A Degenerate Bose-Fermi Mixture of Metastable Atoms

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We report the observation of simultaneous quantum degeneracy in a dilute gaseous Bose-Fermi mixture of metastable atoms. Sympathetic cooling of helium-3 (fermion) by helium-4 (boson), both in the lowest triplet state, allows us to produce ensembles containing more than $10^9$ atoms of each isotope at temperatures below 1 $\mu$K, and achieve a fermionic degeneracy parameter of $T/T_F = 0.45$. Due to their high internal energy, the detection of individual metastable atoms with sub-nanosecond time resolution is possible, permitting the study of bosonic and fermionic quantum gases with unprecedented precision. This may lead to metastable helium becoming the mainstay of quantum atom optics.

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FIG. 1: (a) $^3$He* and $^4$He* energy levels relevant to the magneto-optical trapping of He* atoms in the 2 $^3$S$_1$ state ($F=3/2$ for $^3$He*); the cycling transitions (C3 and D2) are indicated (MOT and Zeeman slower detunings are: $\delta_{\text{MOT}} = -40$ MHz and $\delta_{2S} = -250$ MHz respectively). A repumper exciting the C2 transition ($\delta_{\text{rp}} = -52$ MHz) is applied by simply double passing our $^3$He* Zeeman slower AOM. (b) (color online). Experimental setup for the magneto-optical trapping, magnetic trapping and detection of $^3$He* and $^4$He* atoms. A TOF experiment is performed by dropping the trapped sample on an MCP detector positioned 17 cm below the trap center. (c) Magnetic field dependence of the $^3$He* $F=3/2$ and $^4$He* $J=1$ magnetic substates. Evaporative cooling is performed on the $^4$He* $M_J = 1 \rightarrow M_J' = 0$ transition.

transformation, due to the near (-811 MHz) coincidence of the $^3$He* laser cooling and $^4$He* C9 transitions (Fig.1b). Unable to cool so much $^3$He* [18], we reduce the number of $^3$He* atoms in the two-isotope MOT (TIMOT) to $\approx 10^4$ by either altering the ratio $^3$He:$^4$He in our helium reservoir or, more simply, by loading the TIMOT with $^3$He* for a shorter period.

Spin-polarization of the mixture to the $^3$He* \{3/2, +3/2\} and $^4$He* \{1, +1\} states prior to magnetic trapping not only suppresses PI and AI, but also enhances the transfer efficiency of the mixture into the magnetic trap. The application of 1D-Doppler cooling along the symmetry axis of our magnetic trap [12] (Fig. 1b) reduces the sample temperature to $T = 0.13$ mK without loss of atoms, increasing the $^4$He* phase space density by a factor of 600 to $\approx 10^{-4}$, greatly enhancing the initial conditions for evaporative cooling. We note at this point that the application of 1D-Doppler cooling to the $^4$He* component already leads to sympathetic cooling of $^3$He*, however the process appears to be more efficient if we actively cool both components simultaneously. During these experiments the lifetime of a pure sample of either $^3$He* or $^4$He* in the magnetic trap was limited by the background pressure in our ultra-high vacuum chamber to $\approx 110$ s, whilst the lifetime of the mixture was only slightly shorter at $\approx 100$ s, indicating that the suppression of PI and AI during $^3$He*-,$^3$He* and $^3$He*-,$^4$He* collisions works very well.

