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Quantum degenerate mixture of ytterbium and lithium atoms

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We have produced a quantum degenerate mixture of fermionic alkali-metal ^{6}Li and bosonic spin-singlet ^{174}Yb gases. This was achieved using sympathetic cooling of lithium atoms by evaporatively cooled ytterbium atoms in a far-off-resonant optical dipole trap. We observe the coexistence of Bose-condensed ($T/T_c \simeq 0.8$) ^{174}Yb with 2.3×10^4 atoms and Fermi degenerate ($T/T_F \simeq 0.3$) ^{6}Li with 1.2×10^4 atoms. Quasipure Bose-Einstein condensates of up to 3×10^4 ^{174}Yb atoms can be produced in single-species experiments. Our results mark a significant step toward studies of few- and many-body physics with mixtures of alkali-metal and alkaline-earth-metal-like atoms, and for the production of paramagnetic polar molecules in the quantum regime. Our methods also establish a convenient scheme for producing quantum degenerate ytterbium atoms in a 1064 nm optical dipole trap.

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Quantum degenerate elemental mixtures can be used to study a variety of few- and many-body phenomena and form the starting point for creating quantum degenerate dipolar molecules. While bi-alkali-metal quantum mixtures [1–6] have been produced and studied for about a decade, mixtures of alkali-metal and electron spin-singlet atoms are a more recent development [7–11]. By exploiting the difference in mass of the components, the lithium-ytterbium quantum degenerate mixture may be used to investigate a range of interesting scientific directions including new Efimov states [12,13], impurity probes of the Fermi superfluid [6], and mass imbalanced Cooper pairs [14–16]. Furthermore, unlike the bi-alkali-metal case, mixtures of alkali-metal and alkaline-earth-metal-like atoms can lead to the realization of paramagnetic polar molecules by combining the atoms through field-induced scattering resonances, followed by multiphoton transfer processes to the ground state [17–19]. Such molecules hold great promise for quantum simulation and topological quantum computing applications [20]. They may also be good candidates for sensitive tests of fundamental symmetries, particularly if one of the constituents is a heavy atom, such as Yb [21].

In this paper, we report on simultaneous quantum degeneracy in a mixture of alkali-metal and alkaline-earth-metal-like atoms. In earlier work [11], we reported on collisional stability and sympathetic cooling in the ^{6}Li-^{174}Yb system, together with a measurement of the interspecies s-wave scattering length magnitude. Here we establish a convenient method to produce Bose-Einstein condensates (BECs) of ^{174}Yb. This allows the sympathetic cooling of ^{6}Li to well below its Fermi temperature and the achievement of simultaneous quantum degeneracy in the two species.

The cooling of various isotopes of ytterbium to quantum degeneracy has been pioneered by the group of Y. Takahashi in Kyoto [22–24]. In these studies, the optical dipole trap (ODT) was implemented at the wavelength 532 nm. While suitable for confining ytterbium which has a strong transition at 399 nm, this choice of wavelength will not confine common alkali-metal atoms due to their strong transitions occurring at wavelengths greater than 532 nm. For our ODT, we use 1064 nm light arranged in a straightforward horizontal geometry, and demonstrate efficient evaporative cooling of ^{174}Yb to BEC. This establishes a simple setup for studies with quantum degenerate ytterbium gases, particularly in the context of dual-species experiments.

Our experimental setup (see Fig. 1) is similar to what has been described previously [11]. Briefly, we sequentially load ^{174}Yb and then ^{6}Li from respective magneto-optical traps (MOTs) into the same ODT. We then perform forced evaporative cooling of ^{174}Yb by lowering the power in the ODT. This leads to quantum degeneracy in either single or dual-species experiments. Two improvements to our earlier setup which are crucial for this work are the use of higher power in the Yb Zeeman-slowing beam resulting in larger MOT numbers, and the implementation of a tighter ODT geometry [25] leading to more efficient evaporative cooling.

