R}, \quad g = \frac{G}{\omega_R}, \tag{5}$$

and $\omega_R = \hbar k^2/2M$ is the recoil frequency.

The upper state $|4\rangle$ can be adiabatically eliminated in the case of Raman transitions between the ground states when $\Delta \gg g$. In this case, we assume that $\dot{b}_4 \approx 0$ and obtain from Eq. (4d) the expression

$$b_4 \approx -\frac{g}{\Delta}(b_1 + b_2 + b_3). \tag{6}$$

Terms p_z^2, p_y^2 were dropped here as values negligible in comparison with Δ. The substitution of Eq. (6) into Eqs. (4) leads to the equations

$$i\dot{b}_1 - \left[(p_z - 1)^2 + p_y^2 + \delta_1 + \alpha\right]b_1 = \alpha b_2 + \alpha b_3, \tag{7a}$$
$$i\dot{b}_2 - \left[p_z^2 + (p_y - 1)^2 + \delta_2 + \alpha\right]b_2 = \alpha b_1 + \alpha b_3, \tag{7b}$$
$$i\dot{b}_3 - \left[p_z + 1)^2 + p_y^2 + \delta_3 + \alpha\right]b_3 = \alpha b_1 + \alpha b_2, \tag{7c}$$

where $\alpha = g^2/\Delta$ is the Rabi frequency of the two-photon resonance.

If the atomic population is initially concentrated in state $|2\rangle$ with corresponding amplitude b_2^0, it follows from Eqs. (7) that during the interaction

$$|b_1|^2 + |b_2|^2 + |b_3|^2 = \left|b_2^0\right|^2. \tag{8}$$

To solve Eqs. (7) one can consider some special cases. These are useful for gaining insight into the parameter choices such as pulse duration that optimize the efficiency of the approach.

B. Short-time interaction

Let us consider the case of the short-time interaction when $\alpha\tau \ll 1$. In such a case, variables $b_1, b_3 \approx 0$ and therefore b_1, b_3 vanish from the right-hand side of Eqs. (7). After that, Eq. (7b) can be solved separately, and the substitution of b_2 into Eqs. (7a) and (7c) leads to the solutions

$$|b_1|^2 \approx \left|b_2^0\right|^2\alpha^2\frac{\sin^2 D_1\tau}{D_1^2}, \quad |b_3|^2 \approx \left|b_2^0\right|^2\alpha^2\frac{\sin^2 D_2\tau}{D_2^2}, \tag{9}$$

where the denominators are

$$D_1 = \tfrac{1}{2}(\delta_1 - \delta_2) - p_z + p_y, \quad D_2 = \tfrac{1}{2}(\delta_3 - \delta_2) + p_z + p_y. \tag{10}$$

By substituting Eq. (9) into Eq. (8), we get

$$|b_2|^2 \approx \left|b_2^0\right|^2 \left(1 - \alpha^2 \frac{\sin^2 D_1\tau}{D_1^2} - \alpha^2 \frac{\sin^2 D_2\tau}{D_2^2}\right). \tag{11}$$

Then the atomic populations in ground states, using Eqs. (3), (9), and (11), can be written as

$$|a_1(p_z,p_y)|^2 \approx \left|a_2^0(p_z{+}1,p_y{-}1)\right|^2 \alpha^2 \frac{\sin^2(D_1-1)\tau}{(D_1-1)^2}, \tag{12}$$

$$|a_2(p_z,p_y)|^2 \approx \left|a_2^0(p_z,p_y)\right|^2 \left(1 - \alpha^2 \frac{\sin^2(D_1+1)\tau}{(D_1+1)^2} - \alpha^2 \frac{\sin^2(D_2+1)\tau}{(D_2+1)^2}\right), \tag{13}$$

$$|a_3(p_z,p_y)|^2 \approx \left|a_2^0(p_z{-}1,p_y{-}1)\right|^2 \alpha^2 \frac{\sin^2(D_2-1)\tau}{(D_2-1)^2}. \tag{14}$$

Let us consider atoms originally prepared in state $|2\rangle$ after they interact with a pulse of Raman beams. Corresponding approximate forms of the populations in the momentum-space approach are given by Eqs. (12)–(14). The population transferred to state $|1\rangle$ through Raman transition $|2\rangle \leftrightarrow |1\rangle$ is shown in Fig. 2(a), while the population transferred to state $|3\rangle$ through Raman transition $|2\rangle \leftrightarrow |3\rangle$ is shown in Fig. 2(c). The removed population of state $|2\rangle$ represents a cross as shown in Fig. 2(b). The width of the cross is defined by the pulse duration τ. As seen from Eqs. (10) and (13), the largest excitation probability is reached when

$$\tfrac{1}{2}(\delta_1 - \delta_2) - p_z + p_y + 1 = 0 \quad \text{or}$$
$$\tfrac{1}{2}(\delta_3 - \delta_2) + p_z + p_y + 1 = 0.$$

The position of the cross can be changed by adjusting the detunings from the ground states, allowing one to excite atoms with any two projections of the atomic momentum. The excitation of atoms through two Raman transitions at once essentially increases the efficiency of cooling in a tripod configuration. Note that for Fig. 2, we have used $\alpha\tau = 1$; but the short-interaction limit gives a good account of the basic aspects of the process, because the relevant equations are modified only slightly for increasing $\alpha\tau$ (see Sec. II C).

