Quantum interference-enhanced deep sub-Doppler cooling of $^{39}$K atoms beyond gray molasses

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Abstract

We report enhanced sub-Doppler cooling of the bosonic atoms of $^{39}$K facilitated by formation of dark states due to the quantum interference of excitation amplitudes in the Raman configuration for the cooling and repumping lasers tuned around the D1 resonance. The temperature of about 12 $\mu$K achieved in the two stage D2-D1 molasses is the lowest ever reported for $^{39}$K and spans a very large parameter region where quantum interference persists robustly. We also present results on enhanced radiation heating with sub-natural linewidth ($0.1\Gamma$) and Fano like profile, following the quantum features of 3-level coherently driven atomic system with complexities associated with optical pumping to dark states and Sisyphus effect in standing wave light fields, over and above the Raman quantum interference.

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I. INTRODUCTION

Potassium and Lithium are important alkali group atoms for a variety of experiments employing cold atoms due to the existence of both fermionic and bosonic isotopes. However, laser cooling of their bosonic isotopes to the sub-Doppler temperatures is difficult due to the closely spaced hyperfine levels in the cooling transitions. Further, their evaporative cooling to degeneracy is complicated because of their unfavorable scattering properties. The latter issue is usually solved with either sympathetic cooling with other atoms like Rubidium \[1, 2\] or using Feshbach resonances tuned with a magnetic field, in an optical trap \[3\]. To attain sub Doppler temperatures in \(^{39}\)K, multi-stage molasses cooling strategies with relatively large laser power and large detuning in the first stage have to be implemented, and yet, the lowest temperatures are almost 100 times larger than the recoil limit, compared to a factor of 10 in case of Rubidium. \(^{39}\)K has been cooled to temperatures as low as 30-40\(\mu\)K using D2 line molasses cooling \[4–6\].

Gray molasses aided by optically pumped dark state formation with lasers tuned above the D1 line (blue detuning) of alkali atoms have been shown to result in ultra-low sub-Doppler temperatures \[7, 8\]. Very recently, enhanced cooling due to quantum interference effects and coherent dark state formation in such Raman configuration involving two driving light modes and a 3-level atom have been reported in laser cooling of \(^{40}\)K \[9\] and \(^{7}\)Li \[10\]. We have been working on gray molasses with lasers tuned near the D1 line on the \(^{39}\)K atoms that are precooled in a D2 conventional molasses (see Figure 1) and observed that apart from optically pumped dark states aiding the sub-Doppler cooling by a factor 2-3, quantum interference and coherent dark state formation helps to achieve sub-Doppler temperatures a further factor 3 lower over a very wide tuning range both above and below the D1 line, and even on the D1 resonance (See Figure 1).

While the exact Raman configuration always leads to enhanced cooling, there are regions of relative detuning of the cooling and repumping lasers where strong heating of the atomic cloud is observed which directly translates to an asymmetric Fano like profile with sub-natural linewidth indicating coherence properties of the quantum superposition of the absorbing dressed state. The high reproducibility of the cooling and heating features and the vast parameter region over which the effects persists provides a new test system for the study of interplay between sub-Doppler laser cooling and quantum interference effects.
FIG. 1: D1 line of $^{39}\text{K}$. $\delta_c, \delta_r$ are the cooling ($F = 2 \rightarrow F' = 2$) and repump ($F = 1 \rightarrow F' = 2$) detunings $\delta = \delta_r - \delta_c$ is the relative detuning between the cooling and repump beams, $\Delta$ is the absolute detuning in Raman Condition ($\Delta = \delta_r = \delta_c$).

like CPT, EIT and dressed states of the 3-level atom. In particular, the complexity can be tuned because the multiple physical effects – optical pumping and dark state formation, periodic Stark shifts in standing light fields and Sisyphus effect, and coherent effects involving dressed states from the quantum superposition of the two long lived and one dissipative excited state – depend on the intensity, phase and polarization of the laser beams, and on detuning between the lasers and detuning from the atomic transitions.

