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Cold, optically dense gases of atomic rubidium

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Abstract. 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 $3 \times 10^{12}\,\mathrm{cm}^{-3}$ at a gas temperature of $\sim$20 K, leading to an optical density of the order of 200.

Contents

1. Introduction

The ability to produce ensembles of atoms or molecules with high density and long coherence times is central to several areas of atomic physics research. Such samples play an important role in the development of atomic magnetometry [1]–[6], the study of nonlinear quantum optics [7]–[12], and in tabletop experiments testing fundamental symmetries such as Lorentz invariance [13]–[15]. Alkali atoms in a cold buffer gas have been suggested as an attractive system for such experiments [16].

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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 atoms disappear due to an unknown loss mechanism [10, 16, 17]. Possible explanations include hydrodynamic effects introduced by the ablation, and adsorption by impurities and by clusters formed in the ablation plume. In an alternative approach, rubidium atoms have 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 [18].

We have bypassed the limitations of previous methods and report here the creation of a continuous source of a cold gas of rubidium atoms with optical density (OD) of the order of 200.[4] This has been realized by cooling directly a mixture of helium and rubidium from 430 K to 20 K. Our source is steady-state and produces a clean vapor that is essentially composed only of rubidium and inert helium, because the apparatus is operated at relatively low temperatures (less than $\sim$450 K). This is a major advantage compared to rubidium sources, which rely on laser ablation, where the hot ablation plume is likely a mixture of atoms, ions and unwanted contaminants from the precursor surface.

The dominant decoherence channel in buffer gas cells is through the spin–orbit interaction during collisions with the buffer gas. There is both theoretical [16, 19] and experimental [10, 18] evidence that helium–alkali collisional relaxation cross sections decrease rapidly as the temperature is lowered. Given our high atomic density and projected long coherence times, this system is a very promising alternative to room temperature vapor cells for several experimental applications including nonlinear optics and atomic magnetometry[5].

Moreover, the new method we present here is an ideal approach to fundamental collision studies. In particular, there has been no systematic experimental study of the suppression of decoherence in low-temperature buffer gas cells due to the insufficient vapor pressure of alkalis at these temperatures [16]. Our system is well suited for these studies as it allows for fairly independent tuning of the alkali temperature and density in a regime previously inaccessible due to vapor pressure limitations.

2. Apparatus

Figure 1 shows the apparatus, which is very similar to our previously demonstrated direct flow cooling experiments [20]. Room temperature buffer gas is allowed to flow through an oven containing liquid and vapor rubidium. The mixture then flows through a short ultem tube (polyetherimide), which functions as a thermal break, into a cold (6 K) cell tube where it immediately begins to cool. The cell is continuously pumped with a mechanical rotary pump at about 25 liters s^{-1}.

Our oven is run at a temperature of 450 K producing copious amounts of atomic rubidium (the 1 g sample of rubidium we typically load into the oven lasts a few hours before the rubidium density in the oven starts being limited by the depletion of the source). Most (99%) of the rubidium emanating from the oven ends up plated on the walls of the transition tube and of the

[4] The optical density of the sample is defined as $\mathrm{OD} = -\log_e(I_{\mathrm{observed}}/I_{\mathrm{incident}})$, I being the intensity of the probe light.

[5] The figure of merit for the sensitivity of a measurement is $\delta B \sim 1/N\tau$ [1], where N is the atom number and τ the spin coherence time.

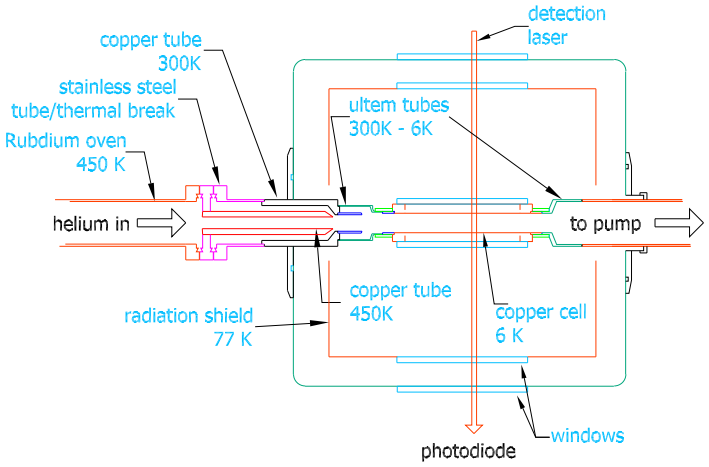

Figure 1. A mixture of helium buffer gas and rubidium flows through an ultem tube (wall thickness 0.5 mm and length 30 mm) from an oven held at ∼450 K, where the rubidium has a significant vapor pressure (10^{-2} torr), to a cryogenic cell anchored to a liquid helium bath. Considerable care is taken to keep the transition region as short as possible in order to minimize losses while maintaining an adequate thermal disconnect. With 250 sccm of helium flowing, the helium pressure is 6 torr at the tube input and 400 millitorr at the tube output, and the forward velocity of the beam is about 3 m s^{-1}. The optical path length within the cold cell is 1 cm.

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, which is currently bound to a few hours before the apparatus must be warmed and restarted. Warmup to room temperature is an overnight process. The problem of rubidium plating could be mitigated if the transfer pipes are replaced by tubes with deep corrugations in their interior walls, thus preventing continuous films of metal from forming. It may also be possible to recycle the plated rubidium, for example by heating the apparatus and flowing warm helium backwards towards the oven.