The ODT is derived from a 1064 nm linearly polarized fiber laser, operated at a power of 45 W. In order to control the trap depth, the output of the laser is sent through an acousto-optic modulator. The first-order output is split into two equal parts with orthogonal linear polarizations which then propagate horizontally toward the atoms. Each beam is focused to a (measured) waist of 26 μm and the foci are overlapped at an angle of 20 degrees. The trapping potential is characterized through measurements of trap frequencies by parametric heating. The relative trap depths and frequencies for the two species are $U_{\rm Li}/U_{\rm Yb} = 2.2$ and $\omega_{\rm Li}/\omega_{\rm Yb} = 8.1$. To monitor atom number and temperature, we quickly switch off the ODT and perform resonant absorption imaging of both species.

In single-species experiments with ^{174}Yb, we load 1.5×10^7 atoms in a MOT in 40 s from a Zeeman-slowed atomic beam. We use 100 mW power in the 399 nm ($^1S_0 \rightarrow {}^1P_1$) slowing beam and a total of 12 mW power in the 556 nm ($^1S_0 \rightarrow {}^3P_1$) MOT beams, operated in retroreflection configuration. A transient cooling and compression scheme then produces an atomic cloud at a temperature of 20 μK containing $\simeq 6 \times 10^6$ atoms.

About 1×10^6 atoms in the $^1S_0$ state are then loaded into the ODT where the background $1/e$ lifetime is 40 s. The initial ODT power at the atoms is 9 W per beam, corresponding to a trap depth of 430 μK. The power is then reduced by a

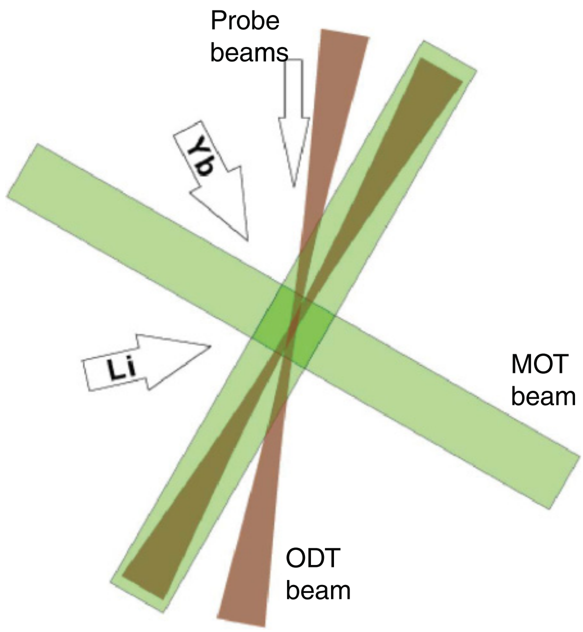

FIG. 1. (Color online) Experimental arrangement (top view) for producing simultaneous quantum degeneracy in lithium and ytterbium. Zeeman-slowed atomic beams of each species propagate along separate axes toward the MOT. The horizontal ODT beams (brown) are crossed at the MOT region at an angle of 20°. MOT beams (green) for both species are overlapped and arranged in a retroreflection configuration. Beams for the vertical MOT axis and Zeeman slowing are omitted from the figure for clarity.

