Laser-cooled Rb Clocks

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Recent calculations predict that the cold collision frequency shift is 15 times smaller in a laser-cooled ^{87}Rb clock than in a Cs clock. In addition, the shift can be eliminated in an ^{85}Rb clock. We will report on experimental progress to measure these frequency shifts in the Rb fountain clock we are constructing. Already we have trapped 2×10^{10} ^{87}Rb in a magneto-optic trap using only diode lasers. Six slave lasers are injected with light from a master laser and deliver more than 500 mW of spatially filtered intensity-controlled light to the trap. Current work is focused on achieving low temperature in the fountain and the construction of the microwave cavity and magnetic shielding.

Introduction and Recent Theoretical Results

Laser-cooling atoms to μK temperatures dramatically reduces nearly all of the usual systematic errors in an atomic clock. However, a new systematic arises due to the quantum nature of the atoms at low temperature and the resulting large wave-like collision cross sections.[1,2] The wave-like cross sections lead to a cold collision frequency shift that is large compared to the sum of all other systematics in a laser-cooled Cs clock.[3,4] For a cold Cs density of 10^9 cm^{-3}, the fractional cold collision shift is $\delta\nu/\nu = -1.7\times10^{-12}$ which is very nearly a resonant cross section at $T \approx 1$ μK.[2,5]

Noting that the shift is extremely large for Cs, Gibble and Verhaar have proposed that laser-cooled atomic clocks based on other atoms may have a much smaller frequency shift and therefore offer better performance.[6] Two attractive candidates are ^{87}Rb and ^{85}Rb for which we have recently calculated the cold collision frequency shifts.[7] We find that the cold collision shift for ^{87}Rb is expected to be 15 times smaller than that for a ^{133}Cs clock. Additionally, the shift for ^{85}Rb, although slightly larger than that for ^{133}Cs, is likely to be cancelable using the technique discussed in Ref. [6]. Even though the shift is cancelable, the lower hyperfine transition frequency for ^{85}Rb is likely to imply that ^{87}Rb is best suited for earth-based fountain clocks. For microgravity clocks however, the choice is less clear since the clock stability is independent of the transition frequency and because the transition Q is not a limitation.[7]

Experimental Results

We are presently constructing an ^{87}Rb fountain clock to measure the cold collision frequency shift. We use a vapor-cell magneto-optic trap[8] (MOT) with large laser beams[9] to collect 2×10^{10} Rb atoms. The laser system is all solid state consisting of an external-cavity master diode laser injecting 6 slave lasers and an external cavity repumping laser. Both external cavity lasers are stabilized to Rb saturated absorption spectra.

We nondestructively test the maximum output power of the slave lasers. To determine the maximum output power, we modulate the diode current and observing the modulation of the output power. With a modulation frequency of 10 kHz, the modulation of the output power has a very rapid drop as the current increases. Using inexpensive Sharp laser diodes, we found that going above the current where the modulation was approximately half of that for low powers would cause a significant and irreversible change to the diode. This behavior was similar for the Spectra Diode Lab lasers and we have shown 2 representative traces in Fig. 1.[10] We initially expected this to work for a modulation frequency of 2 MHz but no easily identifiable and reproducible change was seen in the 2 MHz modulation efficiency before diodes would fail. At very low frequencies, the modulation efficiency is simply the derivative of the power versus current and this does not have the crucial signature that the 10 kHz response exhibits. We speculate that the failure mechanism we probe is a thermal problem, the 2 MHz response is essentially a pulse response (too fast), and, at too low a frequency, the damage occurs before it can be clearly detected.

