Sympathetic Cooling with Two Atomic Species in an Optical Trap

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We simultaneously trap ultracold lithium and cesium atoms in an optical dipole trap formed by the focus of a CO_2 laser and study the exchange of thermal energy between the gases. The optically cooled cesium gas efficiently decreases the temperature of the lithium gas through sympathetic cooling. Equilibrium temperatures down to 25 μK have been reached. The measured cross section for thermalizing ^{133}Cs-^{7}Li collisions is 8×10^{-12} cm^2, for both species unpolarized in their lowest hyperfine ground state. Besides thermalization, we observe evaporation of lithium purely through elastic cesium-lithium collisions (sympathetic evaporation).

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Exchange of heat through thermal contact between two ensembles is the most obvious and ubiquitous thermodynamic process. Heat flows from the hotter component in a gas mixture to the colder one. Thus, as a general method to cool an atomic or molecular ensemble, one can mix it with a colder gas in a combined trap (sympathetic cooling). This process is particularly useful if the heat absorbed by the cooling agent can be extracted in an efficient and direct way, e.g., by laser cooling. Sympathetic cooling has first been demonstrated with charged particles which thermalize through the long-range Coulomb interaction [1]. For neutral atoms and molecules, cryogenically cooled helium gas at well below 1 K can be used as a cooling agent [2]. Only recently, sympathetic cooling has successfully been extended to the ultracold regime [3–8]. Quantum degeneracy of bosons and fermions was obtained by thermalization between atoms of the same species in different internal states [3], between two isotopes of the same species [4–6], and, as a recent highlight, between atoms of different species [7,8]. The degree of quantum degeneracy obtained in those experiments was finally limited by two important loss processes: exoergic collisions between magnetically trapped atoms, and evaporation, which decreases the heat capacity of the cooling agent.

In this Letter, we explore the thermodynamics in a mixture of two different atomic gases at ultralow temperatures. We present an intrinsically loss-free approach which can be generalized to a vast range of atomic species and even molecules. Both the coolant gas and the gas of interest are in their internal energetic ground state, which excludes exoergic binary collision. The gases are confined to the same region in space by the optical dipole force [9], and the coolant gas is cooled by pure optical techniques [10] which can be applied in an optical dipole trap without significant loss. Our model system is a mixture of cesium and lithium in an extremely far-detuned optical dipole trap. Cesium is an excellent cooling agent, since it can be optically cooled to very low temperatures, mainly due to its high mass. Lithium, on the other side, is difficult to cool optically. In addition, it is nearly an ideal gas due to the very small cross section for elastic Li-Li collisions [5].

Thermalization of Li thus occurs purely through collisions with the Cs atoms. From the time scale of thermalization one can deduce the *a priori* unknown interspecies scattering cross section. Sympathetic cooling in a trap of finite depth is in general accompanied by evaporation through elastic Li-Cs collisions (sympathetic evaporation), as we have recently outlined in Ref. [11]. We investigate the relation between these two thermodynamic processes.

To trap a mixture of ultracold species, the focus of a CO_2 laser beam, at $\lambda = 10.6$ μm, constitutes an almost perfect realization of a conservative trapping potential (quasielectrostatic trap, QUEST) [9,12–14]. Atoms and molecules can be stored in any internal state, especially the energetic ground state. For atoms in the lowest-energy hyperfine state, energy-releasing processes in two-body collisions cannot occur. Because of the large detuning of the laser frequency from any atomic resonances, heating through photon scattering can be completely neglected.

