PHYSICAL REVIEW A, VOLUME 64, 021402(R)

Sympathetic cooling of ^{85}Rb and ^{87}Rb

Immanuel Bloch, Markus Greiner, Olaf Mandel, Theodor W. Hänsch,* and Tilman Esslinger
Sektion Physik, Ludwig-Maximilians-Universität, Schellingstrasse 4/III, D-80799 Munich, Germany
and Max-Planck-Institut für Quantenoptik, D-85748 Garching, Germany
(Received 22 December 2000; published 10 July 2001)

We demonstrate sympathetic cooling between magnetically trapped ^{85}Rb and ^{87}Rb atoms. Up to 6×10^6 ^{85}Rb atoms are cooled via elastic collisions with a reservoir of 8×10^8 ^{87}Rb atoms. The temperature of the binary atomic ensemble is adjusted by using radio-frequency evaporation of ^{87}Rb. Temperatures as low as $T=100$ nK have been realized in the binary ensemble. Through a cross-dimensional mixing approach we have been able to measure the interspecies ^{87}Rb-^{85}Rb scattering cross section $\sigma=1.52(34)\times10^{-15}$ m^2.

DOI: 10.1103/PhysRevA.64.021402 PACS number(s): 32.80.Pj, 03.65.Nk, 03.75.Fi, 05.30.Jp

The advent of powerful cooling schemes for neutral atoms has enabled ground breaking experiments in physics. Laser cooling and evaporative cooling have proved to be the crucial ingredients in the realization of Bose-Einstein condensation in dilute atomic gases [1]. Laser cooling can be applied to most atomic species, as long as the required laser wavelengths are available. The conditions under which evaporative cooling can be used to chill a trapped atomic gas are more stringent. This cooling method requires a combination of high atomic density, large atom number, and favorable characteristics of the atomic collisions [2]. Only a very limited range of atomic species has therefore been evaporatively cooled to ultralow temperatures. Sympathetic cooling may provide a way out of this dilemma. It relies on cooling a certain atomic or even molecular species by bringing this species into thermal contact with a cold reservoir of atoms. In the ultracold regime, sympathetic cooling has been demonstrated for different spin states of one atomic species [3,4] and is now being applied to boson-fermion mixtures [5].

In this Rapid Communication we report on the realization of sympathetic cooling between two different bosonic isotopes, namely between the two rubidium isotopes ^{87}Rb and ^{85}Rb. An initially laser cooled sample of less than 10^7 ^{85}Rb atoms is sympathetically cooled via elastic collisions with an evaporatively cooled cloud of ^{87}Rb atoms. Temperatures as low as 100 nK are reached in the mixed isotope gas. We have also been able to produce ^{87}Rb condensates in the presence of an ultracold thermal cloud of ^{85}Rb atoms.

Due to its favorable scattering properties, the ^{87}Rb isotope can easily be cooled by evaporation and it is therefore ideally suited to act as a refrigerator for other atomic species. In contrast, the ^{85}Rb isotope is difficult to cool by evaporation since its *s*-wave scattering cross section vanishes for collision energies of $E\approx k_B\times375$ μK (k_B: Boltzmann's constant). Evaporative cooling of ^{85}Rb has only been possible so far in the lower hyperfine ground state by exploiting a Feshbach resonance to tune the scattering length [6]. By mixing both isotopes we achieve almost an order of magnitude shorter cooling times than those reported before [6]. The cooling efficiency for the ^{85}Rb atoms is boosted by the interactions between the two atomic species. Since only ^{87}Rb atoms are selectively evaporated, the method is not sensitive to the initial number and density of the ^{85}Rb sample.

The crucial aspect of sympathetic cooling is the interaction between the different atomic species. We have quantitatively measured the scattering cross section for collisions between ^{87}Rb and ^{85}Rb atoms and obtain a value for the cross section that is two times larger than the scattering cross section for collisions between ^{87}Rb atoms, in good agreement with theoretical predictions. Sympathetic cooling of atomic mixtures may also pave the way towards degenerate boson-boson or boson-fermion [5] quantum gases of different atomic species. Both systems provide a unique testing ground for the physics of interacting quantum systems with a rich variety of new physical phenomena [7–12] to be explored.

