A simple and efficient all-optical production of spinor condensates

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We present a simple and optimal experimental scheme for an all-optical production of a sodium spinor Bose-Einstein condensate (BEC). With this scheme, we demonstrate that the number of atoms in a pure BEC can be greatly boosted by a factor of 5 in a simple setup that includes a single-beam optical trap or a crossed optical trap. This optimal scheme avoids technical challenges associated with some all-optical BEC methods, and can be applied to other optically trappable atomic species. In addition, we find a good agreement between our theoretical model and data. The upper limit for the efficiency of evaporative cooling in all-optical BEC approaches is also discussed.

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In the last two decades, many techniques have been developed to reliably generate a BEC of more than $10^4$ atoms. Almost every one of these techniques requires evaporative cooling in a trapping potential, including a magnetic trap, an optical dipole trap (ODT), or a combined magnetic and optical potential [1–5]. Among these techniques, all-optical methods have been proven to be versatile and popularly applied in producing quantum degenerate gases of both bosonic [6–14] and fermionic [15] species. ODTs have tight confinement which allows for fast evaporation with a duty cycle of a few seconds [6]. Unlike magnetic potentials that only trap atoms in the weak-field seeking spin state, an ODT can confine all spin components. This is crucial for creating vector (spinor) BECs with a spin degree of freedom [16]. ODTs can also be applied to a wider variety of atomic species (e.g., Ytterbium, alkaline earth metals, and Cesium) which cannot be feasibly condensed in a magnetic trap [8, 13]. In addition, optical trapping does not require magnetic coils around trapped atoms, which not only provides better optical access but also yields less residual magnetic fields.

The simplicity and versatility of ODTs widens the accessibility of BEC research on many-body physics, precision measurements, and quantum information science [15].

Forced evaporation in an ODT can be performed by simply reducing its trap depth $U$ (e.g., lowering the trapping laser power). In this process, collision rates decrease with $U$, which leads to slow rethermalization and eventually stagnation in evaporative cooling. Several methods have been reported to overcome this difficulty, including tilting an ODT with a magnetic field gradient [17], using a misaligned crossed ODT [12, 14], compressing an ODT with a mobile lens [11], or applying multiple ODTs for staged evaporation [8, 10]. In this paper, however, we show that these methods may not be necessary. Good agreements between our model and experimental data enable us to develop an optimal ODT ramp and evaporation sequence for an all-optical production of sodium BECs. With this sequence, we find that the number of atoms in a pure BEC is greatly boosted and evaporative cooling efficiency $\gamma = -d(\ln D)/d(\ln N)$ can be 3.5 in a simple setup that includes a single-beam ODT or a crossed ODT. Here $D$ is the phase space density and $N$ is the atom number. We also show an upper limit for $\gamma$ at a given truncation parameter $\eta = U/k_B T$, and demonstrate that a constant $\eta$ does not yield more efficient evaporative cooling. Here $T$ is the atom temperature and $k_B$ is the Boltzmann constant. This optimal experimental scheme allows us to avoid technical challenges associated with some all-optical BEC approaches.

Figure 1(a) shows a schematic of our apparatus, which
is divided via differential pumping tubes and gate valves into an atomic oven chamber, an intermediate chamber, and a main chamber where a magneto-optical trap (MOT) is located. The intermediate chamber allows us to refill alkali metals and get ultra-high vacuum (UHV) pressures back to the $10^{-12}$ Torr range within 24 hours. A typical experimental sequence of our all-optical BEC approach is shown in Fig. 2. Hot atoms are slowed down by a spin-flip Zeeman slower as elaborated in Ref. [14]. The slowed atoms are collected in a standard MOT which is constructed with six cooling beams and a pair of 24-turn anti-Helmholtz coils. Each MOT cooling beam is detuned by $\delta = -20$ MHz from the cycling transition, has a power of 6 mW, and combines with one 3.5 mW MOT repumping beam in a single-mode fiber. After 8.5 s of MOT loading, a three-step polarization gradient cooling process efficiently cools $3 \times 10^8$ atoms into an atomic oven chamber, an intermediate chamber which is divided via differential pumping tubes and gate valves, and have a 1/$e^2$ waist of 33 $\mu$m at their intersection point, as shown in Fig. (1a). A single-mode polarization-maintaining fiber is used to polish the beam mode, and to minimize pointing fluctuations due to imperfections of the IR laser and thermal contractions of an acoustic-optical modulator. As a result, atoms which are transferred from the MOT into the tightly-focused crossed ODT demonstrate a long lifetime of 8 s and a large collision rate. These are essential for all-optical BEC approaches.