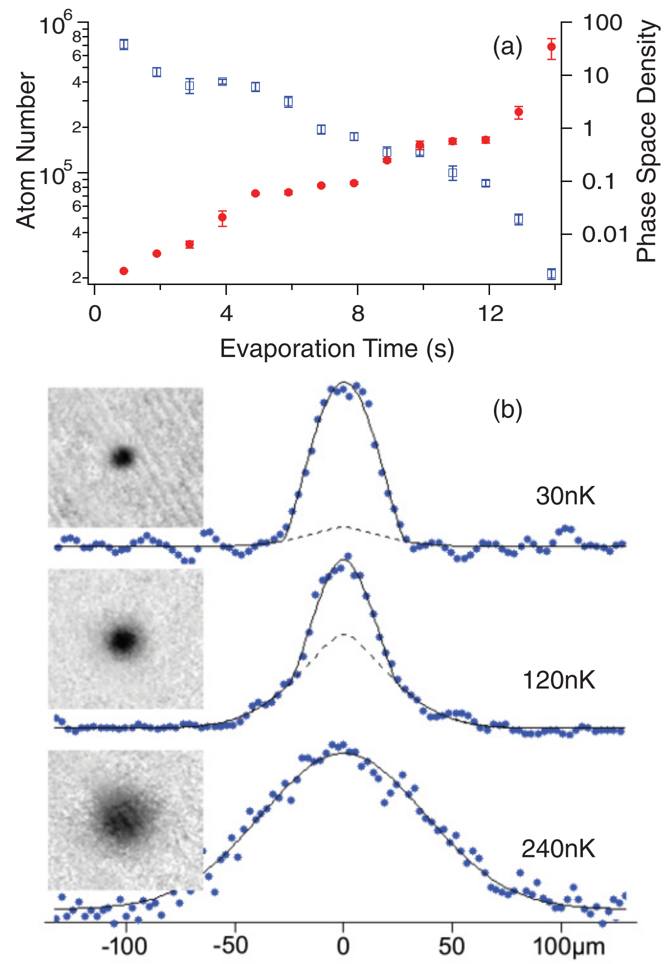

FIG. 2. (Color online) Evaporative cooling of ^{174}Yb to Bose-Einstein condensation in the crossed 1064 nm ODT. Panel (a) shows the evolution of ^{174}Yb number (open squares) and phase space density (filled circles) for a single-species experiment. BEC is achieved after about 12.5 s. Panel (b) shows absorption images and the corresponding atomic density profiles (vertical cross sections of these images) for three different final trap depths, showing the formation of the BEC. The solid line in each plot is a bimodal fit to the distribution with the dashed line showing the thermal component of the fit. The free expansion time after turning off the trap is 8 ms for each image. The total atom numbers and temperatures are 8.0, 5.6, and 2.1 × 10^4 and 240, 120, and 30 nK, respectively.

factor of 100 over a time scale of 14 s, utilizing two stages of approximately exponential shape. The first stage lasts for 5 s with a time constant of 1.5 s. The second stage lasts for the remainder of the evaporation period and has a time constant of 3.6 s.

We observe efficient evaporative cooling with this arrangement [see Fig. 2(a)]. The critical temperature for Bose-Einstein condensation is achieved after evaporating for $\simeq$12.5 s. At this point the atom number is $N_{\mathrm{Yb}} = 7 \times 10^4$ and the temperature is $T_{\mathrm{Yb}} = 170$ nK. By fitting to the data prior to condensation, we extract an evaporation efficiency parameter $-d[\ln(\rho_{\mathrm{Yb}})]/d[\ln(N_{\mathrm{Yb}})] = 3.4(4)$ where ρ_{Yb} is the phase space density. Nearly pure condensates of up to 3×10^4 atoms can be prepared by continuing the evaporation process [see Fig. 2(b)].

For two-species experiments, we add to the optically trapped ^{174}Yb an equal mixture of the two $F = 1/2$ Zeeman states of ^{6}Li with an adjustable total number. After 1 s of interspecies thermalization at constant trap depth, we perform sympathetic cooling of ^{6}Li by ^{174}Yb at near-zero magnetic field by using the same evaporation ramp as described above. Sympathetic cooling works well in this mixture as described in our earlier work [11] where we reported an interspecies s-wave scattering length magnitude of $|a_{^6\mathrm{Li}\text{-}^{174}\mathrm{Yb}}| = (13 \pm 3)a_0$. The ^{6}Li number remains nearly constant due to its greater trap depth. After approximately 14 s of evaporation we observe simultaneous quantum degeneracy in the two species (see Fig. 3). At this point the geometric mean trap frequencies are $\bar{\omega}_{\mathrm{Yb(Li)}} = 2\pi \times 90$ (740) Hz, atom numbers are $N_{\mathrm{Yb(Li)}} = 2.3$ (1.2) $\times 10^4$, and temperatures are $T_{\mathrm{Yb(Li)}} = 100 \pm 10$ (320 ± 36) nK. Here, N_{Li} is the total lithium atom number distributed equally between the two spin states. T_{Yb} is estimated from the fraction of condensed atoms. T_{Li} is a weighted average of three methods: a best-fit to the shape of the distribution using a Thomas-Fermi model with the fugacity as an independent parameter, and two Fermi-Dirac distribution fits to singly and doubly integrated density profiles.

