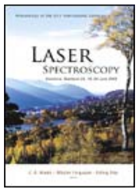
# LASER SPECTROSCOPY



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edited by **E A Hinds** *(Imperial College, London)*, **Allister Ferguson** *(University of Strathclyde, Glasgow)*, & **Erling Riis** *(University of Strathclyde, Glasgow)*

This is the latest volume in the series of proceedings from the biannual International Conference on Laser Spectroscopy, one of the leading conferences in the field. Over its 34-year history, this conference series has been a forum for the announcement of many new developments in laser physics and laser spectroscopy and more recently laser cooling of atoms and quantum information processing. The proceedings include contributions from the invited speakers and a selection of contributed papers.

A particular theme for this volume is precision measurements. Motivated by the untapped potential for vast improvements in accuracy offered by atomic systems, this subject has advanced tremendously in recent years by new developments in laser technology. This has been recognized by the 2005 Nobel Prize in Physics awarded to two of the pioneers in the field and contributors to these proceedings, J L Hall and T W Hänsch.

The other main theme of the proceedings is cold atoms and quantum degenerate gases. This conference marked the 10th anniversary of the first announcement of an atomic Bose-Einstein Condensate at the 12th International Conference on Laser Spectroscopy with a contribution from Nobel Laureate Eric Cornell.

**Contents:**



**Readership:** Graduate students, academics and researchers in laser, atomic, molecular and quantum physics.

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# SYMPATHETIC COOLING OF FERMIONIC LITHIUM VIA A BOSONIC RUBIDIUM GAS *

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The Pauli exclusion principle inhibits $s$-wave collisions between fermionic $^6$Li atoms and renders thermalization and evaporative cooling at low temperatures inefficient. A way around this problem is sympathetic cooling by a different actively cooled atomic species. With this technique, using bosonic $^{87}$Rb as cooling agent, we obtain a mixture of quantum-degenerate gases, where the Rb cloud is colder than the critical temperature for Bose-Einstein condensation and the Li cloud colder than the Fermi temperature. From measurements of the thermalization velocity we estimate the interspecies $s$-wave triplet scattering length $|a_s| = 20^{+9}_{-6}\ a_B$.

## 1. Introduction

Much of the current interest in mixtures of quantum gases is motivated by the hope to form heteronuclear molecules not only at temperatures attainable by optical cooling techniques,[1] but in the quantum degenerate regime. In contrast to homonuclear dimers, heteronuclear molecules exhibit huge permanent electric dipole moments of several Debye in their vibrational ground state,[2] which makes them desired candidates for studying long-range effects [3] or even building robust quantum computers, whose registers would be molecules suspended in free space.[4]

Degenerate mixtures have remarkable physical properties, which cannot be observed in pure quantum gases.[5] A particularly interesting feature is the strong modification of the interaction between fermions in the presence of a bosonic background gas:[6] It is expected that an atomic Fermi gas can be driven into a BCS transition by mediation of a Bose gas. Unfortunately this transition, which mimics the phonon-induced formation of Cooper pairs

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in superconductors or the superfluidity of $^3$He in a $^4$He environment,[7] occurs at very low temperatures. In contrast, Feshbach resonance-enhanced fermionic superfluidity,[8] which makes use of a mechanism to dramatically increase the scattering length and allows for superfluidity at relatively high critical temperatures, has already been observed in experiment.[9]

Cooling pure Fermi gases is complicated by the fact that the Pauli exclusion principle suppresses $s$-wave collisions. Since $s$-wave collisions are necessary for thermalizing ultracold gases, this sets a barrier to evaporative cooling procedures. The key to cooling a Fermi gas is thermal coupling to a second cloud, e.g. atoms in a different magnetic substate.[10] The lowest temperatures reported so far, $T \simeq 0.05 T_F$ where $T_F$ is the Fermi temperature, were reached by sympathetic cooling with a different (bosonic) atomic species.[11,12] Unfortunately, even in this case Pauli-blocking freezes most available low-energy degrees of freedom as the Fermi sea more and more fills up with atoms. Furthermore, cooling is also hindered by the decreased efficiency of elastic scattering between fermions and bosons when the latter are in the superfluid regime.[13] This may thermally decouple the fermions from the bosons well before Pauli-blocking sets in. It is therefore desirable to come to a situation, where the Fermi gas is coupled to a non-condensed Bose gas, i.e. where the Fermi temperature is well above the critical temperature for Bose-Einstein condensation, $T_c \ll T_F$.