A crossed ODT consists of two far-detuned beams which originate from an infrared (IR) laser at 1064 nm and have a 1/$e^2$ waist of 33 $\mu$m at their intersection point. After 8.5 s of MOT loading, a three-step polarization gradient cooling process efficiently cools $3 \times 10^8$ atoms to 40 $\mu$K. To depump atoms into the F=1 hyperfine states, the repumping beams are extinguished 1 ms before cooling beams and MOT coils are turned off.

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We compare the efficiency of transferring laser-cooled atoms to the crossed ODT, when different experimental sequences are applied to ramp up the ODT’s trap depth. Our data in Fig. 2 clearly shows that an optimal ODT ramp sequence can increase the number of atoms loaded into the crossed ODT by a factor of 2.5. This optimal ramp sequence is the best scenario of our first ODT ramp sequence. As shown in Fig. (1b), the ODT in the first ODT ramp sequence is kept at a small trap depth $U_0$ during the entire laser cooling process and then linearly ramped to $U_{\text{max}}$ in $t_{\text{ramp}} = 5$ ms. $U_{\text{max}} \approx k_B \times 800 \mu$K is the maximal trap depth used in this work and $0 \leq U_0 \leq U_{\text{max}}$. This optimal ramp sequence is a trade-off between two competing effects induced by the enormous ODT potential. If the ODT beams do not interact with the MOT, a larger $U$ enables more atoms to be transferred to the ODT. The number of atoms loaded in the ODT is $N_{\text{ramp}} \approx \int_0^{U_0} \rho(e) f(e) de$, where $\rho(e)$ and $f(e)$ are the density of states and occupation number at energy $e$, respectively. This is confirmed by our data (closed blue triangles in Fig. 2) taken with the second ODT ramp sequence, in which the ODT is linearly ramped in 5 ms from 0 to $U_0$ immediately after MOT beams are switched off. On the other hand, if intense ODT beams and MOT beams are turned on simultaneously, atoms experience non-negligible AC Stark shifts in regions where the ODT beams and the MOT overlap. As a result, the MOT’s cooling capability is impaired in the MOT and ODT overlapping regions, and the number of atoms loaded into the ODT decreases when the ODT becomes too deep. $N$ is thus not a monotonic function of $U$, which is the case for our first ODT ramp sequence. The number of atoms loaded into the ODT in the first ramp sequence may be expressed as $N_{\text{ramp}} \sim A \xi_{\text{AC}}(U_0) \int_0^{U_0} \rho(e) f(e) de + \int_{U_0}^{U_{\text{max}}} \rho(e) f(e) de$, where $\xi_{\text{AC}}(U_0) = \exp(-\delta_{\text{AC}}(U_0)^2/\omega_0^2)$ is a correction factor due to the induced AC Stark shift $\delta_{\text{AC}}(U_0)$, while $A$ and $\omega_0$ are fitting parameters. Our data (closed red circles in Fig. 2) collected with the first ODT ramp sequence can be well fit by this model. The fit value of $\omega_0$ is 1.2$\pi$, where $\Gamma/2\pi = 9.7$ MHz is the natural linewidth of sodium. The number of atoms in the ODT reaches its peak when the optimal ramp sequence with $U_0 \approx U_{\text{max}}/2$ is applied. Compared to the second ODT ramp sequence, the optimal ramp sequence allows us to use ODT beams with smaller waists while loading the same amount of laser-cooled atoms to the ODT. The resulted high initial atomic density and high collision rates from the optimal ramp sequence enable very efficient evaporative cooling. This greatly boosts the number of atoms in a BEC by a factor of 5 and a good evaporation efficiency $\gamma = 3.5$ is achieved, as shown in the inset of Fig. 2.