In the experiment, the two rubidium isotopes are first collected in a vapor cell magneto-optical trap (MOT) with large beams (apertured to a diameter of 40 mm). The main cooling light for both isotopes is derived from a master-oscillator power amplifier (MOPA) diode laser system. Up to 100 mW of this laser power is available after an optical fiber at the MOT. The MOT loading process is divided into two stages. During the first 15 s the MOPA system exclusively provides cooling light on the $|F=2\rangle\rightarrow|F=3\rangle$ ^{87}Rb transition (F denotes the total angular momentum of the atom). Then 10% of the MOPA laser power is used to additionally collect ^{85}Rb atoms over the next 900 ms. This is achieved by injecting another laser running on the $|F=3\rangle\rightarrow|F=4\rangle$ ^{85}Rb transition into the amplifier [13]. The laser frequencies are red detuned by 18 MHz with respect to the $|F=2\rangle\rightarrow|F=3\rangle$ ^{87}Rb transition and by 7 MHz with respect to the $|F=3\rangle\rightarrow|F=4\rangle$ ^{85}Rb transition. After an 8-ms optical molasses phase the isotopes are optically pumped into the weak-field-seeking states $|F=2,m_F=2\rangle$ (^{87}Rb) and $|F=3,m_F=3\rangle$ (^{85}Rb), where m_F denotes the magnetic sublevel. A magnetic quadrupole potential is then rapidly turned on in order to confine the atoms. Using a series of computer activated magnet coils, the quadrupole potential is moved over 33 cm into an UHV glass cell [14], where the magnetic quadrupole potential is converted into a Ioffe-type potential using the quadrupole-Ioffe configuration trap mechanism [15]. The trapping frequencies of the final magnetic trap are $\omega_z=2\pi\times24$ Hz in the axial and $\omega_\rho=2\pi\times219$ Hz in the radial direction.

*Also at Department of Physics, University of Florence, Florence, Italy.

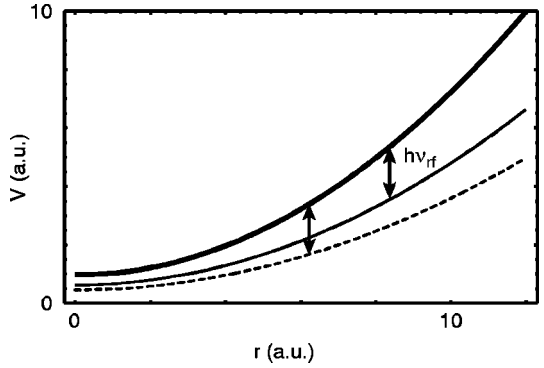

FIG. 1. Potentials of the trapped atomic states $|F=2,m_F=2\rangle$ of ^{87}Rb and $|F=3,m_F=3\rangle$ of ^{85}Rb (thick line) and their neighboring magnetic sublevels $|F=2,m_F=1\rangle$ (^{87}Rb) (dashed line) and $|F=3,m_F=2\rangle$ (^{85}Rb) (thin line). In a mixed cloud at thermal equilibrium the radio frequency, indicated by the arrows, predominantly evaporates ^{87}Rb atoms, since the energy at which the ^{85}Rb atoms are removed is higher than the energy at which ^{87}Rb atoms are removed. Both species experience the same confining potential and overlap completely.

Approximately 8×10^8 ^{87}Rb and 3×10^6 ^{85}Rb atoms are present in the final magnetic trap. The two atomic species are initially prepared in states of equal magnetic moment, so that they experience the same confining potential. However, the different Landé g_F factors of the two hyperfine states ($g_F=1/2$ for ^{87}Rb and $g_F=1/3$ for ^{85}Rb) lead to an unequal splitting between neighboring magnetic sublevels. For the same magnetic field, the energy splitting due to the linear Zeeman effect between neighboring magnetic sublevels in the $|F=2\rangle$ ^{87}Rb manifold is 50% larger than in the $|F=3\rangle$ ^{85}Rb manifold (see Fig. 1). Radio-frequency evaporation therefore predominantly removes hot ^{87}Rb atoms. The ^{85}Rb atoms remain almost unaffected as long as they thermalize with the cooler ^{87}Rb atoms on a time scale that is faster than that given by the radio-frequency sweep. Adjusting the time scale of the evaporation process to the ^{85}Rb thermalizaton time therefore allows us to be highly isotope selective in the removal of hot atoms. A perfectly isotope selective evaporation could be realized by using microwave photons tuned to the ^{87}Rb hyperfine energy splitting.

