Observation of the Bichromatic Force on Metastable Helium

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In the early days of laser cooling, the view of two-level atoms moving in a monochromatic laser beam provided the elementary picture. The topics that could be described this way included atomic beam slowing and cooling, optical molasses, optical dipole traps, lattices and band structure effects, and a host of others. Within a few years, however, it became clear that this simple view was inadequate, and that the multiple level structure of atoms was necessary to explain some experiments. The extension from two-level to multi-level atoms gave an unexpected richness to the topic of atomic motion in optical fields. The added topics included Sisyphus cooling below the Doppler temperature, the MOT, and VSCPT. It seems natural to expect that a comparable multitude of new phenomena is to be found for the motion of two level atoms in multi-frequency fields, but this subject has not received as much attention.

The spontaneous decay rate γ of excited atomic states limits the radiative force on atoms to $\hbar k\gamma/2$. This bottleneck in the dissipative exchange of momentum between atoms and light can be overcome by coherent control of the momentum exchange interactions. The bichromatic force [1, 2, 3] provides such control by using stimulated instead of spontaneous emission to produce the force, while at the same time exploiting spontaneous emission to enable a dissipative interaction. It is implemented with two counterpropagating light beams, each containing the two frequencies $\omega\pm\delta$ (where $\delta \gg \gamma$ and ω is the laser carrier frequency) whose phases, amplitudes and frequency difference 2δ are carefully chosen. We have made careful measurements of the extremely large magnitude F_b and velocity range v_b of this bichromatic force in Rb [4, 5], and have shown that its velocity dependence near the edge of its range is suitable for atomic beam slowing and laser cooling. Our measurements have corroborated various models and calculations of this bichromatic force.

In addition to its very large magnitude $F_b \sim \hbar k\delta/\pi \gg \hbar k\gamma/2$, one of its most attractive features is its very large velocity range $v_b \sim \delta/k \gg \gamma/k$. Since the force covers a much larger range of velocities, Doppler compensation using a multi-kilowatt Zeeman tuning magnet for example, is rendered unnecessary for slowing a thermal beam. Not only is the velocity range v_b very much larger than the usual velocity range for slowing forces, but also it has a strong velocity dependence at its range boundaries so that it can cool. Naturally this (dissipative) velocity dependence originates from the occasional spontaneous emission events at a rate determined by γ, but the magnitude of the force is not limited by this rate. Thus it is a superb method for fast, short-distance deceleration of thermal atoms that minimizes atom loss, thereby making it a most useful and important tool in the production of cold, dense atomic samples for traps, lithography, and other purposes.

We have observed the bichromatic force [6, 7] on metastable 2^3S_1 He (He*) by driving the $2^3S_1 \rightarrow 2^3P_2$ transition at λ =1083 nm. Light from an external cavity-stabilized SDL-6702-H1 diode laser is fed to an AOM to make two frequencies detuned by $\pm\delta \sim \pm 75$ MHz $\sim \pm 50\ \gamma$. Its output beams were combined and injected into a diode-pumped fiber amplifier [8] to produce several hundred mW of bichromatic light. The peak intensity in each of our ~ 3.5 mm diam. beams was ~1.6 W/cm^2, about $10^4 \times I_{sat}$. The average Rabi frequency $\bar{\Omega}_R$ was ~60 γ, where $\gamma^{-1} \equiv \tau \sim 100$ ns is the 2^3P lifetime.

In our first experiments [6] we used this light to apply a transverse bichromatic force to deflect an atomic beam from our LN$_2$-cooled He* source. Its mean atomic velocity was measured by time-of-flight to be 950 m/s, so the interaction time was $\sim 4\ \mu$s $\sim 40\tau$. We measured a force of ~15 times larger than $\hbar k\gamma/2$, the maximum obtainable radiative force, in good agreement with our numerical calculations and about half of that estimated from a simple model.

In our later experiments we used the bichromatic force [7] to slow a thermal beam of He* by driving the same $2^3S_1 \rightarrow 2^3P_2$ transition. We used two diode laser/AOM combinations to make a total of four frequencies appropriately detuned from resonance. These beams were injected into two fiber amplifiers whose output beams were aligned to produce a force at a small angle (5^o) to the velocities of the He* atoms. Up to now (abstract date) our trial experiments have produced a deceleration of ~ 90 m/s, limited only by our beam geometry and AOM bandwidth, but by the conference date we expect our new high-frequency AOM will allow us to produce substantial deceleration. The fully implemented bichromatic force could stop our He* beam in a distance of only ~1 cm! This is so much shorter than the 1 m required to stop He* with the radiative force that we expect much smaller loss caused by the usual small acceptance angles. This will produce much higher loading rates of our He* MOT that is presently under construction.

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