Bose-Einstein Condensation of $^{84}$Sr

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We report Bose-Einstein condensation of $^{84}$Sr in an optical dipole trap. Efficient laser cooling on the narrow intercombination line and an ideal s-wave scattering length allow creation of large condensates ($N_0 \sim 3 \times 10^5$) even though the natural abundance of this isotope is only 0.6%. Condensation is heralded by the emergence of a low-velocity component in time-of-flight images.

The study of quantum degenerate gases continues to be at the forefront of research in atomic and condensed matter physics nearly 15 years after the first observation of Bose-Einstein condensation. Current areas of focus include the behavior of quantum fluids in optical lattices, effects of dimensionality and disorder, exploration of the BEC-BCS crossover regime, and the pursuit of quantum degenerate molecular systems.

Quantum degeneracy in alkaline earth metal atoms and atoms with similar electron structure has become another area of intense activity. These systems have been the subject of many recent theoretical proposals for quantum computing in optical lattices and creation of novel quantum fluids. They possess interesting and useful collisional properties, such as a wealth of isotopes that allow mass-tuning of interactions and creation of various quantum mixtures. Low-loss optical Feshbach resonances in these atoms promise new opportunities because they enable changing the atomic scattering lengths on small spatial and temporal scales. This can lead to creation of matter-wave solitons in two dimensions and random nonlinear interactions in quantum fluids. Many of these ideas take advantage of the existence of long-lived metastable triplet states and associated narrow optical transitions, which are also the basis for recent spectacular advances in optical frequency metrology.

Here we report the observation of Bose-Einstein condensation of $^{84}$Sr. To date, quantum degeneracy with alkaline earth metal atoms and similar elements has been reported in a collection of ytterbium isotopes and very recently in $^{40}$Ca and $^{84}$Sr, demonstrating increasing interest in these systems. Starting with a natural-abundance strontium source, our success in forming a relatively large Bose-Einstein condensate of $^{84}$Sr, which has a natural abundance of 0.6%, demonstrates the power of laser cooling in strontium using the $(5s^2)^1S_0-(5s5p)^3P_1$ narrow intercombination line at 689 nm. It also reflects the near-ideal scattering properties of this isotope, which has an s-wave elastic scattering length of $a = 122.7(3) a_0$, where $a_0 = 0.53$ Å. The ground state scattering properties of all Sr isotopes are well-characterized from one- and two-photon photoassociation spectroscopy, fourier transform molecular spectroscopy, and experiments trapping various isotopes in optical traps.

Our apparatus and experimental sequence for laser cooling atoms and loading them into our optical dipole trap were described in [15, 35, 36], and a timing diagram is shown in Fig. 1. Several techniques are used to enhance initial number and subsequent transfers to overcome the low abundance of $^{84}$Sr. We form an atomic beam and utilize 2-dimensional (2D) collimation and Zeeman cooling to load a magneto-optical trap (MOT), all using the $(5s^2)^1S_0-(5s5p)^3P_1$ transition at 461 nm. The MOT consists of three retro-reflected beams, each with peak intensity of 3.6 mW/cm² and red-detuned from atomic resonance by 60 MHz.

One in $10^5$ $(5s5p)^3P_1$ atoms decays to the $(5s4d)^1D_2$ level and then to the $(5s5p)^3P_1$ and $(5s5p)^3P_2$ states. $(5s5p)^3P_1$ atoms return to the ground state and are recaptured in the MOT, but a fraction of $(5s5p)^3P_2$ atoms, with a lifetime of 9 min [37], are trapped in the quadrupole magnetic field of the MOT. We can accumulate 2.5 x $10^7$ atoms in an axial magnetic field gradient of 60 G/cm with 30 s of loading. $(5s5p)^3P_2$ atoms are then returned to the 461 nm cycling transition by repumping for 35 ms via the $(5s5p)^3P_2-(5s4d)^3D_2$ transition at 3012 nm [38]. We subsequently reduce the...
461 nm beam intensities to about 0.36 mW/cm² for 6.5 ms to reduce the sample temperature to 2 mK.