Various mixtures of bosonic and fermionic alkalis are currently under investigation. Recently, we reported on the first studies with mixtures of fermionic $^6$Li with $^{87}$Rb.[14] We have shown that sympathetic cooling works down to the regime of Fermi degeneracy, provided all Zeeman states other than $|2,2\rangle$ leading to inelastic losses are cleared away from the Rb cloud. We also measured the interspecies thermalization speed and obtained a value for the scattering length for heteronuclear collisions.

## 2. Condensation of $^{87}$Rb

In our experiment $^{87}$Rb and $^6$Li atoms are loaded simultaneously from a dispenser and a Zeeman slower respectively,[15] into superposed standard magneto-optical traps (MOT). The atoms are then transferred into a magnetic quadrupole potential operated with the same coils as the MOT. To transfer both species towards low-field seeking magnetic substates, $|\frac{3}{2}, \frac{3}{2}\rangle$ for Li and $|2,2\rangle$ for Rb, they are optically pumped by a spin-polarizing light pulse. The potential is then compressed, and the atoms are transferred via a second and a third quadrupole trap towards a Ioffe-Pritchard type potential.[14,16] This last potential is generated by a novel trap design combining two coils in anti-Helmholtz configuration with four 0.9 mm thick wires.[17] The principle scheme is shown in Fig. 1. The wires run parallel to the symmetry axis of the quadrupole coils and lie within a common plane. Adjacent wires are passed by currents of opposite signs. This geometry produces steep field gradients in the directions within the plane spanned by the wires and a weak confinement in the orthogonal direction. Trapped atomic clouds thus adopt a cigar-shaped density distribution. Close to the center, i.e. for temperatures of the atoms not higher than a few 10 $\mu$K, the trap is harmonic. In this region typical trap frequencies are $\omega_x \approx \omega_y \simeq 2\pi \times 206$ Hz and $\omega_z \simeq 2\pi \times 50.1$ Hz, obtained at a bias field of 3.5 G.

We cool the Rb cloud by forced evaporation. A microwave radiation resonantly couples the trapped Zeeman state $|2,2\rangle$ of the ground state hyperfine structure and the untrapped $|1,1\rangle$. After 15 s of down-ramping the microwave, the threshold to quantum degeneracy is reached at $T_\mathrm{c} = 620$ nK with about $N_{87} = 1.2 \times 10^6$ atoms. (We assign the subscripts 6 to lithium and 87 to rubidium quantities throughout this paper.) Cooling down further yields almost pure condensates of $5 \times 10^5$ Rb atoms.

## 3. Sympathetic cooling of $^6$Li

The Li cloud consists of initially about $2 \times 10^7$ atoms. While the Rb cloud is evaporatively cooled, the Li cloud is cooled sympathetically provided the evaporation ramp is slow enough, i.e. in practice 25 s. The Fermi temperature is reached with typically $N_6 = 2 \times 10^5$ Li atoms *above* the critical temperature for Bose-Einstein condensation: $T_\mathrm{F} = 3.9 T_\mathrm{c} \simeq 2.4$ $\mu$K. The fact that the bosonic cloud is non-condensed ensures a good spatial overlap and the presence of friction between the clouds. When the Rb cloud is cooled further to temperatures below $T_\mathrm{F}$, we observe that the axial radius of the trapped Li cloud reaches a lower bound at values below the *rms*-Fermi radius, $\sigma_{z,6} < Z_\mathrm{F}/\sqrt{2} = \sqrt{k_\mathrm{B} T_\mathrm{F} / m_{87} \omega_z^2} \simeq 62$ $\mu$m, but above the theoretical prediction, $\sigma_{z,6} > Z_\mathrm{F}/\sqrt{8}$ [cf. Fig. 2(a)]. This behavior may be explained by a joined impact of fermionic quantum statistics and a deceleration of sympathetic cooling as the number of Rb atoms decreases through forced evaporation. The weakening of the thermal coupling, which seems to have played a role in previous experiments [10,11], is more pronounced in our case due to the slow Li-Rb cross species thermalization rate.

