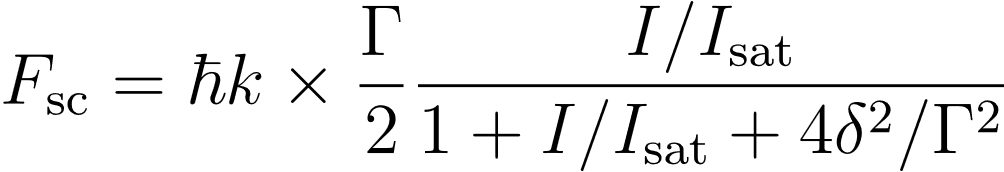
**Intro**

Hello everyone, so today I will be talking about a new-ish laser cooling technique called “Sawtooth-wave adiabatic passage cooling” developed by a group at Colorado led by James Thompson and Murray Holland.

**Some background**

So… typically in our labs we use a number of laser cooling techniques to trap and cool alkali atoms such as Li and Na like in BEC1. For example: we use our lasers for Zeeman cooling/slowing and for the magneto-optical trap. The goal is of course to use the interaction between atom and light to exert some force on the atoms to slow them down… transforming the velocity distribution of the atoms towards one with a large and narrow peak near zero velocity.

And as you may already know, the two key ingredients are the Doppler effect and the scattering force that light exerts on the atoms. This is given in the following expression:



Where Gamma is the natural linewidth of the transition being used and delta is the detuning associated with the Doppler shift. Here, hbar-k is the photon momentum, and the second part on the right is the scattering rate, given in terms of Gamma times a detuning and intensity-dependent part.

As it turns out, there are temperature limits to these usual cooling techniques. And as you may already know, there is the Doppler limit which is dependent only on the natural linewidth, and the recoil limit, which is dependent only on the light wavenumber and the atomic mass.

Typically, for alkali atoms we use the D1/D2 lines, and these have natural linewidths of roughly tens of megahertz. As a result, the Doppler cooling limit is roughly hundreds of micro Kelvins, whereas the recoil limit is roughly 1 micro Kelvin. For standard laser cooling techniques (say, Doppler cooling for the MOTs), the limit is the Doppler limit (of course, I’m ignoring Sisyphus cooling in the MOT, and so on) – so this is roughly speaking.

The natural question to ask is whether we can cool atoms to below these temperatures. And sure, there are already ways to circumvent certain limitations in these “standard” cooling schemes. Either we use different cooling techniques to avoid limitations of Doppler cooling: these techniques are not surprisingly called, well, sub-Doppler cooling: like Sisyphus cooling, as well as Raman and VSCPT – these are sub-recoil cooling, but ok.

Alternatively, we could just pick a transition with a narrower linewidth, since the Doppler limit goes like Gamma. However, there are some problems associated with this approach. Most obvious is that since the ideal MOT detuning often goes like some near-unity fraction of the natural linewidth, reducing the linewidth reduces the capture range of the MOT, as one often ends up cooling and trapping very few atoms.

There are ways to circumvent this of course. For example, for Sr, it is well-known that by first cooling and trapping Sr in blue-MOT (following a Zeeman slower), one can load the atoms into a red-MOT for further cooling. Here, the blue MOT has a natural linewidth of typical size (30 MHZ), while the red MOT has a linewidth that is orders of magnitude smaller – aka with much smaller Doppler limit.

What I will describe today will be a technique that claims to be able to also have high capture range, but with a simpler experimental setup… with potential applications to cooling atoms and molecules that lack a cycling transition for example. SWAP cooling.

**Slide 3: Basic mechanism**

The basic mechanism for laser cooling by sawtooth-wave adiabatic passage (or SWAP!) is rather intuitive because is it based on the Doppler effect and adiabatic transfer of atoms to and from a long-lived optically excited state.

Consider the model 2-level system as shown. The internal degrees of freedom are the two basis states (e, for excited, and g, for ground). The external degree of freedom is the motion of the atom – it has momentum **p**. The atom is initially in the ground state and is traveling with velocity **v** in the lab frame in the presence of two counter-propagating laser beams whose frequency is swept across the atomic transition frequency of the atom. The sweep is repeated so that there is a sawtooth pattern in time. The light as wavenumber **k** and frequency **ωL**. The full range of the sweep is **Δs**.

The cooling mechanism can be explained as follows. In the reference frame of the atoms, both beams start below the resonance with the atomic transition. However, Doppler shifts due to the relative motion of the atom with the beam cause the beam propagating against the atom velocity to be upshifted by **kv** while the co-propagating beam downshifted by **kv**. As a result, when the frequency of the light (in the lab frame) is swept up, the counter-propagating beam becomes resonant first and adiabatically transfer the atom from the ground state to the excited state.

Since lifetime of the excited state is large (remember, we’re interested in a narrow linewidth transition here), the atom remains in the excited state until the co-propagating beam sweeps over the resonance and adiabatically transfers the atom back to the ground state.