Using a commercial sealed-tube laser, we obtain a power of 108 W in the vacuum chamber, focused to a waist $w_0 = 86$ μm. For a Gaussian laser beam, with power P the trap depth is given by $U_0 = \alpha_{stat}P/(\pi \varepsilon_0 c w_0^2)$ where α_{stat} denotes the static polarizability of the atom. For cesium and lithium one gets $U_0^{Cs}/k_B = 0.85$ mK and $U_0^{Li}/k_B = 0.34$ mK, respectively, with an experimental uncertainty of 10%. The radial and axial oscillation frequencies of trapped Cs (Li) atoms are $\omega_{x,y}/2\pi = 0.85$ kHz (2.4 kHz) and $\omega_z/2\pi = 18$ Hz (50 Hz). The measured axial oscillation frequency is half as large as the value expected for a pure Gaussian beam which indicates aberrations in our laser focus [11]. Atoms are transferred into the dipole trap from magneto-optical traps (MOT) for lithium and cesium which are superimposed on the focus of the CO_2 laser beam. Both MOTs are loaded from Zeeman-slowed atomic beams. The lifetime of the gas is limited only by rest-gas collisions to $\approx$100 s. Details of our apparatus and of the procedure for loading atoms into the QUEST are given in Refs. [11,14].

When loaded separately, we obtain 5×10^5 Cs atoms in the QUEST, which we cool by polarization gradient cooling to 20 μK. We find that, for comparable densities,

the temperature is lower for a shallower trap, while in free space we reach temperatures below 3 μK. Apparently, the Stark shifts caused by the QUEST influence the cooling process. The Cs is optically pumped into the lowest hyperfine state ($F = 3$), and since we compensate the magnetic field, the atoms are distributed evenly over the degenerate m_F states. The peak density of Cs atoms in the QUEST is $\sim 2 \times 10^{11}$ cm^{-3}. Since the scattering length of the Cs is larger than the typical inverse relative wave vector in collisions, the internal thermalization of the Cs gas is dominated by the unitary maximum s-wave scattering cross section [15] $\sigma_{CsCs} = 4\pi/k^2$, where k is the relative wave vector. We use the expression for distinguishable atoms since the majority of the collisions are between atoms in different m_F states. The collision rate is approximately 7 s^{-1}, and thermalization through Cs-Cs collisions is estimated to take ~ 2 s [15].

The situation for Li is different: since the temperature reached in the MOT is higher than the trap depth, only approximately 10^5 atoms are transferred. Numerical simulations indicate these atoms occupy a truncated thermal distribution with an internal energy of $\sim 3k_B \times 75$ μK, which only very weakly depends on the MOT temperature. The lithium atoms are optically pumped into the $F = 1$ hyperfine state, and in the absence of a magnetic guiding field distribute themselves over the degenerate m_F states. As the scattering length of Li in the $F = 1$ state is anomalously small [5], the distribution does not thermalize on the 100 s time scale of our experiment.

In order to simultaneously trap the two species, a Cs MOT is loaded and the atoms transferred into the QUEST in optical molasses. Subsequently, a Li MOT is loaded at a slightly different position, to minimize light-induced atom loss in a two-species MOT [16]. Once it reaches the desired density, the Li MOT is compressed and overlapped with the QUEST for a few ms to optimize transfer of Li atoms. We can simultaneously trap typically 4×10^4 Li atoms with up to 10^5 Cs atoms.

After a variable interaction time in the QUEST, usually a few seconds, we analyze the gas sample. The temperature and atom number of Cs are determined by absorption imaging and time-of-flight velocimetry. The lithium gas in our trap is too dilute to use absorption imaging. We determine the temperature of the lithium gas using a release-recapture method. The dipole trap potential is suddenly turned off for a variable ballistic expansion time of order 1 ms. After this time, the dipole trap is turned on again for ~ 500 ms to recapture the remaining fraction of atoms. The number of recaptured atoms is then measured by the fluorescence in a MOT.

Figure 1 shows two such release-recapture measurements: one for a pure Li ensemble and one for a Li ensemble that has been trapped simultaneously with cold Cs. The pure Li gas is seen to be lost from the trap in ~ 0.4 ms, while the ensemble of Li that has been in thermal contact with cold Cs is seen to contain many
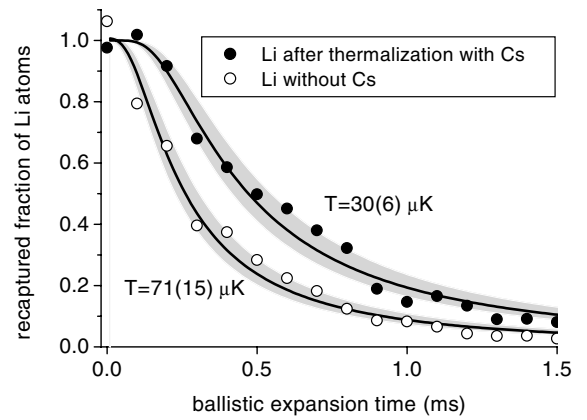