The number and temperature of the atoms during the evaporation process are measured using absorption imaging after an adjustable ballistic expansion time. In a single run of the experiment we are able to detect both atomic species by using the following procedure. We first apply a 100-μs pulse of light tuned to the ^{85}Rb $|F=3\rangle\rightarrow|F=4\rangle$ transition and 2 ms later we apply a 100-μs pulse of light tuned to the ^{87}Rb $|F=2\rangle\rightarrow|F=3\rangle$ transition. During 18 s of radio-frequency evaporation we are able to cool the mixed atomic sample to temperatures well below 1 μK. The number of atoms of both isotopes are displayed in Fig. 2 for different temperatures below 60 μK along the evaporation trajectory. While cooling the sample to a temperature of 2 μK, the number of ^{87}Rb atoms has decreased by roughly three orders of magnitude, whereas the number of ^{85}Rb atoms has decreased only by a factor of 3. We have furthermore observed that all ^{85}Rb atoms are removed in the evaporation process if there are no

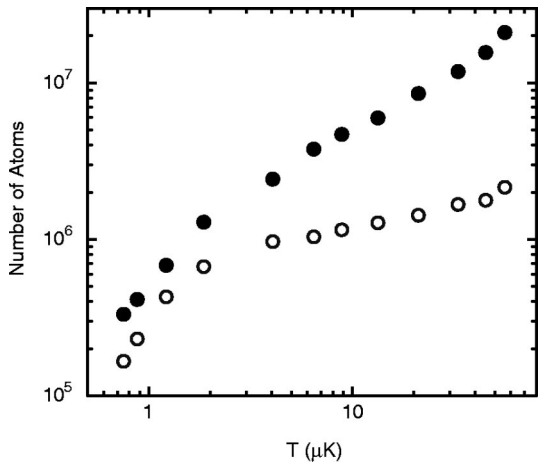

FIG. 2. Number of atoms versus temperature along the evaporation trajectory of the mixed species ensemble. The filled circles denote the number of ^{87}Rb atoms, while the open circles denote the number of ^{85}Rb atoms.

^{87}Rb atoms present in the magnetic trap. This is caused by the fact that thermalization of the pure ^{85}Rb cloud is suppressed by the vanishing *s*-wave collision cross section of ^{85}Rb for collision energies of $E\approx k_B\times375$ μK [16]. Therefore all atoms are removed during evaporation. This property is responsible for the severe difficulties associated with evaporatively cooling ^{85}Rb [6]. In a cloud of ^{85}Rb atoms adiabatic compression results in a dramatic decrease of the elastic collision rate, as the scattering cross section decreases by orders of magnitude with increasing temperature [16]. For our case the initial ^{85}Rb intraspecies collisions are completely negligible and we therefore conclude that interspecies collisions play a crucial role in thermalizing the ^{85}Rb cloud of atoms at higher temperatures during the evaporation process. Indeed, Burke *et al.* [16] predict an almost constant and large interspecies collision cross section between the ^{87}Rb-^{85}Rb isotopes for temperatures up to 1 mK. For temperatures below 1 μK the evaporative cooling process becomes inefficient, as can be seen from the increased slopes of the $\log N$ vs $\log T$ graph of Fig. 2. This can partly be attributed to the increasing number of inelastic events predicted for collisions of atoms in the $|F=2,m_F=2\rangle$ (^{87}Rb) and $|F=3,m_F=3\rangle$ (^{85}Rb) states and also to the fact that the number of atoms in our ^{87}Rb cooling medium are approaching the number of ^{85}Rb atoms so that we cannot sustain a completely isotope selective evaporation. Furthermore, the triplet scattering length in ^{85}Rb has a large and negative value, and allows only condensates with a very small number below 100 atoms to be produced. Presently, such a low number of atoms cannot be detected unambiguously in our setup. Nevertheless, we have been able to produce ^{87}Rb condensates of up to 10^5 atoms coexisting with a thermal cloud of ^{85}Rb atoms.