Through this process, the atom absorbs one photon from the counter-propagating beam, changing its momentum by **-hbar k**, and emits (via stimulated emission) a photon into the co-propagating beam, changing its momentum by another **-hbar k**. In total, the atom loses **2 hbar k** against its motion. Since the frequency jumps and the end of the sweep is diabatic, the process repeats! Applying this argument for an atom initially moving in the other direction, we see that the atom is decelerated either way!

**Slide 4: Requirements**

Each laser interacts with the atom with Rabi frequency **Ω** which is larger than the spontaneous emission rate **γ** for the two-level system.

From the description of the cooling mechanism, we must make sure the parameters involving the light and the sweep are appropriate. Specifically, meeting the time-ordering and adiabatic condition is critical. In addition, we must make sure that the atoms are in the ground state at the beginning of each sweep, since atoms in the excited state will *gain* momentum from this scheme.

The relevant parameters for this scheme are as follows: the sweep range **Δs**, the sweep duration **Ts**, and the Rabi frequency associated with the atom-light interaction.

If the particle is in the excited state at the beginning of a sweep, it will *gain* rather than lose momentum. As a result, we must rely on spontaneous emission to ensure that the particle begins a sweep in the ground state. This is enforced by making the sweeping range sufficiently large so that the particle spends more time *outside* of the two resonances. This condition also enforces the condition that the sweeping range is sufficiently large so that both beams can achieve resonance with the atom.

Separately, we do not want the particle to have a large probability of decay when it is between the resonances. Therefore, we require that the **τe** be much less that the lifetime of the excited state.

Finally, we want the Rabi frequency and the sweep rate **α** to satisfy the well-known adiabatic condition. Here we have defined the adiabaticity parameter **κ** to be the ratio **Ω^2/α**. We want this ratio to be at least unity to obtain a substantial probability for the atom to be the excited state after interacting with the first beam.

Now, as an aside, I just wanted to emphasize that this cooling scheme not only reduces the velocity of the atoms but also increases the phase-space density, by means of a small amount of spontaneous emission. In the absence of spontaneous emission, the atom would find itself on a heating trajectory after initial cooling. The presence of spontaneous emission ensures that the atom is preferentially in the ground state at the beginning of each sweep. This breaks time reversal symmetry, enabling cooling and phase space compression to occur.

**Slide 5: Validity**

Not surprisingly, this cooling scheme is not always valid. Atoms in different velocity classes behave differently when interacting with the SWAP light.

It turns out that the atoms must be travelling sufficiently fast to interact with the counter-propagating beams in the manner described before. This is called the *high-velocity regime* which I will specify later. But the reason is as follows: As the atom is slowed to near-zero velocity, the Doppler shift becomes small compared to the Rabi frequency **kv ~** **Ω**, and the condition for deterministic time-ordering of adiabatic transfers from the two beams (as described in the ideal scenario above) fails to hold. One can see the narrowing of the resonance window in this graph on the left from a simulation.

When this happens, simple picture where the atom is sequentially excited and deexcited is no longer valid, and the probability that the atom remains in the excited state after a sweep becomes appreciable (as opposed to vanishing). And as we have seen, an atom in initially in the excited state will *gain* momentum following a sweep – this is undesirable.

So, we must be in a *high-velocity regime*. To define this, we must look in detail the time-ordering of the excitation-deexcitation process.

As shown, there are two time-related quantities here: **Tjump**, the time it takes to adiabatically transfer a particle between its internal states, and **Tres**, the time interval separating the two resonances. The total excited time, **Te**, is the sum of **Tjump** and **Tres.**

Since roughly half of each **Tjump** overlaps with **Tres**, the *high-velocity regime* is the range of velocities for which **Tjump < Tres.** Since we can relate these quantities to the sweep parameters, we obtain the following relation: **|Ω0| < |kv - 2ωr|.**

You might be worried that once atoms are cooled below the high-velocity regime, they get heated up – However this is only true if the evolution of the system is entirely unitary. It turns out that spontaneous emission helps here. In the presence of spontaneous emissions, the atom preferentially starts in the ground state at the beginning of each sweep. Like I said before, this breaks tie-reversal symmetry and phase space compression can occur.

**Slide 6: Force and capture range – without dissipation**

We first look at the case where we do not include effects of spontaneous emission. To characterize force without dissipation (aka conservative force), the authors consider the change in the atom’s rms momentum due to a single sweep. The reason they do as opposed to looking at the expectation value of momentum is to exclude effects of *Bragg oscillations.* (explain this!)

There are three relevant velocity regimes.

* If **|kv|> Δs/2** then the lasers are never on resonance with the atoms. This is not relevant.
* If **|kv|< |Ω0|** then as we can see the dynamics is more complicated as the momentum approaches zero. We can also explicitly see that a particle initially in the ground state with zero momentum will gain momentum from a sweep. This is because it will first get transferred to the excited state, which according to what was described before, gains momentum. So, in order to minimize this effect, we require the first condition on slide 4, which on average resets the particle to the ground state for the next sweep via spontaneous emission.
* If **|Ω0|<|kv|< Δs/2** then we’re (consistently) in the high-velocity regime as discussed before. The dynamics here is as expected. Here, we pay attention to the difference between diabatic and adiabatic cases. In the diabatic sweep, the particle receives a small impulse but fails to return to its initial internal state. In contrast, when the sweep is adiabatic, there is an impulse of size **|p\_rms| = 2 hbar k**, as expected and significant return to the initial internal state.