Similar to 1D Raman cooling, an elementary cycle of 2D Raman cooling consists of two steps. In the first step, atoms prepared in state $|2\rangle$ are selectively transferred by a pulse of Raman beams. In order to suppress the Raman transfer of atoms with the momentum projection $p_z, p_y = 0$, we can choose the pulse duration

$$\tau = \frac{2\pi}{\delta + 2}, \tag{15}$$

where $\delta_1 - \delta_2 = \delta_3 - \delta_2 = \delta$. In the second step, atoms return to state $|2\rangle$ via optical pumping. The π-polarized laser is switched off, and the σ_+, σ_- lasers are tuned into resonance with transitions $|1\rangle \leftrightarrow |4\rangle$ and $|3\rangle \leftrightarrow |4\rangle$, respectively. An atom is excited to state $|4\rangle$ with a gain of momentum along the z direction, so $p_z' = p_z \pm 1$. Then the atom returns to state $|2\rangle$, emitting a photon with momentum $\Delta\vec{p}$ where $|\Delta\vec{p}| = 1$. Because of momentum conservation, the atomic momentum

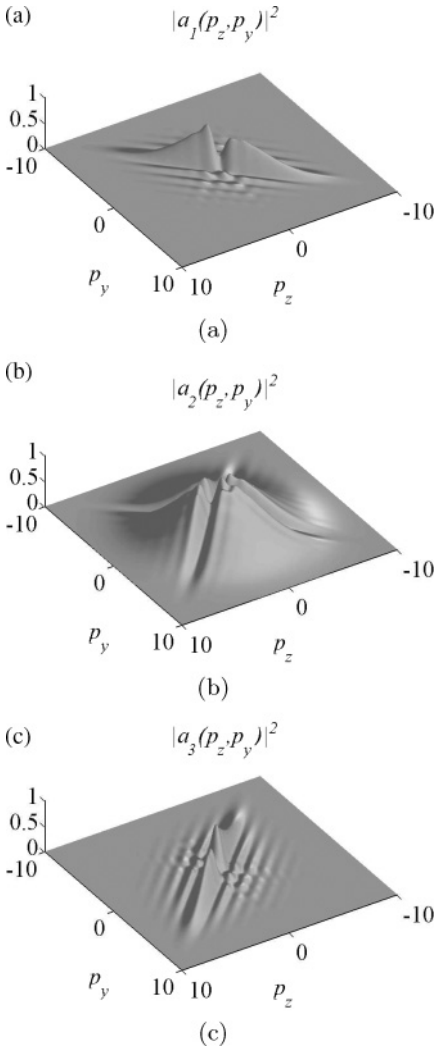

FIG. 2. The momentum distribution of atoms originally prepared in state $|2\rangle$ after they interact with a pulse of Raman beams. (a), (c) The population transferred to states $|1\rangle$, $|3\rangle$ through Raman transitions $|2\rangle \leftrightarrow |1\rangle$ and $|2\rangle \leftrightarrow |3\rangle$, respectively; (b) cross appearing in state $|2\rangle$ due to these transfers. The duration of Raman pulse is $\tau = 2$, the Rabi frequency of two-photon resonance is $\alpha = 0.5$. The detunings from ground states are $\delta_m = 0$ ($m = 1,2,3$).

changes by $-\Delta\vec{p}$. So, the atomic population in state $|2\rangle$ becomes

$$|a_2'(p_z,p_y)|^2 = |a_2(p_z,p_y)|^2 + |a_1(p_z{-}1{+}\Delta p_z, p_y{+}\Delta p_y)|^2 + |a_3(p_z{+}1{+}\Delta p_z', p_y{+}\Delta p_y')|^2.$$

Different momentum groups can be excited from state $|2\rangle$ by adjusting the duration τ and the difference of detunings δ, consistent with (15). The set of detunings δ used by us is

$$\delta = 2^k - 2, \quad k = 0,1,\ldots,5. \tag{16}$$

The position of the cross for large τ is situated in immediate proximity to zero projections, which results in only very cold atoms being left in state $|2\rangle$.