In the rest of the paper, we report the main results and their analysis, especially the ultra-low temperatures achieved in the molasses and the Fano-like profiles with sub-natural linewidth in radiation heating. A more detailed report of the studies will be presented later elsewhere.

II. EXPERIMENT AND RESULTS

The MOT is formed using 767nm laser tuned below the D2 transition of $^{39}\text{K}$ atoms. Details of our experimental set up are described in [5]. The cooling and repump beams are derived from the same laser using AOMs and then mixed and amplified in a tapered amplifier. To capture the atoms into the MOT efficiently, the cooling beam is kept detuned by -24 MHz from $F = 2 \rightarrow F' = 3$ transition and the repump laser is detuned by -14 MHz from $F = 1 \rightarrow F' = 0$. We capture about $1 \times 10^8$ atoms in the MOT at a temperature of about 1 mK. The atoms are then put through a compressed-MOT (C-MOT) stage during
which the magnetic field is ramped up and the cooling laser detuning is increased to -42 MHz. At the end of this stage the density of the trapped atoms is enhanced but the atoms are heated to temperatures >5 mK. Precooling of these atoms in a D2 sub-Doppler phase reduces their temperature to 40 μK [3]. The D2 molasses cooling lasts for about 4ms and during this phase the detuning of the cooling is reduced to -10 MHz and that of the repump to -11 MHz. Another laser (Toptica DLPro) tuned to 770.1 nm is used for addressing the D1 transition. The ‘cooling laser’ for the D1 Λ-molasses is near \( F = 2 \rightarrow F' = 2 \) transition with detuning \( \delta_c \) and the ‘repump’ is near \( F = 1 \rightarrow F' = 2 \) transition with detuning \( \delta_r \). These are derived from the same beam using AOMs and the relative detuning \( \delta = \delta_r - \delta_c \) as well as the absolute detuning (\( \Delta \)) from the D1 \( F' = 2 \) line are tunable over a wide range. The D1 laser beams are switched on immediately after the D2 sub-Doppler phase. This second D1 sub-Doppler phase cools the atoms by another factor of 4 or so in the optimal case of the parameter range we explored, down to about 12μK without loss of atoms. We achieve the lowest temperatures over a wide range of detuning \( \Delta \) of the cooling and the repump beams from \( F = 2 \rightarrow F' = 2 \) transition, extending both on the blue and red side of the transition, and even on the \( F = 2 \rightarrow F' = 2 \) transition, while forming a Λ configuration with \( \delta = \delta_r - \delta_c = 0 \), which is in the Raman resonance condition. This a clear indication of the robust contribution of coherently formed dark states (in contrast to optically pumped dark states) to the cooling process. This is perhaps the first time quantum coherent dark state-enhanced sub-Doppler laser cooling in optical molasses is explored and established over such a wide range of absolute detunings. We now present further detailed studies on the D1 \(^{39}\)K sub-Doppler processes.

Though we observe that cooling beyond the D2 molasses occur over a range of relative detuning \( \delta \), extending ±2\( \Gamma \) around \( \delta = 0 \), the deepest cooling occurs when the Raman resonance \( \delta = 0 \) is satisfied. Figure 2 (with \( \Delta = 28 \) MHz) indicates how the resonant cooling occurs in a very narrow band (\( \ll \Gamma \)) around the Raman condition. The intensity ratio between the cooling (\( I_c \)) and repump (\( I_r \)) beams is about 3 for optimum cooling, which is much smaller than the ratio used in the case of \(^{7}\)Li [10]. For larger ratios of \( I_c/I_r \) the cooling is less efficient. Temperature as low as 12 μK is observed at the Raman resonance.