In order to characterize the interactions between the two atomic species we have measured the ^{87}Rb-^{85}Rb interspecies scattering cross section through a cross-dimensional mixing approach [18]. At temperatures of 6.6 μK, samples of atoms are prepared with 3.3×10^5 ^{85}Rb atoms and 1.5×10^5 ^{87}Rb

atoms. The mixed atomic ensemble is then heated parametrically by modulating the radial trapping frequency at twice its resonance frequency for 50 ms. Energy is thereby added to the radial axes of the atomic ensemble. This leads to a nonequilibrium situation with a radial temperature of the cloud larger than the axial temperature of the cloud. In this nonequilibrium state the cloud of atoms has a smaller aspect ratio $\Delta z/\Delta\rho$ than in the equilibrium situation, where $\Delta z/\Delta\rho=\omega_\rho/\omega_z$. Here $\Delta\rho$ and Δz are the radial and axial extensions of the trapped cloud of atoms. The subsequent relaxation of the aspect ratio of the trapped ensemble of ^{87}Rb atoms towards the equilibrium value due to elastic collisions is then monitored versus time. In order to verify that this relaxation of the aspect ratio is in fact due to elastic collisions and not due to anharmonic mixing between the motion of the atoms along the three trapping axes, we have verified that the relaxation rate scales with the density of our trapped ensembles. We have also checked that the change in density of both atomic species due to loss of atoms or heating rates is below 2% for a thermalization time of 1 s. Furthermore, the total energy of the atoms remains constant within our measurement time. We obtain the interspecies scattering cross section by comparing the time constant of the relaxation process of ^{87}Rb in the presence of ^{85}Rb with the time constant of the relaxation of a pure cloud of ^{87}Rb.

The relaxation rate Γ_{87}^{mix} for the ^{87}Rb component of the mixed atomic gas can be described by

$$\Gamma_{87}^{mix}=\alpha^{-1}\Gamma_{87}^{el}+\tilde{\alpha}^{-1}\Gamma_{87-85}^{el}$$
$$=\alpha^{-1}\bar{n}_{87}\sigma_{87}\bar{v}_{87}+\tilde{\alpha}^{-1}\bar{n}_{85}\sigma_{87-85}\bar{v}_{87-85}. \quad (1)$$

Here Γ^{el} denotes the elastic collision rate, α and $\tilde{\alpha}$ are constants relating the elastic collision rate to the cross-dimensional mixing time, $\bar{n}$ is the effective density of the atoms $\bar{n}=\int n^2(\mathbf{r})d^3r/\int n(\mathbf{r})d^3r$, σ is the elastic collision cross section, and $\bar{v}$ is the average relative velocity of the atoms. The respective indices 87, 85, and 87–85 indicate whether values for the single atomic species or the mixed species have to be inserted into the formula. The average relative velocity between ^{87}Rb atoms is given by $\bar{v}_{87}=4\sqrt{k_BT/\pi m_{87}}$, whereas the average velocity between ^{87}Rb and ^{85}Rb atoms can be expressed by $\bar{v}_{87-85}=\sqrt{8k_BT/\pi}\sqrt{(m_{87}+m_{85})/(m_{87}m_{85})}$ [17].

Through Monte Carlo simulations of the collision process and an analytical model, the constant α for intraspecies collisions has been found to be $\alpha\approx 2.7$ [18,19]. For the interspecies ^{87}Rb-^{85}Rb collisions we expect $\tilde{\alpha}$ to be slightly smaller, as the ^{85}Rb cloud is almost thermalized already after a short time due to its large scattering cross section. Therefore energy is more efficiently redistributed for collisions of ^{87}Rb atoms with these thermalized ^{85}Rb atoms. Using an analytical model based on Boltzmann's equation and a multispecies Monte Carlo simulation of the thermalization process, we find that $\tilde{\alpha}\approx\alpha/1.2(1)$ for our measurement parameters. In the analysis we have also assumed dominant *s*-wave scattering for ^{85}Rb-^{87}Rb interspecies and ^{87}Rb intraspecies collisions.