C. Arbitrary Rabi frequency solution

To simplify the task, we assume that $\delta_1 = \delta_3 = \delta_2 + \delta$, and consider only the atoms of momentum projection $p_z = 0$. These atoms are characterized by the coherence between states $|1\rangle$ and $|3\rangle$, which in turn is derived from the difference of Eqs. (7a) and (7c), that is,

$$i\frac{d}{d\tau}(b_1 - b_3) - \left(1 + p_y^2 + \delta_1\right)(b_1 - b_3) = 0. \tag{17}$$

Before the Raman pulse starts, the atoms are contained in state $|2\rangle$. Hence $b_1^0, b_3^0 = 0$, and one obtains from Eq. (17) that

$$b_1 = b_3. \tag{18}$$

After the substitution of Eq. (18), Eqs. (7) are reduced to a system of two equations:

$$i\dot{b}_1 = \left(1 + p_y^2 + \delta_1 + 2\alpha\right)b_1 + \alpha b_2, \tag{19}$$

$$i\dot{b}_2 = [(p_y - 1)^2 + \delta_2 + \alpha]b_2 + 2\alpha b_1. \tag{20}$$

Then the interaction with Raman beams is described by the effective Hamiltonian and probability function

$$\hat{H}_{\text{eff}} = -\hbar \begin{pmatrix} 0 & \alpha_{\text{eff}} \\ \alpha_{\text{eff}} & \delta_{\text{eff}} \end{pmatrix}, \quad \Psi_{\text{eff}} = \begin{pmatrix} -\sqrt{2}b_1 \\ b_2 \end{pmatrix} e^{i(1+p_y^2+\delta_1+2\alpha)\tau}, \tag{21}$$

where $\delta_{\text{eff}} = \delta + 2p_y + \alpha$ and $\alpha_{\text{eff}} = \sqrt{2}\alpha$.

The Hamiltonian (21) in the dressed-state picture is presented by the eigenstates of the probability amplitudes

$$\psi_+ = \psi_1 \cos\phi - \psi_2 \sin\phi, \quad \psi_- = \psi_1 \sin\phi + \psi_2 \cos\phi, \tag{22}$$

$$\tan\phi = \frac{\sqrt{4\alpha_{\text{eff}}^2 + \delta_{\text{eff}}^2} - \delta_{\text{eff}}}{2\alpha_{\text{eff}}},$$

with the corresponding eigenfrequencies

$$\omega_\pm = -\frac{\delta_{\text{eff}}}{2} \pm \frac{1}{2}\sqrt{4\alpha_{\text{eff}}^2 + \delta_{\text{eff}}^2},$$

where ψ_1, ψ_2 are the probability amplitudes of states in presentation (21). Expression (22) gives original $\psi_\pm$ after the substitution of $\psi_1^0 = 0$, $\psi_2^0 = b_2^0$, i.e., the probability amplitudes are written as

$$\psi_+ = -b_2^0 \sin\phi\, e^{-i\omega_+\tau}, \quad \psi_- = b_2^0 \cos\phi\, e^{-i\omega_-\tau}. \tag{23}$$

By inverting Eq. (22) we get

$$\psi_1 = \psi_+ \cos\phi + \psi_- \sin\phi, \quad \psi_2 = -\psi_+ \sin\phi + \psi_- \cos\phi,$$

which gives via Eq. (23) the probability amplitudes

$$\psi_1 = \frac{b_2^0}{2} \sin 2\phi (e^{-i\omega_-\tau} - e^{-i\omega_+\tau}),$$

$$\psi_2 = b_2^0(\sin^2\phi\, e^{-i\omega_+\tau} + \cos^2\phi\, e^{-i\omega_-\tau}).$$

Thus the populations in states $|1\rangle$, $|2\rangle$, consistent with Eqs. (3), are given by

$$|a_1(-1, p_y{+}1)|^2 = \left|a_2^0(0, p_y)\right|^2 \frac{\alpha^2}{D_{\text{eff}}^2} \sin^2 D_{\text{eff}}\tau,$$

$$|a_2(0, p_y)|^2 = \left|a_2^0(0, p_y)\right|^2 \left(1 - \frac{2\alpha^2}{D_{\text{eff}}^2} \sin^2 D_{\text{eff}}\tau\right),$$

where $2D_{\text{eff}} = \sqrt{(\delta + 2p_y + 2 + \alpha)^2 + 8\alpha^2}$. Atoms in the zero velocity group remain in state $|2\rangle$ for the pulse duration

$$\tau = \frac{2\pi}{\sqrt{(\delta + 2 + \alpha)^2 + 8\alpha^2}}, \tag{24}$$

which corresponds to $|a_2(0,0)|^2 = |a_2^0(0,0)|^2$. One can easily see that in the limit of small α this result agrees with Eq. (15).

