# Cold, Optically Dense Gases of Atomic Rubidium

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Cold and optically dense gases of atomic rubidium are produced using buffer gas cooling in combination with rapid, high flow vapor injection. The observed rubidium density is $3 \times 10^{12}$ cm$^{-3}$ at a gas temperature of $\sim 20$ K, leading to an optical density greater than 200.

## I. INTRODUCTION

The ability to produce dense ensembles of atoms and molecules with long decoherence times is central to several areas of atomic physics research. Such samples play an important role in the development of atomic magnetometry [1, 2], the study of non-linear quantum optics [3–8], and in tabletop experiments testing fundamental symmetries such as Lorentz invariance [9–11]. Alkali atoms in a cold helium buffer gas have been suggested as an attractive system for these types of experiments[12]. The low thermal velocity increases diffusion time (thus increasing laser-atom interaction time and sometimes density), and there is both theoretical [12] and experimental [6, 13] evidence that helium-alkali collisional relaxation cross sections should drop rapidly with lowering of temperature.

Several groups have demonstrated the loading of buffer gas cells via laser ablation of a solid precursor. These experiments can produce cold, dense samples, but the rubidium disappears due to an unknown mechanism [6, 12, 14]. Possible explanations include adsorption by clusters formed in the ablation plume, hydrodynamic effects introduced by the ablation, and adsorption by impurities. In an alternative approach, alkali atoms have also been loaded into cold buffer gas cells via light induced atomic desorbtion (LIAD). Long lifetimes and long coherence times have been observed, but densities have in general been low ($\sim 10^8$ cm$^{-3}$) due to limited desorbed flux [13].

We report here the production of a cold, dense gases of atomic rubidium made by directly cooling a mixture of helium and rubidium from 430 K to 20 K. Continuous, high ($> 100$) optical densities are demonstrated [21]. No point in the apparatus is ever warmer than 450 K, leading to a vapor that is mostly free of contaminants. This is a major advantage when compared to experiments where a solid precursor is vaporized via laser ablation, producing a very hot ablation plume which is likely a mixture of atoms, ions, and unwanted contaminants from the surface of the solid precursor. Non-fundamental technical limitations discussed below bound our current system operation time to a few hours before the apparatus must be warmed and restarted.

## II. APPARATUS

Figure 1 shows the apparatus, which is very similar to our previously demonstrated direct flow cooling experiments [15]. Room temperature buffer gas is allowed to flow through an oven containing liquid and vapor rubidium. The mixture then flows through a short plastic tube [22], which functions as a thermal break, into a cold (6K) cell tube where it immediately begins to cool.

Our oven is run at a temperature of 450K producing copious amounts of atomic rubidium. (The 1 gram sample of rubidium we typically load into the oven lasts a few hours before the Rb density in the oven starts being limited by depletion of the source.) The majority (99%) of the rubidium emanating from the oven ends up plated on the walls of the transition tube and of the cold cell tube. The heat load on our cell rises substantially towards the end of a run, suggesting either that this metal layer conducts heat directly into the cell, or that the now metal-coated transition tube acts as a light pipe for the substantial blackbody radiation emitted by the oven. This parasitic heating is the dominant limitation to our run time.

## III. RESULTS

Cold rubidium is detected via absorption spectroscopy on the Rb D2 transition at 780 nm. Direct measurement of high optical densities is a challenge as the transmitted signal can be dominated by a small fraction of off-resonant light present in the laser light source. However, the density of the sample can be determined with some accuracy from measurements performed on the lorentzian wings of the absorption profile. This signal is not very sensitive to the sample temperature. We independently determined the sample temperature by studying the system at low Rb density but identical gas flow rates. Under these conditions a clear doppler width is measured.

Figure 2 shows absorption signals for cold Rb under conditions of identical gas flow and oven temperature. Figure 2a shows an absorption signal taken with very little Rb in the oven (the oven was nearly empty, thus providing low Rb flux). The sample was at a temperature of $\sim$20 K and a Rb density of $1.5 \times 10^{10}$ atoms/cm$^3$. Figure 2b shows a typical signal when the oven is full.