In order to further increase the collision rate in our cloud, we adiabatically compress it during 200 ms by increasing the trap frequencies to their final radial and axial values: $\nu_r = 273$ Hz and $\nu_a = 54$ Hz for $^3$He*, and $\nu_r = 237$ Hz and $\nu_a = 47$ Hz for $^4$He* (the difference is due to their differing masses). We now perform forced evaporative cooling on the $^4$He* component by driving radio-frequency (RF) transitions to the untracked $M_J = 0$ and -1 spin states (where $M_J$ is the projection of total electronic angular momentum quantum number $J$ on the quantization axis), thereby sympathetically cooling $^3$He*. The atoms couple only weakly to the magnetic field, and the energies of the various magnetic sub-states vary linearly with magnetic field: $E_{M_J,J} = g\mu_B M_J B$, where $g$ is the gyromagnetic ratio, $\mu_B$ the Bohr magneton, and $B$ the magnetic field strength (Fig. 1c). Because of the differing $^3$He* and $^4$He* gyromagnetic ratios (4/3 and 2 respectively) the frequency, at any given B-field, for transitions between the magnetic substates in $^4$He* is 3/2 times that of $^3$He* (Fig. 1c) and we only remove $^4$He* during evaporative cooling (assuming that the mixture remains in thermal equilibrium). Furthermore, at the trap minimum ($B = 3$ G) the difference in transition frequencies is 2.8 MHz. Thus, when the temperature of the trapped sample is low enough (< 20 $\mu$K) we may selectively remove either $^3$He* or $^4$He* from the trap by applying an appropriate RF sweep (despite having to drive two transitions in order to transfer $^3$He* atoms into an untrapped magnetic substate). This allows us to perform measurements on the mixture as a whole, or on a single component. Upon release a time-of-flight (TOF) experiment is performed (Fig. 1b); by fitting TOFs (Fig. 2) with the applicable quantum statistical distribution functions we can extract the temperature of the gas and, having previously calibrated the MCP with absorption imaging [12], the number of atoms.

A single exponential ramp of the RF frequency to below 8.4 MHz removes all $^4$He* atoms from the trap,
and leads to the production of a pure degenerate Fermi gas of $^3\text{He}^*$ (Fig. 2b). An analysis of the TOF signals shows that we have achieved a maximum degeneracy ($N_{^3\text{He}^*} = 2.1 \times 10^6$ at $T = 0.8 \, \mu\text{K}$ and $T/T_F = 0.45$; and $N_{^3\text{He}^*} = 4.2 \times 10^5$ ($T/T_F = 0.5$) and $N_{^3\text{He}^*} = 1 \times 10^5$ atoms. The dashed curve is the result of fitting a Fermi-Dirac velocity distribution to the wings, while the dot-dashed curve is a fit to a pure Bose-Einstein condensate (showing the characteristic inverted parabolic shape).

FIG. 2: Time-of-flight spectra for: (a) a degenerate Fermi gas of $^3\text{He}^*$ together with the fitted Fermi-Dirac TOF function, from which we conclude that $N_{^3\text{He}^*} = 2.1 \times 10^6$ at $T = 0.8 \, \mu\text{K}$ and $T/T_F = 0.45$; and (b) a degenerate mixture of $N_{^3\text{He}^*} = 4.2 \times 10^5$ ($T/T_F = 0.5$) and $N_{^3\text{He}^*} = 1 \times 10^5$ atoms. The dashed curve is the result of fitting a Fermi-Dirac velocity distribution to the wings, while the dot-dashed curve is a fit to a pure Bose-Einstein condensate (showing the characteristic inverted parabolic shape).

Therefore the temperature of the sample. By fitting only the more "classical" wings of a TOF these effects are negated, and the fitted temperature should either fall (fermions), rise (bosons), or stay constant in the case of a classical gas. The high signal-to-noise ratio of our TOF spectra allows us to see this behavior clearly (Fig. 3). By taking the temperature from a TOF for which we have removed 1.75 $\sigma_0$ (where $\sigma_0$ is the root-mean-square width of a gaussian fit to the entire TOF, see Fig. 3a), and the number of atoms calculated by integrating the TOF, we again recover a degeneracy parameter of $T/T_F = 0.5$.