To optimize $\gamma$, it is necessary to understand the time evolution of the system energy $E$ and the atom number $N$ during an evaporation process. Similar to Ref. [14, 21, 22, 23], we use $\kappa k_B T = (\eta - 5)/(\eta - 4) k_B T$ to represent the average kinetic energy taken by an atom when it is removed from the ODT, and assume the mean kinetic energy and mean potential energy to be $E/2$ when $\eta$ is
From solving the above equations, \( k \) where \( \tau \) than 1 s. Inset: \( \gamma_{\text{best}} \) as a function of \( \eta \) extracted from the main figure. The solid line sets an upper limit for \( \gamma \) based on Eq. (1) by assuming \( k_i = k_s = 0 \) (see text).

large. The time evolution of \( E \) and \( N \) is thus given by,

\[
\dot{E} = -\frac{2(\eta - 4)e^{-\eta}N}{\tau_2}(U + k_{\text{in}}T) + \frac{\dot{U}E}{U^2} + \dot{E}_{\text{loss}} ,
\]

\[
\dot{N} = -\frac{2(\eta - 4)e^{-\eta}N}{\tau_2} + \dot{N}_{\text{loss}} ,
\]

where \( \tau_2 \) is the time constant of the two-body elastic collision. In Eq. (1) \( \dot{E}_{\text{loss}} \) and \( \dot{N}_{\text{loss}} \) are due to various inelastic loss mechanisms and may be expressed as,

\[
\dot{E}_{\text{loss}} = k_2N - k_1N(3k_{\text{in}}T - k_3n^2N(2k_3T) ,
\]

\[
\dot{N}_{\text{loss}} = -k_1N - k_3n^2N ,
\]

where \( k_1 \) and \( k_3 \) are one-body and three-body loss rates, respectively. \( k_{\text{in}} \) represents heating introduced by ODT beams via a number of different mechanisms, such as pointing fluctuations of the ODT beams, bad laser beam mode, and spontaneous light scattering. The term \( 2k_3T \) in Eq. (2) accounts for the fact that atoms in the ODT’s center have higher density and thus are more affected by the three-body inelastic loss [12].

In our apparatus with the UHV pressure in the 10^{-12} Torr range, background collisions are negligible. Since the ODT beams are delivered via a single-mode polarization maintaining fiber, heating induced by the ODT beams is minimized. \( k_1 \) and \( k_3 \) are thus very small. If we ignore \( k_1 \) and \( k_3 \), Eq. (1) can be simplified to

\[
\dot{E} = \dot{N}_{\text{eff}}k_2T + \frac{\dot{U}E}{U^2} ,
\]

where \( \eta_{\text{eff}} = \eta + \kappa - R(\eta + \kappa - 2) \). We define \( R = \dot{N}_{\text{loss}}/\dot{N} = 1/(1 + 2(\eta - 4)e^{-\eta}R_{e\text{Tb}}) \) to represent the portion of atom losses due to inelastic collisions, where \( R_{e\text{Tb}} \) is the ratio of inelastic collision time constant to \( \tau_2 \). From solving the above equations, \( \gamma \) may be expressed as,

\[
\gamma = \eta_{\text{eff}} - 4 = \eta + \kappa - R(\eta + \kappa - 2) - 4 ,
\]

The value of \( \eta \) in many publications on optical production of BECs was held constant with \( \Delta \eta = 0 \) [6, 7, 11, 12, 14, 15, 17]. Our data in Fig. 3 however, shows that a constant \( \eta \) does not lead to better evaporation or a larger \( \gamma \). The values of \( \gamma \) in this figure are extracted from 36 evaporation processes in which the forced evaporation speed and the hold time at \( U_{\text{max}} \) are changed independently, although they all start with the same initial number of cold atoms in the crossed ODT. \( \Delta \eta = \eta_{\text{eff}} - \eta \) is the change of \( \eta \) during forced evaporation, where \( \eta_{\text{eff}} \) and \( \eta \) are the values of \( \eta \) at \( U_{\text{max}} \) (i.e., the beginning of forced evaporation), and at \( U_{\text{f}} \), respectively. In order to avoid overestimating \( \gamma \) due to the Bose enhancement near the BEC transition temperature, we choose \( U_{\text{f}} = k_3 \times 30 \mu K \) where no BEC appears. We find that \( \Delta \eta \) tends to be a non-negative value when the forced evaporation time is longer than 1 s (closed black squares in Fig. 3), which is a good indication of sufficient rethermalization. We also find that \( \gamma \) is too small to yield a BEC when \( \Delta \eta < -2.5 \).