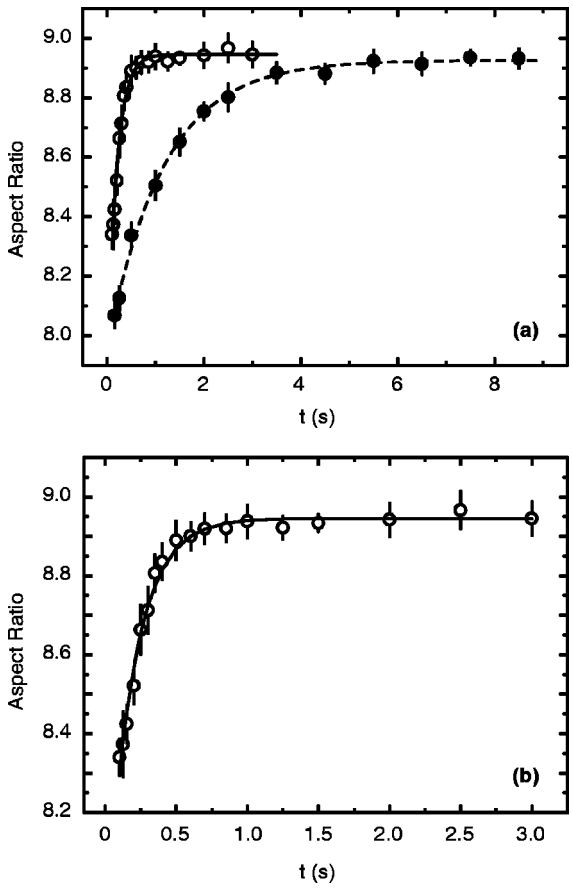

FIG. 3. Relaxation of the aspect ratio of an ensemble of ^{87}Rb atoms after parametric heating of the radial axes of the trapped atom cloud. (a) Closed circles denote the data for a pure ^{87}Rb ensemble of 1.5×10^5 atoms, while the open circles are the datapoints for the ^{87}Rb ensemble in the presence of 3.3×10^5 ^{85}Rb atoms. (b) Close-up of the ^{87}Rb data in the presence of ^{85}Rb. The solid and broken lines are fits to the data assuming an exponential decay of the aspect ratio towards the equilibrium value ω_ρ/ω_z. Each datapoint is an average over eight measurements and the error bars display the corresponding statistical errors. The temperature of the ensemble during the measurement was $T\approx 7$ μK. The $1/e$ time constant for the relaxation of the pure ^{87}Rb ensemble is $1/\Gamma_{87}=1160(100)$ ms. For the ^{87}Rb ensemble in the presence of ^{85}Rb it is $1/\Gamma_{87}^{mix}=190(20)$ ms.

Assuming Gaussian distributions for the density of the atoms, one can find a simple expression for the interspecies scattering cross section σ_{87-85}. By comparing the relaxation rate of ^{87}Rb in the mixed isotope ensemble to the relaxation rate of a pure ^{87}Rb ensemble at the same temperature and with the same number of ^{87}Rb atoms, one obtains

$$\sigma_{87-85}=\sqrt{2}\left\{\frac{\Gamma_{87}^{mix}}{\Gamma_{87}}-1\right\}\left(1+\frac{m_{87}}{m_{85}}\right)^{-1/2}\frac{N_{87}}{N_{85}}\frac{\tilde{\alpha}}{\alpha}\sigma_{87}. \quad (2)$$

Using the experimentally measured relaxation times from Fig. 3 with $N_{85}/N_{87}=2.2(2)$, we obtain $\sigma_{87-85}=1.92(40)\times\sigma_{87}$.

The single species ^{87}Rb cross section σ_{87} for atoms in the $|F=2,m_F=2\rangle$ state can be expressed through the ^{87}Rb trip-

let scattering length a_T^{87} as $\sigma_{87}=8\pi(a_T^{87})^2$. This triplet scattering length is well known through photoassociation spectroscopy, collision cross-section measurements and the location of the ^{85}Rb Feshbach resonance [20]. Since the rubidium isotopes are distinguishable from each other, the interspecies collision cross section is related to the interspecies triplet scattering length a_T^{87-85} by $\sigma_{87-85}=4\pi(a_T^{87-85})^2$. Using a recent value for $a_T^{87}=106(4)a_0$ (a_0 being the Bohr radius) [20,21], we obtain $\sigma_{87-85}=1.52(34)\times10^{-15}$ m^2 and $|a_T^{87-85}|=208(23)a_0$ for the absolute value of the interspecies triplet scattering length. This is in good agreement with recent theoretical predictions of $a_T^{87-85}=213(7)a_0$ (theory) [21].