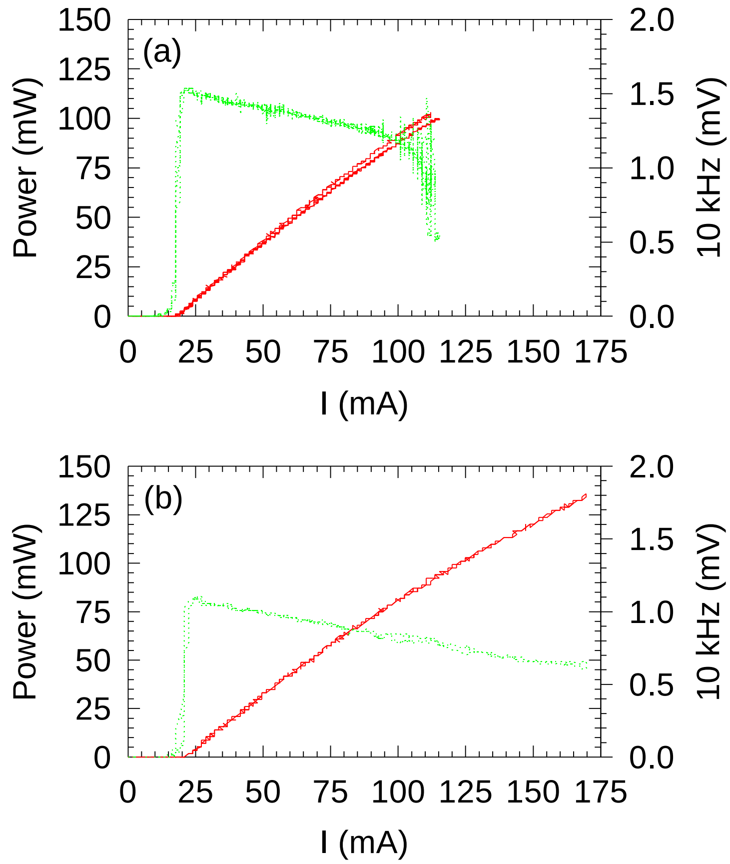

Fig. 1. Output power and 10 kHz modulation amplitude versus current for 2 SDL diode lasers. In (a) we see the 10 kHz modulation efficiency become noisy and drop dramatically at a power of 100 mW whereas for (b) the laser can emit more than 135 mW.

We operate the fountain by collecting atoms for a time on the order of 0.5 s and then launch the atoms into the fountain by shifting the frequency of the 3 downward propagating laser beams. We then lower the intensity of the cooling laser beams to adiabatically expand the potential wells[11] as we have previously demonstrated in a Cs fountain.[12] Here, we achieve a temperature of 1.85 μK determined from a time-of-flight spectrum as shown in Fig. 2 for a 30 cm high fountain. This is the lowest temperature achieved by laser-cooling Rb.

The fountain clock consists of the vapor cell MOT and a series of microwave cavities. Immediately above the MOT are 2 rectangular TE_{102} microwave cavities which will be used to state prepare atoms for the clock. We will launch the ^{87}Rb atoms in the F=2 state. The first microwave cavity will transfer atoms from the F=2 $m_F=0$ state to the F=1 $m_F=0$ state and all the other atoms can be cleared in the detection region above these cavities. The second cavity will be used to transfer atoms into the F=1 $m_F=\pm1$ states so that we can measure the collisional shift of these states to better check the atomic theory. Other schemes can be used to prepare atoms in one of the $m_F=0$ states and any other m_F state for similar measurements. The atoms then enter the 2 layer magnetic shield and the clock cavity. For this prototype, the clock cavity is a rectangular TE_{102} cavity with a high Q. This will excite an atomic coherence on the way up and then convert the coherence to a population difference on the way down before the atoms enter the detection region where the populations are probed by laser induced fluorescence. In addition, the drift region above the clock cavity is a cylindrical $TE_{0,1,11}$ cavity so that we can excite the F=1 $m_F=\pm1 \rightarrow$ F=2 $m_F=\pm1$ transition to probe the C-field as a function of height. We expect to soon observe Ramsey fringes for ^{87}Rb and to measure the cold collision frequency shift.