The difference in temperature between the two species is largely attributable to the relative center-of-mass displacement at the end of the evaporation ramp arising from gravitational sag. Assuming perfect overlap, the estimated interspecies thermalization time at this stage is $\simeq$1 s, which is reasonably short. However, the separation of the two clouds due to unequal

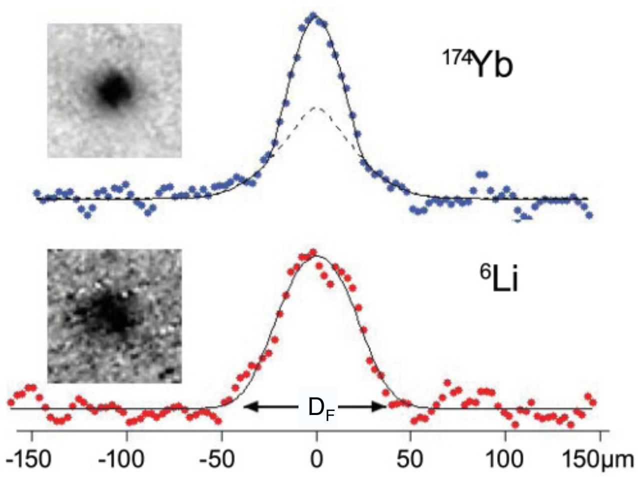

FIG. 3. (Color online) Quantum degenerate mixture of ^{174}Yb and ^{6}Li. The absorption images and density profiles correspond to the same experimental iteration with 14 s of evaporation. The free-expansion times are 8 ms for Yb and 0.7 ms for Li. Here $N_{\rm Yb} = 2.3 \times 10^4$ and $T_{\rm Yb} = 100$ nK, corresponding to $T_{\rm Yb}/T_{\rm C,Yb} = 0.8$, while $N_{\rm Li} = 1.2 \times 10^4$ and $T_{\rm Li} = 320$ nK, corresponding to $T_{\rm Li}/T_{\rm F,Li} = 0.3$. For ^{174}Yb, the solid line is a bimodal fit with the dashed line showing the thermal component of the fit. For ^{6}Li, the solid line is a Thomas-Fermi fit. The extent of the momentum-space Fermi diameter D_F, corresponding to the Fermi energy, is also indicated in the figure. The image was taken at near-zero magnetic field and includes both spin components.

effects of gravity is 5.1 μm while the lithium in-trap Fermi radius is 5.8 μm in the vertical direction. A numerical model of the cooling process incorporating this effect predicts a $1/e$ reduction of the interspecies collision rate due to separation when $T_{\rm Yb} \simeq 300$ nK, suggesting that sympathetic cooling does indeed become inefficient toward the end of evaporation.

Our results establish a new quantum system comprised of simultaneously degenerate one- and two-electron atomic gases. We also demonstrate a new method for achieving Bose-Einstein condensation of ^{174}Yb using a straightforward horizontal optical trapping arrangement with 1064 nm laser beams. Our setup could also be suitable for combining Yb with other alkalis such as Cs and Rb, since the trap depth and relative sizes would be amenable for sympathetic cooling by ytterbium. Further improvements to our cooling scheme include independent control over the powers in the two ODT beams and an additional magnetic field gradient to improve spatial overlap of the two species.

Extending our method to incorporate alternate ytterbium isotopes (such as the fermion ^{173}Yb [23]) appears realistic. This would then realize Fermi degenerate mixtures with a large mass ratio. Finally, our results represent a significant milestone toward the production of quantum gases of paramagnetic polar molecules. Theoretical work on the LiYb molecule has already been initiated by several groups [26–28]. Future experimental work on our system includes photoassociative spectroscopies and searches for Feshbach resonances [29] in this mixture, which are key steps toward forming the molecule.

Note added. Recently, we became aware of similar work [30] in which quantum degenerate mixtures of ^{6}Li-^{174}Yb and ^{6}Li-^{173}Yb were obtained.

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