In the ^{85}Rb and ^{87}Rb mixture the atom-atom interactions can be tuned via Feshbach resonances. The system is therefore ideally suited to study the behavior of two species Bose-Einstein condensates. In ^{85}Rb a Feshbach resonance in the $|F=2,m_F=-2\rangle$ state [6] allows one to tune the scattering length between ^{85}Rb atoms. In addition, there is a theoretical prediction for an interspecies Feshbach resonance in collisions between ^{87}Rb atoms in the $|F=1,m_F=-1\rangle$ state and ^{85}Rb atoms in the $|F=2,m_F=-2\rangle$ state that should allow one to adjust the interspecies scattering length [16].

In conclusion, we have demonstrated sympathetic cooling between ^{87}Rb and ^{85}Rb atoms in a magnetic trap. The severe difficulties in evaporatively cooling ^{85}Rb due to the zero *s*-wave scattering cross section of ^{85}Rb at collision energies of $E\approx k_B\times375$ μK have been circumvented by exploiting interspecies collisions between ^{87}Rb and ^{85}Rb atoms. We have furthermore been able to measure the collision cross section between different atomic species at ultralow temperatures.

We would like to thank Anton Scheich for experimental assistance during the construction of the experiment. We also acknowledge support by the Deutsche Forschungsgemeinschaft.

[1] M.H. Anderson *et al.*, Science **269**, 198 (1995); K.B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995); C.C. Bradley *et al.*, *ibid.* **75**, 1687 (1995); **78**, 985 (1997).

[2] W. Ketterle and N.J. van Druten, Adv. At. Mol. Phys. **37**, 181 (1996).

[3] C.J. Myatt *et al.*, Phys. Rev. Lett. **78**, 586 (1997).

[4] B. DeMarco and D.S. Jin, Science **285**, 1703 (1999).

[5] F. Schreck *et al.*, e-print cond-mat/0011291; A.G. Truscott *et al.*, Science **291**, 2570 (2001).

[6] J.L. Roberts, N.R. Claussen, S.L. Cornish, and C.E. Wieman, Phys. Rev. Lett. **85**, 728 (2000); S.L. Cornish *et al.*, *ibid.* **85**, 1795 (2000).

[7] T. Ho and V.B. Shenoy, Phys. Rev. Lett. **77**, 3276 (1996).

[8] C.K. Law *et al.*, Phys. Rev. Lett. **79**, 3105 (1997); H. Pu and N.P. Bigelow, *ibid.* **80**, 1130 (1998).

[9] B.D. Esry and C. Greene, Nature (London) **392**, 434 (1998).

[10] K. Mølmer, Phys. Rev. Lett. **80**, 1804 (1998).

[11] L. Viverit, C.J. Pethick, and H. Smith, Phys. Rev. A **61**, 053605 (1999).

[12] L. Vichi *et al.*, Eur. Phys. J. D **11**, 335 (2000).

[13] G. Ferrari, M.-O. Mewes, F. Schreck, and C. Salomon, Opt. Lett. **24**, 151 (1999).

[14] M. Greiner, I. Bloch, T.W. Hänsch, and T. Esslinger, Phys. Rev. A **63**, 031401 (2001).

[15] T. Esslinger, I. Bloch, and T.W. Hänsch, Phys. Rev. A **58**, 2664 (1998).

[16] J.P. Burke, Jr., J.L. Bohn, B.D. Esry, and C.H. Greene, Phys. Rev. Lett. **80**, 2097 (1998); J.P. Burke, Jr., Ph.D. thesis, University of Colorado, 1999.

[17] G.A. Bird, *Molecular Gas Dynamics and the Direct Simulation of Gas Flows* (Oxford Science, Oxford, 1994).

[18] C.R. Monroe *et al.*, Phys. Rev. Lett. **70**, 414 (1993); N.R. Newbury, C.J. Myatt, and C.E. Wieman, Phys. Rev. A **51**, 2680 (1995).

[19] H. Wu and C. Foot, J. Phys. B **29**, L321 (1996).

[20] J.L. Roberts *et al.*, Phys. Rev. Lett. **81**, 5109 (1998).

[21] J.P. Burke, Jr. and J.L. Bohn, Phys. Rev. A **59**, 1303 (1999).