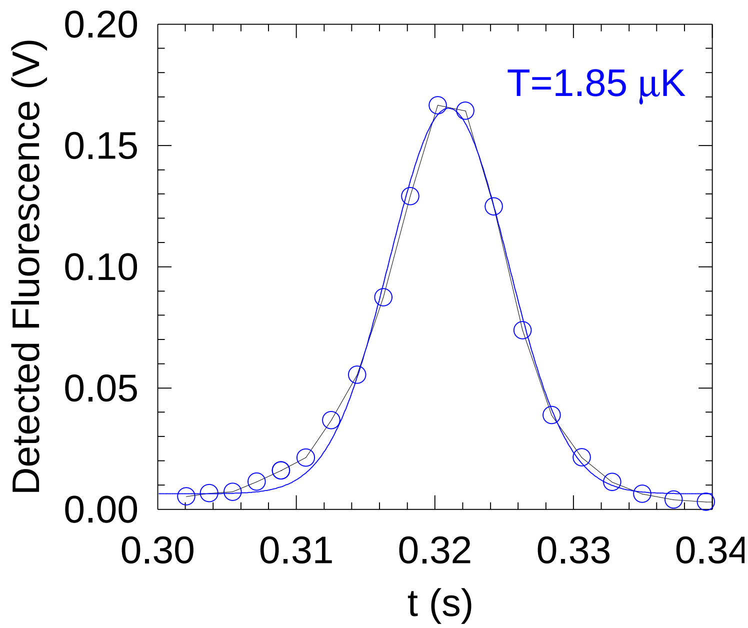

Fig. 2. Rb fountain time-of-flight spectrum. Here t is the time after the launch from the MOT.

Juggling Fountain Experiments

We expect future fountain clocks will "juggle" atoms to enhance the short-term stability of the clock. In all of the fountain experiments to date, atoms are loaded in a MOT or optical molasses for typically 0.5 s and then launched for a flight time of ≈0.5 s so that the entire cycle is ≈1 s. The cycle time can be dramatically reduced by launching a ball of atoms potentially as often as every 30 ms so that as many as 15 balls of atoms are "in the air" at a time. The short-term stability of such a juggling fountain clock improves by $30^{1/2}$ and the averaging time required to reach a desired precision decreases by 30.[4] For microgravity clocks, multiple launches (it no longer looks like juggling in microgravity) is essential for a microgravity clock to achieve higher stability than an earth based fountain.[13]

We have recently juggled atoms in a laser-cooled Cs fountain to study collisions. The juggling is performed by launching 2 balls of atoms in rapid succession. The delay between launches, as short as 7 ms, determines the collision velocity - 7 ms implies $v_r = g\ \Delta t = 6.9$ cm/s corresponding to a 19 μK collision energy. In Fig. 3, we show preliminary juggling data for atoms prepared in the F=4 m_F=4 state colliding with atoms in the F=3 m_F=3 state. Here we show the velocity distribution of scattered atoms for launch delays of 7 to 10 ms corresponding to collision energies from 19 to 38 μK.