It is known that under the Raman condition \( \delta_c = \delta_r \) coherent population trapping occurs in a Λ-system [11] when the Rabi frequency of one of the couplings is much higher than the other. The interaction of the two laser beams with the three level atoms results in three
new perturbed energy levels and eigen states, one of these is a coherent superposition of the two long lived ground states $c_1 |g_1\rangle + c_2 |g_2\rangle$ with $c_1\Omega_1 + c_2\Omega_2 = 0$, and this state is a dark state, decoupled from the exciting light fields. However the observed deep cooling implies that there is a very strong and effective cooling force even though excitation to the upper state is prohibited. It has been shown in [12], that enhanced cooling occurs for a very small velocity class of atoms, due to the low frequency coherence term between the two ground states, $\Gamma_{12}$. For all atoms outside the velocity class it would result in a large heating. The D2 sub-Doppler phase in our experiment, lowers the temperature from few milli-Kelvin to about 40 $\mu$K and avoids any such loss.

The other two new (perturbed) eigenstates are ‘bright’, one of which has an effective long ‘life-time’ or low dissipation that is much less than the excited state width $\Gamma$, and the other with width similar to $\Gamma$. Hence, away from the Raman condition we expect strong scattering of light from the atom, and hence heating with resonances at the relative detunings corresponding to these bright states. Of course, this is complicated by other heating or cooling mechanisms occurring simultaneously, due to transitions causing inverse Sisyphus heating as discussed in reference [10]. However, we see clear and dramatic signatures of the quantum interference effects corresponding the bright state with sub-natural linewidth and asymmetric Fano profile, close to the dark state on the side of $\delta = \delta_r - \delta_c$ positive as expected. The strong heating, almost divergent, by a factor of 1000, to temperatures beyond
10 mK, has a width less than 0.2Γ indicative of the scattering on the narrow bright state. The asymmetric Fano profile, typical of excitation probability in such atomic systems with interfering excitation pathways [13] is visible clearly in detailed measurements as shown in the figure (Fig. 2).

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FIG. 3: Temperature as a function of the detuning from $F' = 2$ in the Raman configuration ($\Delta = \delta_c = \delta_r$)

The molasses cooling in Raman configuration seems to be effective over a wide range of absolute detuning ($\Delta = \delta_c = \delta_r$) from the atomic transition as can be seen from Figure 3. Even at the atomic resonance, the Raman condition reduces the temperature of the atoms. Indeed, over a range of $\Delta \approx (+40, -25)$ MHz, the quantum coherence-enhanced cooling is relatively independent of the value of $\Delta$. Cooling is observed until the absolute detuning ($\Delta$) is such that the cooling ($\omega_c$) and repump ($\omega_r$) frequencies approach midway between $F' = 1$ and $F' = 2$, with a separation of 56 MHz. Strong heating starts about 25 MHz red of $F' = 2$ and persists till the $F' = 1$ line, below which we recover the temperatures reached in the D2 sub-Doppler cooling for a small range of detuning. However, the behaviour is complicated, with strong heating starting again when $\Delta < -20$ MHz from the $F' = 1$ level.

When the lasers are tuned between $F' = 1$ and $F' = 2$ preserving the Raman resonance condition, two Λ-configurations become operational in the atom, namely the transitions ($F = 1 \rightarrow F' = 2, F = 2 \rightarrow F' = 2$) and ($F = 1 \rightarrow F' = 1, F = 2 \rightarrow F' = 1$). Clearly, the model for cooling or heating based on the 3-level Λ configuration will not be adequate and the interference between the two configurations possibly results in ineffective cooling and even anomalous heating over a certain range of $\Delta$. 
The two lasers driving the transitions in our experiments on D1 Λ– dark state cooling have an intensity ratio, $I_c/I_r = (\Omega_2/\Omega_1)^2 \simeq 3.5$ when these parameters are optimized for best sub-Doppler cooling. This is much smaller than the ratio of intensities used in the experiments with Lithium [10] and has significant implications on the exact nature of the dark state formation. Given the peculiar situation for Potassium, we can test the role of quantum coherences in sub-Doppler cooling further by inverting the roles of the pumping and repumping lasers, by inverting the ratio of their intensities, keeping the overall total intensity more or less the same. CPT physics predicts the same dark states and two coupled states with the populations inverted. The atomic population is trapped in the ground state driven by the weaker beam. If the dominant cooling comes from the quantum coherent dark state formation rather than from the dark state formed by optical pumping by circularly polarized light, then inverting the intensity ratio $I_c/I_r$ to below unity, by making the repump laser much stronger than the cooling (pumping) laser, also inverts the roles of the light drives in the formation of the dark state. We then expect the dark state superposition is predominantly contributed by the state $|g_2\rangle$ corresponding to the state $F = 2$ in this case. Deep cooling will continue to occur at the Raman resonance $\delta = 0$, but the Fano-profiled heating will change side and will appear in the negative relative detuning, $\delta = \delta_r - \delta_c < 0$. This is exactly what we observe in the experiment, with $I_c/I_r = 0.28$. We plot the temperature versus the relative detuning of the repump ($\delta = \delta_r - \delta_c$) around $\delta_c = 28$ MHz in Figure 4. Though the extra sub-Doppler cooling at the Raman resonance and the heating are not as effective as in the case of $I_c/I_r \gg 1$, the general trend is clear, especially the sub-natural width of the strong
heating region indicative of quantum coherence. Also, additional cooling happens only at
the Raman resonance and at all other detuning we observe some mild heating, with the
strong resonant heating to several mK occurring in a narrow range of $\delta < 0$, of width much
smaller than $\Gamma$, close to the Raman resonance.