D. Full cooling process

Full Raman cooling consists of varying Raman pulses, decreasing the detuning δ as in set (16). After every six elementary cycles, the direction of the π-polarized beam is alternated, so the next cycles excite another side of the velocity distribution. During cooling process, atoms are piled up in a narrow peak near zero momentum. As the number of Raman cycles increases, the number of atoms in the peak increases, so the momentum distribution becomes narrower, and the temperature of atoms decreases. The efficiency of growth increases as the Rabi frequency α of two-photon resonance increases. Numerical calculations show that deep Raman cooling is only achieved in the case of quite large $\alpha\tau$. Figure 3 shows the result after applying 420 elementary cycles of 2D Raman cooling with $\alpha = 1$. The velocity spread of atoms is defined as $\sigma = (\text{FWHM})/\sqrt{8\ln 2}$ in units of the recoil velocity v_{rec}. It has been reduced from $3v_{\text{rec}}$ to $0.1v_{\text{rec}}$, corresponding to effective temperature $T_{\text{eff}} = 0.01T_{\text{rec}}$.

Consider the 2D Raman cooling under conditions of experiment [20] where the same atomic and field configurations were realized in a metastable Ne beam. The σ_+- and σ_--polarized waves were provided by lasers with $\lambda_{\text{Pump}} = 588$ nm, while laser with $\lambda_{\text{Stokes}} = 617$ nm generated the π-polarized wave. Hence the final effective temperature of cooled atoms is given by

$$T_{\text{eff}} \approx 0.01\frac{\hbar^2}{2k_B M}\left(k_{\text{Pump}}^2 + k_{\text{Stokes}}^2\right) = 26\,\text{nK},$$

where k_B is the Boltzmann constant, and M is the Ne atomic mass. The duration of only Raman pulses in our scheme is

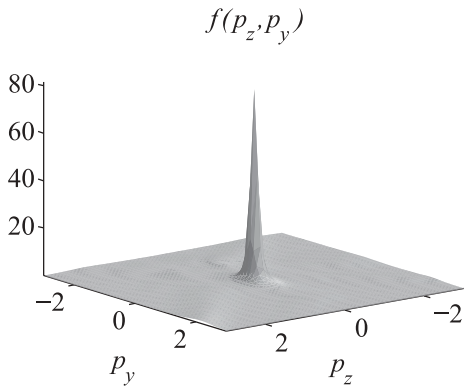

FIG. 3. Momentum distribution of atoms after applying 420 elementary cycles of 2D Raman cooling. Atoms have been piled up in a narrow peak near zero momentum with effective temperature equal to $0.01T_{\text{rec}}$. The height of the peak is about 80 times larger than that of the original distribution, the width (full width at half maximum, FWHM) is about 0.24 in units of $\hbar k$.

about 400 ω_R^{-1}, where ω_R^{-1} for metastable Ne equals 6 μs. Full Raman cooling in turn takes a few milliseconds. The number $N_{\rm decay}$ of atoms spontaneously decaying from the upper state to a ground state during a Raman pulse is given by

$$\dot{N}_{\rm decay} = \gamma N_4, \quad N_{\rm decay} \approx \frac{\gamma\tau}{\omega_R} N \frac{g^2}{\Delta^2} = N \frac{\gamma}{\omega_R \Delta} \alpha\tau,$$

where N is the number of atoms, γ is the decay rate; the number $N_4 \approx N g^2/\Delta^2$ of atoms in the upper state is obtained from Eq. (6). Decay from the upper state can be neglected when $N_{\rm decay} \ll N_{1,3}$. Using Eqs. (12) and (14), one gets the inequality

$$N_{\rm decay} \ll N(\alpha\tau)^2, \tag{25}$$

which can be written in two alternative forms:

$$\alpha\tau \gg \frac{\gamma}{\omega_R \Delta}, \qquad \frac{G^2}{\gamma^2} \gg \frac{\omega_R}{\gamma}, \tag{26}$$

where in the latter form it was assumed that $\tau \sim 1$ and $\alpha = G^2/\omega_R^2 \Delta$ [see Eq. (5)]. Thus by increasing either the detuning related to the upper state or the pulse intensities, we can avoid the effects of spontaneous emission during the Raman pulses.

III. CONCLUSIONS

We have demonstrated that one can obtain very narrow velocity distributions ($\sigma \lesssim 0.1 v_{\rm rec}$) simultaneously in two directions with our straightforward scheme. The tripod approach presented here sets a further restriction on the available atomic structure, but this is not necessarily a major problem. Appropriate optically coupled $J = 1$ and $J = 0$ states are available, e.g., in Rb and Ne*. In addition to 3D cooling by thermalization, the approach can be used to cool atoms in a 1D optical lattice, where the sample is "sliced" into 2D pancake-like structures. This approach is used for investigating optical frequency standards with alkaline-earth-metal atoms [6]. The simplicity of our approach, coupled with the expected efficiency, opens new possibilities for all-optical studies of ultracold atoms.

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