Simultaneous *in-situ* absorption pictures of the Li Fermi-gas and the Rb Bose-gas are taken at different stages of the evaporation process. Tem-

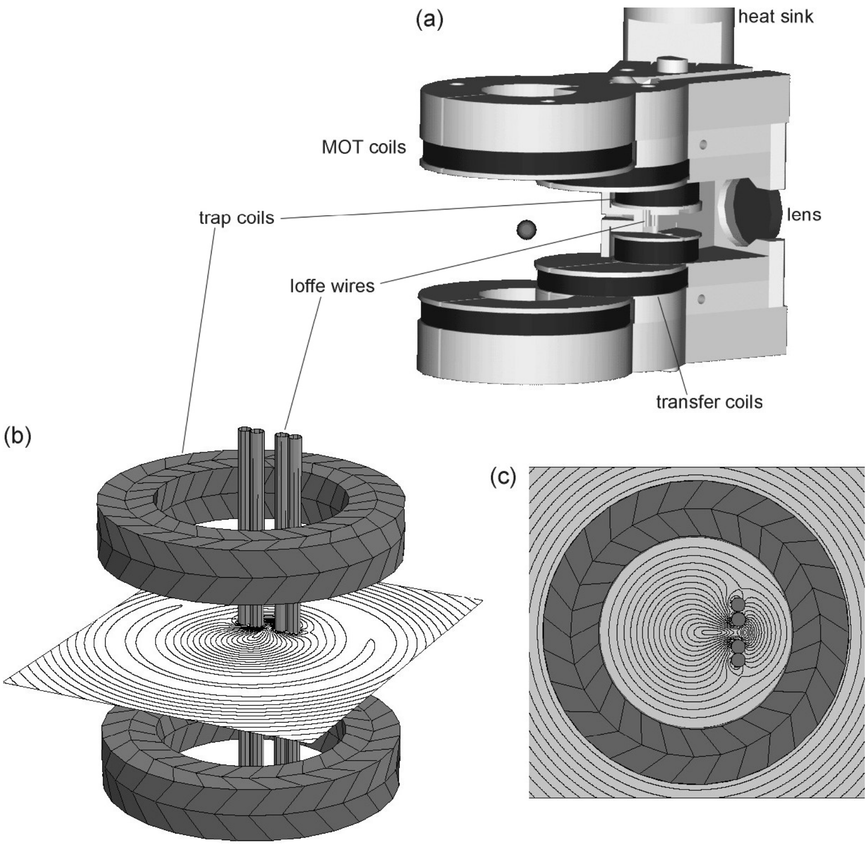


Figure 1. (a) Setup for simultaneous trapping of lithium and rubidium. Both species are prepared in superposed MOTs, loaded into a magnetic quadrupole trap, and then transferred adiabatically into a Ioffe-Pritchard trap. Here the two clouds are compressed. While the Rb cloud is cooled by radiofrequency evaporation, the Li cloud is cooled through thermal coupling to the Li cloud. Both clouds can be observed simultaneously by absorption imaging through a microscope lens. All parts are located inside the vacuum chamber. (b) Zoom of and (c) cut through the Ioffe-Pritchard trap showing equipotential lines.

peratures are determined from 15 ms time-of-flight absorption images of the Rb cloud. The axial (horizontal) size of the Li cloud is clearly limited to values $2\sigma_{z,6} \gtrsim 80$ $\mu$m. In contrast, the Rb condensate shrinks at lower temperatures.

In the presence of Rb atoms we observe a fast decrease in the Li atom number. If no measure is taken to slow it down, the Li cloud disappears well

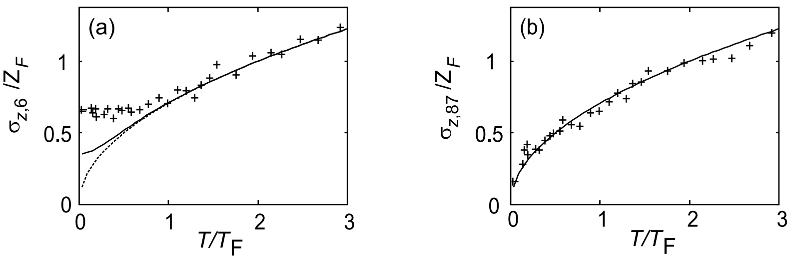


Figure 2. From absorption images we determine the temperature dependence of the axial *rms*-radii of (a) the trapped Li cloud and (b) the trapped Rb cloud. The theoretical curves show the temperature dependence expected for a gas of classical particles (dotted lines) and for a gas of fermions (solid lines) with $N_6 = 2 \times 10^5$ particles. The Rb and the Li data have been scaled with a common factor to rule out uncertainties in the magnification of the imaging system.