FIG. 1. Release-recapture thermometry for Li atoms. The atoms are recaptured into the optical dipole trap after a variable time of free expansion. Open circles: Li without Cs. Closed circles: Li thermalized with Cs for 5 s. Solid lines: Fit of Eq. (1) to the data. The gray area depicts a 20% variation in the temperature.

more slow atoms, which indicates cooling. We derive an analytical approximation of the number of recaptured atoms for a gas at low temperature ($k_B T \ll U_0$) in an extremely elongated Gaussian trap ($\omega_{ax} \ll \omega_{rad}$):

$$N_r(t) = \frac{N_0}{1 - e^{-\eta}} \{1 - \exp[-\eta W(\tilde{t}^2)/\tilde{t}^2]\}. \quad (1)$$

Here w_0 is the Gaussian beam waist, $\eta = U_0/k_B T$, $\tilde{t}^2 = m w_0^2 t^2 / 4 U_0$, and $W(z)$ is the product logarithm function, satisfying $W(z) \exp(W(z)) = z$. The analytical approximation of Eq. (1) agrees with numerical simulation for temperatures up to $k_B T \sim 0.15 U_0$. Full numerical calculation of $N_r(t)$ is possible for any T and shows that for $k_B T > 0.2 U_0$ (75 μK for Li) the width of the recapture curve becomes essentially independent of temperature; i.e., release-recapture measurements no longer provide reliable temperature data. Hence, Eq. (1) can be used over the entire range of useful parameters. For the temperature range of interest, we estimate the accuracy of this method to be better than 20%. The release-recapture curve of the pure Li in Fig. 1 can be reproduced by assuming a thermal distribution at $T_{Li} = 71 \pm 15$ μK. The sympathetically cooled Li ensemble is well described by $T_{Li} = 30 \pm 6$ μK, which is equal to the Cs temperature within the uncertainty margins, indicating that the gases have fully thermalized.

The thermalization time is measured by taking a series of temperature measurements for both components, as seen in Fig. 2. The Cs and Li temperatures converge to the same value $\bar{T} = 33$ μK. The measured atom numbers show that no significant loss of either Li or Cs occurs during thermalization. The thermalization time is 1.6(2) s, indeed, much shorter than the rest-gas induced decay time of the trapped gas. In a gas mixture with energy independent cross section, the average energy transferred per collision is $k_B \Delta T \xi$, where ΔT is the temperature difference
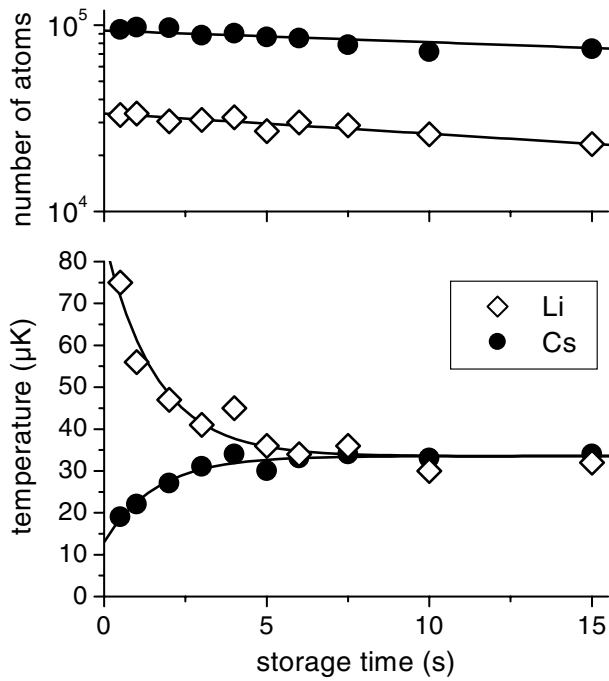
FIG. 2. Evolution of Cs and Li temperatures (lower graph) and atom numbers (upper graph) during simultaneous storage. The temperatures exponentially approach equilibrium with a thermalization time constant of 1.6(2) s (solid lines in lower graph). The decay constant of the number of trapped atoms is 70 s for Cs and 40 s for Li.

