A Laser–cooled Cesium Fountain Frequency Standard and a Measurement of the Frequency Shift due to Ultra–cold Collisions

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Abstract

A frequency standard based on an atomic fountain of cesium atoms may have an accuracy of 10^{-16} due to longer interaction times and smaller anticipated systematic errors. All of the known systematic effects that now limit the accuracy of the Cs frequency standard increase either linearly or as some higher power of the atom's velocity. The one systematic frequency shift which is dramatically different is the frequency shift due to the collisions between the laser cooled atoms. At a temperature of a few μK, the de Broglie wavelength ($\lambda_{deB} = h/p$, where h is Planck's constant and p is the momentum of the atom) is much larger than the scale of the interatomic potential. Under these conditions the collision cross sections can be as large as λ_{deB}^2/π and the frequency shift due to these collisions has been recently calculated[1].

In our Cs atomic fountain, we laser cooled and trapped 10^{10} Cs atoms in 0.4 s[2]. By shifting the frequencies of the laser beams, the atoms were launched upwards at 2.5 m/s and a fraction of the atoms were optically pumped into the F=3 ground state. The unwanted atoms in the F=4 ground state were removed from the fountain with radiation pressure from a laser beam tuned to excite only those atoms. The Cs atoms in the F=3 state traveled ballistically upwards, were excited by the microwave cavity, and then returned back through the same cavity in the atomic fountain configuration[3].

By varying the cold atom density, we measured a density dependent shift of -12.9 $\pm$ 0.7 mHz or -1.4 $\times$ 10$-$12 for an average fountain density of (2.7 $\pm$ 1.5) 10^9 atoms/cm^3. This measurementwas made with uniformly populated Zeeman sublevels, while only the atoms in the m_F=0 sublevel contributed to the signal. We also made frequency measurements where the atoms in the F=3 $m_F \neq 0$ states were removed since those atoms do not add to the signal but contribute to the frequency shift. A 97% pure m_F=0 state was made in the following way: after cooling the atoms in optical molasses, they are in the F=4 hyperfine level. Atoms from the F=4 m^F=0 state were then transferred to the F=3 m^F=0 state with microwave radiation and the remaining F=4 atoms

in the other Zeeman sublevels were again pushed out of the way with radiation pressure. By varying the number of atoms transferred to the F=3 m_F=0 state, we determined the frequency shift due to the collisions between atoms in the m^F=0 states as a function of density. At a density of $(3.5 \pm 2.0)\times 10^8$ cm^{-3} (where the signal size is comparable), we measured a shift of -5.5 $\pm$ 0.5 mHz.

The extrapolation of the frequency shift to zero density is reproducible with an uncertainty of 4×10^{-14} and can be improved, indicating that it may be possible to control the cold atom density at the 0.1% level and to continuously evaluate the shift at this level.

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2. K. E. Gibble, S. Kasapi, and S. Chu, Opt. Lett. 17, 526 (1992).
3. M. A. Kasevich, E. Riis, S. Chu, and R. G. DeVoe, Phys. Rev. Lett. 63, 612 (1989); A. Clairon, C. Salomon, S. Guellati, and W. D. Phillips, Europhys. Lett. 16, 165 (1991).

QUESTIONS AND ANSWERS

Question: You mentioned that density of the atoms is going to have pulling effects. Is it ultimately going to be a stability limitation as well?

K. Gibble, Stanford University: At the moment it looks like we can control the density and is in a sense automatically controlled by the laser cooling to an accuracy of about 1%. That is what we see at the moment. It might in fact be better than that. Clearly, much more evaluation needs to be done but we are encouraged at this point to see where it will go.