3. Results

Cold rubidium is detected via absorption spectroscopy on the rubidium 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 carried out 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 rubidium density but identical gas flow rates. Under these conditions a clear Doppler width is measured.

Figure 2 shows absorption signals for cold rubidium under conditions of identical gas flow and oven temperature. Figure 2(a) shows an absorption signal taken with very little rubidium in

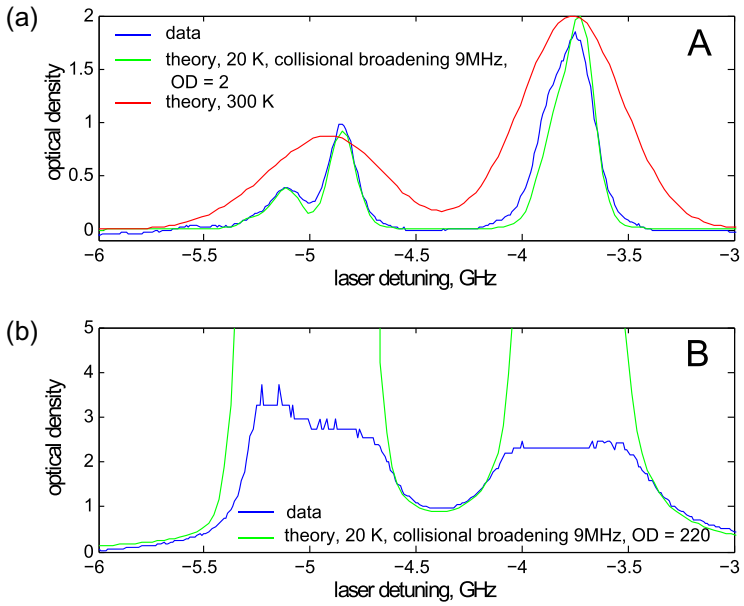

Figure 2. Absorption spectra of cold Rb. (a) The spectrum is taken with the Rb in the oven nearly gone. The low density of the sample means that it can be well fit to a Doppler-broadened spectrum, with a measured temperature of 20 ± 4 K and a measured optical density of 2.0. (b) The spectrum is taken 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 110 times the measured density in A. Except for the oven Rb level, conditions in A and B are identical (oven at 450 K, 250 sccm of helium flow). The measured temperature of the cell in both cases is 7 K. The optical density was estimated by fitting the spectrum to calculated spectra with different values for temperature, pressure broadening and optical density, and choosing the parameters that lead to the closest fit. Equally good fits were found for the spectrum in B with pressure broadening of 40 MHz and a temperature of 10 K.

the oven (the oven was nearly empty, thus providing low rubidium flux). The sample was at a temperature of ∼20 K and an Rb density of 1.5×10^{10} cm^{-3}. Figure 2(b) shows a typical signal when the oven is full. Due to the very small fraction of Rb in the flow in both cases we believe the temperatures to be close to identical.

The exact temperature distribution of the Rb vapor is unknown, although we can say that most of the Rb is at a temperature less than 25 K. Doppler broadening is the dominant broadening mechanism in this regime (Doppler linewidth ∼70 MHz), but the role of Lorentzian collisional broadening, especially in the wings of the spectrum, cannot be ruled out. Our spectra can in fact show satisfactory fits to both a 20 K sample with small collisional broadening (∼7.5 MHz) and a 10 K sample with significant collisional broadening (∼40 MHz). The former case is shown in figure 2. The low-temperature He–Rb broadening parameters are at present unknown [21] although they are expected to scale as $1/\sqrt{T}$, where T is the gas temperature [21, 22]. Using previous data taken in the 300 K regime [21]–[23], this temperature scaling and a worst-case pressure for the buffer gas in the cell of 1 torr, we estimate pressure broadening in our spectra to be in the 7–20 MHz regime. The uncertainty in this calculation precludes us

from measuring our ultimate optical density to better than a factor of 2; the peak optical density attained was 100–200.

Any rubidium atom that 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 satisfies $\sigma_{A-\mathrm{He}} > \sigma_{\mathrm{He}-\mathrm{He}}$ [24]. With species that have larger cross-sectional area it is possible to find a helium density such that thermalization is essentially complete while loss to the walls is minimal [20], resulting in a large increase in phase space density[6]. With smaller species the experimenter must compromise. In our system we observe that at low helium densities ($n_{\mathrm{He}} \approx 10^{17}\,\mathrm{cm}^{-3}$, 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, $n_{\mathrm{Rb}} \approx 10^{10}\,\mathrm{cm}^{-3}$) of the rubidium remains in the gas phase. At higher helium densities ($n_{\mathrm{He}} \approx 4 \times 10^{17}\,\mathrm{cm}^{-3}$, 400 sccm flow rate) the rubidium density is larger ($n_{\mathrm{Rb}} \approx 3 \times 10^{12}\,\mathrm{cm}^{-3}$), 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.

4. 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. Typical parameters for the rubidium gas are densities of $3 \times 10^{12}\,\mathrm{cm}^{-3}$ at temperatures of 20 K. This is a new source of optically dense samples of atomic rubidium with a variety of technological and scientific applications.

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[6] We are using the term to refer to the density occupancy of quantum states. 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.

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