between the components, and $\xi = 4m_1 m_2/(m_1 + m_2)^2$ is the reduction factor due to the mass difference ($\xi = 0.19$ for a Li-Cs mixture). The heat capacity of a harmonically trapped atomic gas is $3k_B$ per atom, leading to an average number of $3/\xi$ collisions per Li atom (assuming $N_{Cs} \gg N_{Li}$) needed for thermalization [11,15,17]. The thermalization rate is given by

$$\gamma_{therm} = -\frac{1}{\Delta T}\frac{d}{dt}\Delta T = \frac{\xi}{3}\frac{N_{Cs} + N_{Li}}{N_{Cs}}\gamma_{Li}, \quad (2)$$

where the collision rate per Li atom γ_{Li} is determined by the total Li-Cs collision rate $\Gamma_{LiCs} = \gamma_{Li}N_{Li}$. From the measured thermalization rate we calculate $\gamma_{Li} = 7(1)$ s^{-1}.

The Li atoms have as high a collision rate with Cs as the Cs atoms themselves, even though the Cs-Cs collisions have the maximum s-wave cross section. The explanation for this lies in the small unitary cross section and the low thermal velocity for Cs, both a result of the high mass. The collision-enhancing effects of the low Li mass compensate the loss of thermalization efficiency that is caused by the mass ratio factor ξ. The inferred cross section for Li-Cs collisions is $\sigma_{LiCs} = 8(4) \times 10^{-12}$ cm^2, where the main limitation of the accuracy is the determination of the absolute densities. Assuming s-wave scattering dominates, we find an effective s-wave scattering length $|a_{LiCs}| = (\sigma_{LiCs}/4\pi)^{1/2} = 180^{+40}_{-50}a_0$ [18].

In a trap of finite depth, thermalizing collisions lead to evaporation of particles. This evaporation is practically absent in two cases: if the temperature is much lower than the trap depth (as is the case for pure Cs samples in our trap) or if the collision rate is extremely small (as is the case for pure Li samples in our trap). The thermalizing Li-Cs collisions enable, besides cooling, evaporation of the Li from the trap. The Li evaporates even under conditions where the Cs evaporation is negligible, as the trap depth for Li is significantly smaller than for Cs. Assuming energy-independent cross sections, the evaporation probability per collision in an ensemble where the Cs and Li are thermalized is $P_{evap} \sim \eta \exp(-\eta)$, where $\eta = U_0^{Li}/k_B T$. In numerical simulations [11] for the relevant mass ratio and range of η, we find an atom loss rate $\gamma_{evap} \simeq 0.5\eta e^{-\eta}\gamma_{Li}$. In particular, the simulations confirm that P_{evap} is almost independent of the mass ratio as long as $\eta > 2/\xi$.