We compare the evaporation efficiency at different values of \( \eta_{\text{f}} \), as shown in the inset of Fig. 3 \( \gamma_{\text{best}} \) (the best achieved value of \( \gamma \) at a given \( \eta_{\text{f}} \) in our system) does not show a strong dependence on \( \eta_{\text{f}} \) if \( 8 < \eta_{\text{f}} < 10 \), while \( \gamma_{\text{best}} \) sharply diminishes when \( \eta_{\text{f}} \) becomes too large or too small. In the inset of Fig. 3 the similar relationship between \( \gamma \) and \( \eta_{\text{f}} \) is also predicted by the solid (blue) line, which is a result based on Eq. (1) by ignoring \( k_1 \) and \( k_3 \) and by applying a non-zero \( \eta_{\text{best}} \) (i.e., \( R_{e\text{Tb}} = 4000 \) [3]). All of our data lie below the solid line in this figure, which may indicate that \( k_1 \) and \( k_3 \) are larger than 0 and cannot be ignored. Therefore, based on Fig. 3 we need to choose a value between 8 and 10 for \( \eta_{\text{f}} \) and keep \( \Delta \eta \) larger than -0.5 in order to optimize evaporation efficiency \( \gamma \).

The maximum achievable value for \( \eta_{\text{f}} \) appears to be 10.8, as shown in the inset of Fig. 3. To understand this, we monitor the time evolution of \( \eta \) and find that \( \eta \) has a maximal value (\( \eta_{\text{max}} \)) at a given ODT depth \( U \). The value of \( \eta_{\text{max}} \) decreases exponentially with \( U \) and \( \eta_{\text{max}} \) at
$U_{\text{max}}$ is 10.8, which agrees well with our theoretical prediction (solid red line in Fig. 4). Therefore, if one wishes to keep $\eta$ unchanged during forced evaporation, $\eta$ must be limited to 10.8 even though $\eta_{\text{max}}$ can be much higher at low ODT depths (e.g., $\eta_{\text{max}} > 13$ for $U/k_B < 100 \, \mu K$). This may be one reason why a constant $\eta$ does not yield more efficient evaporative cooling. We also find that the time evolution of $\eta$ at every $U$ discussed in this paper can be well fit with our model. Two typical fitting curves are shown in the inset of Fig. 4.

A pure F=1 BEC of $1.2 \times 10^5$ sodium atoms at 50 nK is created from a 0.45 s free evaporation at $U_{\text{max}}$ followed by a 5 s forced evaporation in which $U$ is exponentially reduced. This evaporation curve provides two important parameters for efficient evaporative cooling: $\eta_i$ is between 8 and 10, and the forced evaporation time is long enough for sufficient rethermalization but short enough to avoid excessive atom losses. Three time-of-flight absorption images in Fig. 5(a) show a typical change of the condensate fraction (CF) after interrupting the evaporation curve at various $U$. When an external magnetic field gradient is applied, three spin components in a F=1 BEC spatially separate, as shown in Fig. 5(b). We also apply the above all-optical approach to evaporate atoms in a single-beam ODT. A similar result can also be achieved in the single-beam ODT as long as its 1/$e^2$ beam waist is smaller than 16 $\mu m$ to provide a high enough collision rate.

In conclusion, we have presented an optimal experimental scheme for an all-optical production of sodium spinor BECs. With this scheme, the number of atoms in a pure BEC is greatly boosted by a factor of 5 and $\gamma = 3.5$ is achieved in a simple setup that includes a single-beam ODT or a crossed ODT. We have showed an upper limit for $\gamma$ at a given $\eta$, demonstrated that a constant $\eta$ could not yield a larger $\gamma$, and discussed good agreements between our model and experimental data. This optimal scheme avoids technical challenges associated with some all-optical BEC approaches, and can be applied to other optically trappable atomic species and molecules [24].

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The first polarization gradient cooling step compresses the MOT for 20 ms by increasing the power of each cooling beam to 12 mW while changing $\delta$ to $-15$ MHz. In this step, the power of each MOT repumping beam is also drastically reduced to 45 $\mu$W. Then during a 5 ms pre-molasses step, every cooling beam is further red detuned in addition to its power being increased to 16 mW. This is followed by a 18 ms optical molasses, in which a cooling beam is detuned to $\delta = -45$ MHz and its power linearly drops to 8 mW. The magnetic field gradient is also reduced to 3 G/cm over the 18 ms.