It is interesting to note that we have produced degenerate Fermi gases with evaporative cooling ramps as short as 2.5 s ($N_{^3\text{He}^*} = 4 \times 10^6$ and $T/T_F = 0.75$), signifying that the process of rethermalization is very efficient. At densities of $10^{10} - 10^{12}$ atoms/cm$^3$ this indicates a large heteronuclear scattering length. Recently theory and experiment finally agreed upon the $^4\text{He}^*$-$^3\text{He}^*$ scattering length ($a_{44} = 7.64(20)$ and 7.512(5) nm respectively). An extension to the theory of Przybytek and Zegerski suggests that the $^3\text{He}^*$-$^4\text{He}^*$ scattering length should also be very large and positive ($a_{44} = +28.8_{-3.3}^{+3.9}$ nm). Such a large heteronuclear scattering length leads us to expect that losses, in particular boson-fermion (BBF) 3-body losses (which scale with $a^4$), will have a significant impact on the mixture. We can estimate (order of magnitude) the BBF 3-body loss rate constant by using $K_{BBF} = 120\hbar a_{44}^2 \sqrt{d+2}/(m_4 \sqrt{3})$, where $d$ is the $^3\text{He}$-$^4\text{He}$ mass ratio, $m_4$ is the $^4\text{He}$ mass and we assume the theoretical value of $a_{44}$ given above. This gives $K_{BBF} \approx 1.4 \times 10^{-24} \text{ cm}^6/\text{s}$, indicating an atom loss rate that is 1-3 orders of magnitude larger than in the case of pure $^4\text{He}^*$, and a condensate

![Diagram](https://example.com/diagram.png)
lifetime ($\tau_C$) which is significantly shorter in the degenerate mixture than in the absence of $^3\text{He}^\ast$. These estimates are in agreement with initial observations that $\tau_C^{(3+4)} \sim 0.01 \text{ s}$ while $\tau_C^{(4)} \sim 1 \text{ s}$ [12]. Given the large magnitude of $a_{34}$ and having seen no evidence for a collapse of the mixture, we may further suppose that $a_{34}$ is positive. This is then the first Bose-Fermi system to exhibit boson-fermion and boson-boson interactions which are both strong and repulsive. A possible disadvantage, however, may be that the system is only expected to be sufficiently stable against Penning ionization when the atoms are all in the fully stretched magnetic substates, hampering the exploitation of possible Feshbach or optical resonances.

In conclusion we have successfully produced a degenerate Fermi gas of metastable $^3\text{He}^\ast$ containing a large number of atoms with $T/T_F = 0.45$ and have also seen that we can produce a degenerate Bose-Fermi mixture of $^3\text{He}^\ast$ and $^4\text{He}^\ast$. This source of degenerate metastable fermions, bosons, or mixtures of the two, could form the basis of many sensitive experiments in the area of quantum atom optics and quantum gases. Of particular interest is the recently realized Hanbury Brown and Twiss experiment on an ultracold gas of $^4\text{He}^\ast$ [13], demonstrating two-body correlations (bunching) with neutral atoms (bosons); we now have the ideal source to study anti-bunching in an ultracold Fermi gas of neutral atoms. The extremely large and positive $^3\text{He}^\ast$-$^4\text{He}^\ast$ scattering length lends itself to the hitherto unobserved phenomena of phase separation in a Bose-Fermi mixture [14] and, if the scattering lengths can be tuned only slightly, may allow a study of $p$-wave Cooper pairing of identical fermions mediated by density fluctuations in a bosonic component [15]. Given the naturally large and positive scattering lengths, loading such a mixture into an optical lattice will provide a new playground for the study of exotic phases and phase transitions [16], including supersolidity [17]. The possibility of ion detection as a real-time, non-destructive density determination tool will be very helpful in observing these and other phenomena. Finally, the ultralow temperatures to which we can now cool both isotopes will allow unprecedented accuracy in high resolution spectroscopy of the helium atom. This could improve the accuracy to which the fine structure constant is known and may allow, via isotope shift measurements, an accurate measurement of the difference in charge radius of the $^3\text{He}$ and $^4\text{He}$ nucleus [18], challenging nuclear physics calculations.

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