before the Fermi temperature is reached. These Li trap losses are induced on one hand by $|1, -1\rangle$ Rb atoms, which remain in the trap because the initial spin polarizing pulse fails to transfer all atoms into the fully stretched state. On the other hand, we observe a continuous inelastic spin relaxation of the $|2, 2\rangle$ cloud into $|2, 1\rangle$ Rb atoms. The $|2, 1\rangle$ atoms then inelastically collide with $|\frac{3}{2}, \frac{3}{2}\rangle$ Li atoms, which results in trap losses.[11,18]

To eliminate the harmful impact of the $|2, 1\rangle$ atoms, we selectively remove them from the trap. This is done with a short microwave pulse coupling this state to the magnetically untrapped Zeeman substate $|1, 0\rangle$. The purifying procedure has to be repeated several times during the evaporation process, because the $|2, 1\rangle$ state is continuously refilled. In contrast the $|1, -1\rangle$ atoms are removed from the trap once for all at the beginning of the evaporation ramp via irradiation of a microwave swept across the transition to the anti-trapped $|2, -2\rangle$ state.

## 4. Interspecies scattering length

The cross-species scattering length is the essential quantity governing the coexistence of Li and Rb and their interactions. The scattering length is related to the collision rate, which in turn depends on the spatial overlap of the two clouds, their relative gravitational sag, and their temperatures. An experimentally accessible quantity, the interspecies thermalization rate, also depends on the collision rate. Thus it suffices to measure the time required for rethermalization of the two clouds once they have been brought out of thermal equilibrium,[19] which corresponds to the time constant for sympathetic cooling.

The heat capacity of the atomic clouds depends on the geometry of the trapping potential.[20] Therefore the number of collisions needed to entirely thermalize an atomic sample also does. In a harmonic trap about $3/\xi$ collisions per atom are needed,[21] where $\xi = 4 \cdot 6 \cdot 87/(6+87)^2$ is the reduction factor due to the mass difference of the collision partners.[22] In radial direction however at temperatures well above 10 $\mu$K, our potential adopts a linear shape, so that the required number of collisions is expected to be slightly modified (around 4 collisions).

Experimentally, we make use of the fact that the thermal equilibrium between the clouds can be disturbed by evaporating the Rb cloud faster than the Li temperature can follow. I.e. we rapidly cool the Rb cloud to a certain temperature and then record the evolution of the Li temperature as a function of time. We evaporate the Rb cloud to 12 $\mu$K within 20 s and wait for the Li cloud to follow up. We then rapidly pursue the evaporation ramp for the Rb cloud down to 5 $\mu$K within 300 ms. At that time we find the Li temperature still at 12 $\mu$K. Starting with this situation we observe the gradual thermalization of the Li cloud. The microwave radiation is parked at the final frequency of the evaporation ramp, where it skims off those Rb atoms which are heated during the thermalization process. Because of this and because of the larger heat capacity of the bigger Rb cloud, its temperature remains stable, while the Li cloud reduces its temperature until thermal equilibrium with the Rb cloud. Applying the model outlined above, we find that the best fit to the data is compatible with the cross species $s$-wave triplet scattering length $|a_s| = 20^{+9}_{-6}\ a_{\mathrm{B}}$. The small value of the interspecies scattering length explains why the sympathetic cooling dynamics is so slow that it decouples from the forced evaporation process of Rb. The measurement agrees well with a recent theoretical prediction of the scattering length claiming $a_s = 24\ a_{\mathrm{B}}$.[23] However the authors of the calculations recommend to take the results with care, because they are based on inaccurately known interaction potentials. The accuracy of the measured scattering length is limited by the uncertain number of Rb atoms and anharmonicities of the trapping potential not taken into account in the thermalization model.

## 5. Conclusion

In conclusion, we have observed sympathetic cooling of a cloud of fermionic lithium by an actively cooled rubidium cloud, although the cross-species thermalization is hindered by two facts: First of all, inelastic collisions with Rb atoms in wrong Zeeman states introduce important losses for the Li cloud, which quickly annihilate the cloud. And second, the very low value for the interspecies scattering length considerably slows down the thermalization process. By repeatedly purifying the Rb cloud and by choosing a slow cooling ramp we could avoid these problems and drive the Li cloud to quantum degeneracy.

We now plan to study cross-species thermalization in other Zeeman substates. Since those states are, in contrast to the fully stretched states, couple to the $X^1\Sigma^+$ ground state interaction potential, this should help to determine the singlet scattering length. This and the quantitative study of inelastic loss rates should help pinning down the shape of the long-range behavior of the interaction potentials for Li-Rb collisions, which is yet unknown to date.

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