**Slide 7: Force and capture range (cont.) – with dissipation**

While interesting, the analysis above does not include dissipation.

When dissipation is included, the impulse may be defined simply as the change in the expectation value of the momentum before and after one sweep. The plot below shows the various quantities after one sweep as a function of the initial momentum: the impulse, the steady-state population, and the average number of scattering events.

As you can see, SWAP cooling gives impulse away from zero momentum for DeltaS/4 < kv < DeltaS/2 and impulse towards zero momentum for kv < DeltaS/4. As a result, the range of the frequency sweep determines the capture range.

Also, (sorry but they did not an inset for this figure), if we look at p\_i = 25 hbar k we see that the atoms receive an impulse of 2 hbar k. Associated with this point is a low scattering rate (at about 0.2 events per sweep). Moreover, the momentum states around 25 hbar k also receives a large force: it can calculated by taking the impulse divided by the sweep time, giving 2 hbar k gamma.

From AMO1, we know that the maximum scattering force is given by hbar k times the maximum scattering rate, which is Gamma/2. So, we see that for this velocity class the average force is four times the maximal radiation pressure force at saturation.

However, there is something I’d like to point out… is that the dynamics near zero momentum is more complicated and unexpected. More specifically there is a sharp linear feature near p=0. As it turns out this is due to Bragg oscillations, which puts atoms in a superposition of opposite momentum states: plus and minus p before the particles resonate with the lasers.

(optional)

A result of Bragg oscillations is that its effect is independent of sweep direction. So, in order to see this, we can look at the sum of the impulses when the laser is swept up versus swept down. When looking at the sums, all other effects acquire a sign when flipping the sweep direction except for Bragg oscillation, so any residual effect is due to it.

And there it is on the plot: the sharp linear feature as expected.

For an introduction on the theory of Bragg oscillations, check out this paper written in 1988 by David Pritchard and his collaborators. The main idea is that when we consider the momentum states of the particle in a dispersion relation picture, we have the following plot. At certain light detuning, the Bragg resonance condition is met, and the atom initially in momentum state p is put in a superposition of momentum states p and minus p before interacting with the laser. This along with ambiguous time-ordering and other effects (which you can find in the paper) complicates the dynamics.

**Temperature limit as Gamma 🡪 0.**

The last part of the talk is simply the temperature limit extracted from simulation and a quick view of some experimental results.

The simulation here shows that for this sweep-wait scheme (which mimics cooling for ultra narrow linewidth transitions), the final temperature (which is extracted from the momentum distribution) approaches twice the recoil temperature. However, as we will see later on, this is a simulation of an ideal system.

Another interesting aspect to look at is the scaling of the final temperature versus the Rabi frequency. Simulation shows that the lowest possible temperature is achieved in the vicinity of the adiabatic parameter being unity and scales linearly with the Rabi frequency as it increases (in the adiabatic regime).

The reason for the increase in temperature away from the Rabi^2 = sweep rate is as follows: for high Rabi frequencies, the time ordering between the adiabatic transfers decreases. Also, for high Rabi frequencies, the particles spend more time in the excited state, and as a result there are more scattering events. In the diabatic regime, conservative forces are reduced and also because of increased excited state population at the end of each sweep.

**Application**

Finally, I want to show here an experimental demonstration of SWAP cooling in the 7.5 kHz linewidth transition 1S0 – 3P1 in 88Sr. Here, the atoms are precooled to about 600 micro Kelvins before being subjected to a pair of counter-propagating SWAP light.

The observed one-dimensional temperature is further reduced to 45 micro Kelvins. But after some more optimization of the SWAP parameters, they reported that the lowest possible temperature achieved to be 2.3 micro Kelvins, which is roughly the recoil temperature, as predicted by theory! However, we notice that the Doppler limit for this transition is 0.4 micro Kelvin. So, SWAP cooling does not achieve the lowest possible temperature.

The scaling of the final temperature against the Rabi frequency associated with the light is also consistent with theoretical predictions.

Just to end, I will just say that there appears to be several merits such as (1) it allows for strong forces on weak transitions, (2) large capture range (which depends only on the Rabi frequency associated with the light), and (3) reduced reliance on spontaneous emission (even though spontaneous emission is still necessary for good SWAP protocols).

To know in the background:

* Bragg oscillations
* How does this cooling compare to usual cooling such as Zeeman cooling and chirped-frequency cooling? How does the momentum distribution of atoms change due to SWAP cooling versus the above two cooling techniques?
* Know intuitively how to explain different trends in the various graphics in the slides.
* What is the role of photon scattering in laser cooling?
  + Answers: the purpose of scattering of photons is to reduce energy and bring the system close to equilibrium. Here, energy is removed by means of photon scattering. The “cooling efficiency” can be defined in terms of incoherent scattering – due to spontaneous emission: it is the energy carried away from the system per scattering event. This definition is motivated in part by the potential application of SWAP cooling to systems where closed cycling transitions may not be accessible and therefore a large number of spontaneous emission events are undesirable.