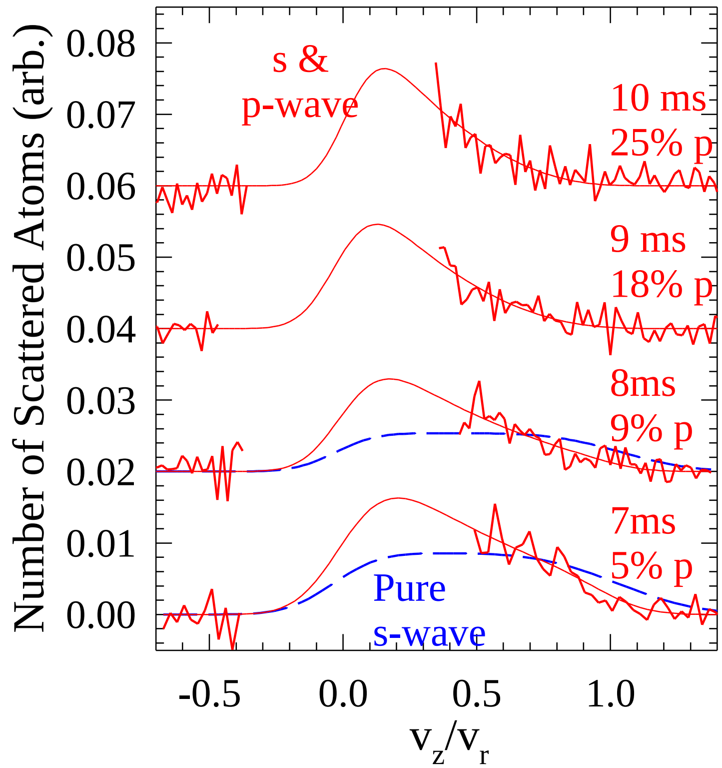

Fig. 3. Measured velocity distributions for F=4 m_F=4 colliding with F=3 m_F=3 for a range of collision energies from 19 mK to 38 mK. Solid curves are a combination of s and p-wave scattering and the dashed curves are pure s-wave scattering. The central peak of atoms near v_z=0 is omitted.

In fig. 4 we show the preliminary s and p-wave cross-sections we extract from this data for energies up to 75μK. We see a nearly resonant behavior of the purely triplet s-wave cross-section much like Dalibard's group,[14] as well as a p-wave scattering threshold for the first time. From the data in Fig. 3, we can clearly see the interference of s and p-wave scattering. The velocity distribution for pure s-wave scattering is shown and, for pure p-wave, the distribution is 2 peaks with no atoms scattered at 90° (v_z/v_r = 0.5 in Fig. 3). The curves are clearly inconsistent with pure s-wave and also clearly show that the s and p-wave scattering amplitudes constructively interfere in the forward direction. Even a 5% p-wave cross section for 19 μK creates a dramatically different velocity distribution.

This is the first "perfect" scattering experiment with laser-cooled atoms. These are the nearly mono-energetic, state-to-state measurements of differential cross-sections for laser-cooled atoms. For juggling clocks, the potential frequency shift due to collisions between different balls of atoms is potentially important and, in the future, these measurements will be extended to study these collisions in a juggling fountain clock.

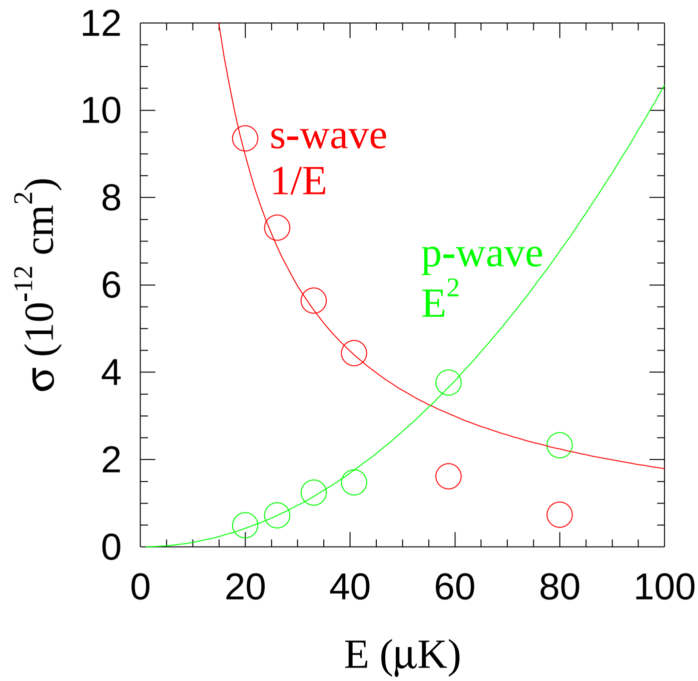

Fig. 4. Preliminary s & p-wave cross-sections from the juggling data in Fig. 3. and higher energies. At low energies the s-wave cross-section shows a 1/E resonance and the p-wave shows an E^2 threshold.

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