Figure 3 shows the evolution of the number of trapped Li atoms in thermal contact with a Cs gas at a temperature of 37 μK. The inset shows the evaporation rate γ_{evap} as a function of temperature. We fit the numerical model to the data, with γ_{Li} as the only free parameter, and obtain a fit at $\gamma_{Li} \sim 30$ s^{-1}, which results in an effective cross section for evaporation of about 3×10^{-11} cm^2. Because of simplifying assumptions in the numerical model and because of the experimental uncertainties mainly in the determination of the temperature, we estimate an uncertainty of a factor of 3 for this value of the cross section [19]. The cross section is thus consistent with the more precise cross section determined from thermalization. Obviously, sympathetic evaporation of the Li gas is accompanied by a transfer of thermal energy from the "cold" Cs to the "hot"
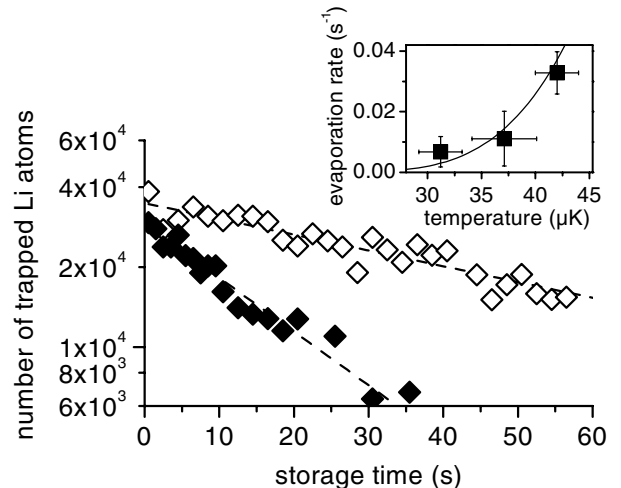

FIG. 3. Evaporation of Li atoms through Li-Cs collisions. Main graph: Evolution of the number of stored Li atoms without Cs (open diamonds) and with Cs at a temperature $\bar{T} = 37(2)$ μK (closed diamonds). Inset: Evaporation loss rate (corrected for rest-gas losses) versus temperature. The solid line is a model fit to the data (see text).

Li ensemble. By choosing appropriate conditions for the Cs particle number and initial temperature, we could indeed observe the decrease of the Cs temperature through sympathetic evaporation of Li.

Sympathetic evaporation poses a limit to thermalization in shallow traps: a considerable fraction of the atoms is lost during the first thermalization time for traps with $U_0^{Li}/k_B\bar{T} < W(3/\xi)$ ($\bar{T}$ is the average temperature, W is the product logarithm function). For the Li-Cs mass ratio, thermalization without significant loss is possible if $\eta \gtrsim 4$. In the initial few collisions, the Li distribution is far from thermal equilibrium with the Cs, and the evaporation loss cannot be estimated analytically. In numerical simulations we see a small loss of Li atoms in the initial few collisions, which is $<10\%$ if $k_B T_{Cs} < U_0^{Li}/10$, in qualitative agreement with the experimental data in Fig. 3.

The usefulness of sympathetic cooling depends strongly on the time scale of thermalization. To reach the quantum degenerate regime in our trap geometry, the temperature of the Li gas must be decreased by 2 orders of magnitude from the initial temperature after loading, which takes ~5 thermalization times, assuming the Cs is optically cooled to be always much below the Li temperature. This means only an average number of ~50 Li-Cs collisions are needed for sympathetic cooling, compared with more than 1000 Li-Li collisions for evaporative cooling of Li to BEC.

The heat which the Li transfers to the Cs can be removed by repeated pulsed optical cooling. This is more efficient than continuous cooling since the light-induced inelastic collisions can act only during the short (20 ms) cooling pulses, while thermalization continues over longer time. In this way, we have been able to reach Li temperatures down to 25 μK. The main limitation for reaching lower temperatures is the base temperature of the Cs polarization-gradient cooling. Different optical cooling schemes such as Raman-sideband cooling [20] may provide lower Cs temperatures and ultimately an evaporation-free route to quantum degeneracy of both the fermionic and bosonic lithium isotopes.

Another intriguing aspect of the Li-Cs mixture is the formation of cold heteronuclear molecules. By loss-free sympathetic cooling, we reach densities of 2×10^{10} cm^{-3} and 2×10^{11} cm^{-3} for lithium and cesium, respectively, which provide good starting conditions for photoassociation experiments [21]. Once the cold molecules are formed they may be stored in the quasielectrostatic trap together with the atomic gases as a first step towards cold quantum chemistry. In addition, the large electric dipole moment of the LiCs dimer can be used to manipulate and control internal and external degrees of freedom of the molecules.

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