

Motional Quantum Ground-State Cooling Outside the Lamb-Dicke Regime – Supplemental material

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1. SIMULATION OF 3D RAMAN SIDEBAND COOLING

1.1. Overview

We use a computer simulation to study the importance of different effects and guide the optimization of cooling. The simulation uses quantum jump method[1] (or Monte-Carlo wavefunction method) to accurately calculate the evolution within each laser pulse while different energy eigenstates are assumed to decohere immediately on spontaneous emission of photon and on pulse boundaries. Such approximations are valid for simulation of the cooling and greatly simplifies the computation at the cost of limiting the applicability of the simulation to processes that requires stronger coherence such as Ramsey spectroscopy and rapid push-out.

A few other approximations are used in the simulation either because they are proved to have negligible effect on the experiment or because they'll increase the complexity of the simulation and can be optimized through other methods in the experiment. A list of the most important approximations is,

1. All Raman pulses are assumed to be resonantly driving only one sideband/carrier order.
We tweak the pulse shape, power and length to suppress any deviation from this in the experiment. We do still see deviation from this in the experiment but the effect is small for the short pulse we use for cooling and is the most pronounced for long detection pulses.
2. No heating from other sources including trap switching.
We measured the heating rate and observed that it mainly comes from off-resonance scattering of photons from various sources which we already include so additional heating can be ignored.
3. Trapping frequency difference between different states are ignored.
This effect is negligible for Na in the ground state due to the small fine structure. It is easy to include

this effect if the calculation needs to be repeated on a system where this is not the case (e.g. directly laser cooled molecules)

Some of the important effects that are included are,

1. Full 3D simulation.
This includes 3D motional states, accurate 3D wavevector, and different emission pattern for different photon polarizations.
2. Off resonant scattering from all beams.
Including Raman, optical pumping and dipole trap.
3. Optical pumping polarization imperfection.

The optical pumping polarization and the off resonant scattering are especially important for accurate simulation since they are the main heating source that is present for ground motional dark state atom and therefore are the main limitation on cooling performance.

1.2. Simulation of each pulse

Each pulse in general has a coherent part from the Raman drive (zero for optical pumping pulse) and an incoherent part from scattering (optical pumping or off-resonance scattering). This nicely fits the general formula of the quantum jump method. Due to the large number of states that we need to take into account (30–150 states in each of the three axis and 8 hyperfine states, giving a total of 10^6 states), the generic wavefunction propagation is very inefficient. Therefore, this is further simplified by reducing the number of states to be kept track of during the coherent propagation and apply quantum jump using a set of reduced jump operator that describes the total jump probability from a certain states (sum over all final states). The coherent propagation is then accurately solved in order to avoid having to use a time step much shorter than the scattering rate (up to hundreds of kHz)[3].

In order to simulate a pulse, we first start with the coherent propagation that includes the modification from the jump operators as in quantum jump method. When a jump happens, we pick a final internal state to jump to based on the rates ratio of different scattering sources and their branching ratios. This process also determines the polarization and emission pattern of the photon and

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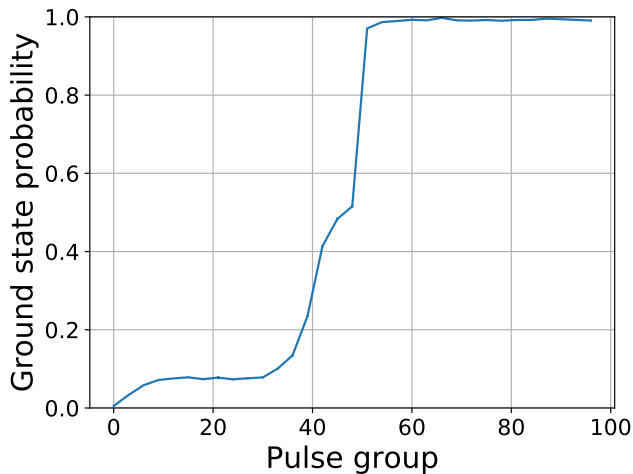


FIG. 1: Simulated ground state population as a function of cooling cycles without technical imperfections. The ground state probability reaches $> 99\%$.

a particular wave vector for the emitted photon is then selected as the next step. The recoil is now fixed so the final motional state of the atom can now be selected. This process is then repeated on the same pulse until the pulse time is used up before we start to simulate the next pulse.

1.3. Measurements

We apply “virtual” measurements on each results of the cooling which we then average to obtain the expected value of qualities that we are interested in. Due to the decoherence approximation, the measurement has to commute with the Hamiltonian. Particularly useful measurements used in our simulation are hyperfine state distribution, Average motional energy, loss rate (where an atom is assumed to be lost if its motional energy goes above a certain threshold at any time) probability of being in

certain states (e.g. ground state).

1.4. Sample results

When not considering the off-resonant scattering from the Raman beams and the tweezer as well as optical pumping polarization misalignment, the simulation shows that there isn’t a cooling limit despite the large Lamb-Dicke parameter and high initial temperature (Fig 1). However, when these effects are taken into account, the ground state probability can saturate at a lower value (Fig 2) and require much more careful tweaking.

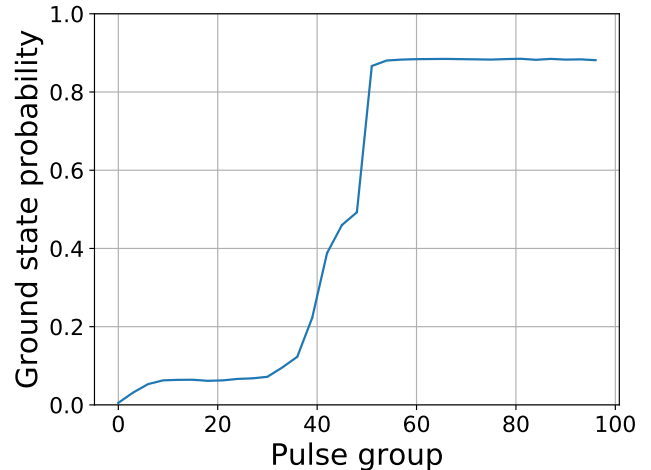


FIG. 2: Simulated ground state population as a function of cooling cycles including effect of off-resonant scattering from all beams and OP misalignment. For this particular sequence, the ground state probability saturates $\approx 88\%$.

1.5. Code

The simulation is written in Julia[2]. All code are available under GPLv3 license at [4] and [5]

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- [1] R. Chrétien, *Laser cooling of atoms: Monte-Carlo wave-function simulations* (2014), URL http://www.oq.ulg.ac.be/master_thesis_rc.pdf.
 - [2] J. Bezanson, A. Edelman, S. Karpinski, and V. B. Shah, *SIAM Review* **59**, 65 (2017), ISSN 0036-1445 (print), 1095-7200 (electronic).

- [3] [note about modification to the quantum jump method \(https://goo.gl/EZ13wt\)](https://goo.gl/EZ13wt)
- [4] [Library code \(https://goo.gl/WLJwJp\)](https://goo.gl/WLJwJp)
- [5] [Top level code \(https://goo.gl/XXVreq\)](https://goo.gl/XXVreq)