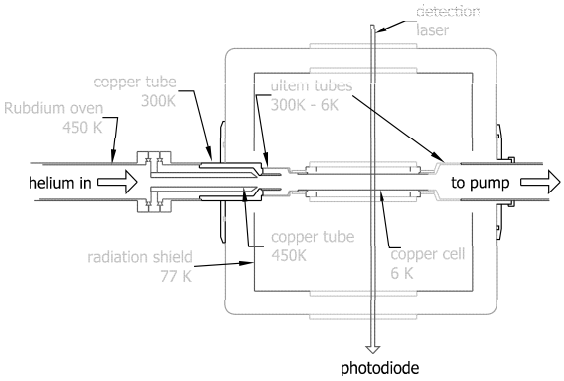


FIG. 1: A mixture of helium buffer gas and rubidium flows down an Ultem tube (wall thickness .5 mm, length 30 mm) from an oven held at $\sim 450$ K, where the rubidium has a significant vapor pressure ($10^{-2}$ Torr), to a cryogenic cell anchored to a liquid helium bath. Considerable care is taken to keep the transition region as short as possible to minimize losses while maintaining an adequate thermal disconnect. With 250 sccm helium flowing, the helium pressure is 6 Torr at the tube input and 400 mTorr at the tube output. The optical path length within the cold cell is 1 cm.

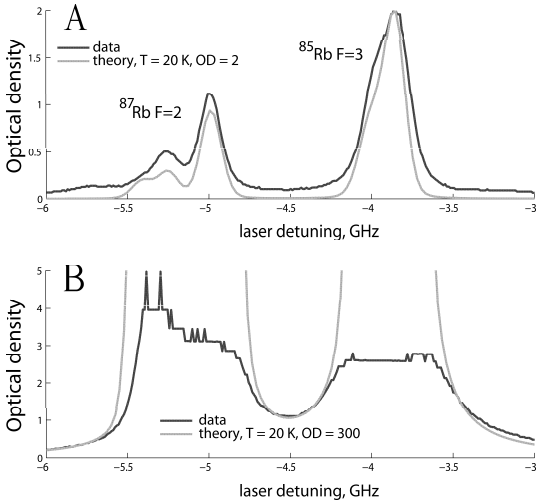


FIG. 2: Absorption spectra of cold rubidium. On top, a spectrum is taken with the Rb in the oven nearly gone. The low density of the sample means that it can be well fit to a doppler-broadened spectrum, with a measured temperature of $20 \pm 4$ K and a measured optical density of 2.0. On bottom, the spectrum is taken with the oven full. The peaks of the spectrum are dominated by saturation effects, but the wings fit reasonably well to a theoretical spectrum with 150 times the measured density in the A. Except for the oven rubidium level, conditions in A and B are identical (oven at 450 K, 250 sccm helium flow). The measured temperature of the cell in both cases is 7 K.

Due to the very small fraction of Rb in the flow in both cases we believe the temperatures to be close to identical.

The peak OD attained was $300 \pm 50$, limited eventually by the buildup of solid rubidium on the walls and thus heating of the cold cell.

Any rubidium atom which diffuses to the cold cell walls is adsorbed and lost from the gas. A species $A$ entrained in the buffer gas will cool with little loss as long as the elastic scattering cross section $\sigma_{A-He} > \sigma_{He-He}$ [16]. With larger species[15] it is possible to find a helium density such that thermalization is essentially complete while loss to the walls is minimal, resulting in a large increase in phase space density[23]. With smaller species the experimenter must compromise. In our system we observe that at low helium densities ($n_{He} \approx 10^{17}$ cm$^{-3}$, 100 sccm flow rate) the mixture thermalizes reasonably well with the cold cell tube (12 K measured temperature), but only a small fraction ($10^{-4}$ fraction, $n_{Rb} \approx 10^{10} cm^{-3}$) of the rubidium remains in the gas phase. At higher helium densities ($n_{He} \approx 4 \times 10^{17}$ cm$^{-3}$, 400 sccm flow rate) the rubidium density is larger ($n_{Rb} \approx 3 \times 10^{12} cm^{-3}$), but at a warmer temperature of about 20 K. The Rb phase space density in this case is approximately equal in the 450 K oven and the 20 K cold mixture.

Warm Rb cells are one of the workhorse platforms for non-linear optics [3–8]. Our system combines lower temperatures (and thus potentially lower ground state decoherence rates [6, 12, 13, 17–20]) with higher densities. These conditions provide a promising environment for the observation of strong optical non-linearities.

## IV. CONCLUSION

A simple, robust system has been demonstrated for producing steady-state cold, clean, and dense samples of rubidium in a helium buffer gas cell.

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[21] The optical density of the sample is defined as $OD = -Log_e \frac{I_{observed}}{I_{incident}}$, $I$ being the intensity of the probe light.
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[23] Phase space density also increases far more dramatically for a molecule, rather than an atom, as rotational and vibrational degrees of freedom are also cooled.