Though we were expecting heating, rather than cooling, when the two lasers are very close
to or on the D1 $F' = 2$ resonances, due to the large probability for excitation and spontaneous
emission, what is observed is extra sub-Doppler cooling when the Raman resonance condition
in the $\Lambda$–configuration is satisfied. In fact, we get the same deep cooling to about $12 \mu K$, when $\Delta = \delta_c = \delta_r = 0$. This shows that the dark state formation overwhelms all other
processes and retains its robustness as long as the Raman resonance condition is satisfied
and atoms are pre-cooled (so that atomic motion does not strongly violate the Raman
resonance condition).

III. DISCUSSION AND CONCLUSION

The plausible theoretical framework to analyze results on sub-Doppler cooling where
multiple effects like polarization state optical pumping, spatially varying Stark shifts and
quantum coherent dark state formation in the $\Lambda$–configuration has been discussed in some
detail in ref. [10, 12]. Most theoretical work on this important area of interplay of quantum
coherences and laser cooling have mainly considered the situation in 1D, with lasers in the
lin-lin polarization states. Unlike the case of VSCPT, which works in 1D to 3D, where
random walk into the sub-recoil energy and coherent population trapping into the dark
state causes accumulation of ultra-cold atoms, subtle polarization and intensity effects are
present in gray cooling coupled with $\Lambda$–cooling. Also, though the frequency difference of
the two laser is maintained well because the two beams are derived from a single beam using
AOMs, random jitter of relative phase on time scales of ms is still possible due to the optical
configuration that make up the six independent cooling beams. It is in fact surprising that
the 1D model discussed in [10] reproduces the general features of what is observed. Trying to
reproduce quantitatively the entire set of observations is expected to be complicated in 3D
due to the spatially varying polarization and intensity patterns of the six bi-chromatic laser
beams that are actually circularly polarized, instead of in the assumed lin-lin configuration,
and will perhaps need a full Monte-Carlo simulation. However, as we have established with
some detailed data on $^{39}$K atoms, the atom-light interactions and resulting cooling and heating close to the Raman resonance in the Λ−configuration can be well understood in terms of the coherent superposition states and their scattering properties, especially that of the decoupled dark state and its closest bright state with sub-natural width of a Fano profile. These two states are motionally coupled.

We thus observe that a two stage sub-Doppler cooling in molasses of $^{39}$K results in a significant decrease in temperature. The temperature, measured to be about 12 $\mu$K is the lowest attained in $^{39}$K molasses. Pre-cooling in the D2 molasses avoids any loss of atoms in D1 gray molasses. Thus the atomic cloud is well suited for transfer to magnetic or optical traps for further cooling. The large parameter range explored in the experiments require more detailed theoretical modeling than available so far.

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IV. SUPPLEMENTARY MATERIAL

FIG. 5: Timing sequence for the MOT and sub Doppler stages.