The 461 nm light is then extinguished, and a second stage of cooling begins using the 689 nm \((5s^2)^1S_0\)-(\(5s5p\))^3P_1\) intercombination line. This MOT light, consisting of three retro-reflected beams with 2 cm diameters, is initially detuned 1 MHz red of resonance and broadened by 700 kHz (peak-to-peak dither amplitude) to enhance our 689 nm MOT capture rate. The peak intensity is 0.75 mW/cm² per beam, and the magnetic quadrupole field gradient is 0.1 G/cm. Over the next 150 ms, the field gradient is increased to 0.8 G/cm, the laser spectrum is reduced to single frequency and detuned by only \(\sim 30\) kHz, and the power is reduced to 0.15 mW/cm². This results in \(1.6 \times 10^7\) atoms at a temperature of 0.4 \(\mu\)K and a peak density of \(\sim 10^{12}\) cm⁻³.

An optical dipole trap (ODT) consisting of two crossed beams is then overlapped with the intercombination-line MOT for 115 ms with modest power (2.5 W) per beam. The ODT is formed by a single beam derived from a 20 W multimode, 1.06 \(\mu\)m fiber laser that is recycled through the chamber. No attempt is made to change the polarization of the beam during recycling. The beams cross nearly perpendicularly, but the plane of the lasers is inclined by approximately 10.5° from horizontal. This results in a trap with equipotentials that are nearly oblate spheroids, with the tight axis close to vertical. Each beam has a waist of approximately 100 \(\mu\)m in the trapping region. This is slightly different than other realizations of quantum degeneracy in two-electron atoms, in which at least one beam had a waist that was significantly smaller [16, 23, 24, 26, 27].

Immediately after extinction of the 689 nm light, the ODT power is ramped in 20 ms to 10 W to obtain a sample of \(3 \times 10^6\) atoms at 5 \(\mu\)K. The trap depth is 31 \(\mu\)K, and the peak density at this point is \(4 \times 10^{13}\) cm⁻³, which implies an average collision rate of 1000 s⁻¹. The peak phase space density (PSD) is \(10^{-2}\). For diagnostics, we record absorption images of samples released from the trap after a time of flight varying from 10 to 40 ms, and the optical depth profile can be related to the areal density, which, for these long delays, also provides the velocity distribution.

Figure 2 shows the number, temperature, and phase space density evolution for a typical forced evaporation trajectory. We ramp down the power in the lasers according to \(P = P_0/(1 + t/\tau)^{\beta}\), with time denoted by \(t\), \(\beta = 1.5\), and \(\tau = 1.5\) s. This trajectory is designed to approximately maintain a constant ratio of trap depth to temperature (\(\eta\)) during evaporation. The lifetime of atoms in the ODT is 30 s, limited primarily by background gas collisions. This allows efficient evaporation at a measured \(\eta \approx 8 \pm 1\) for most of the trajectory.

After 3 s of evaporation to a power of 2 W, \(1 \times 10^6\) atoms remain at a temperature of 0.4 \(\mu\)K. For this trap, our measured trap oscillation frequencies [40] yield a trap depth, including the effect of gravity, of \(3.5 \pm 0.3\) \(\mu\)K and a mean trap frequency of \(f = (f_x f_y f_z)^{1/3} = 84 \pm 5\) Hz. These values indicate that the sample is at the critical transition temperature for a harmonic trap [41],

\[
T_c = \frac{1}{k_B} \frac{\hbar\pi N^{1/3}}{\zeta(3)},
\]  

at which the PSD is 1.2, where \(N\) is the number of trapped atoms, \(k_B\) is Boltzmann’s constant, \(\hbar\) is Planck’s constant, \(\zeta\) is \(2\pi f\), and \(\zeta\) is the Riemann zeta function.

The evaporation is quite efficient. We lose a factor of 3 in the number of atoms from initiation of forced evaporation to the onset of degeneracy, while the phase space density increases by about a factor of 100. The predicted scaling \(\rho/\rho_i = (N_i/N)^{\eta - 4}\) [39], where \(\rho_i\) and \(N_i\) are the initial phase space density and number, and \(\eta = (\eta - 5)/(\eta - 4)\), implies that \(\eta = 7.5\), in excellent agreement with our estimate from knowledge of the optical trap parameters and measured sample temperature.

Figure 3 shows false color 2D rendering and 1D slices through the time-of-flight images recorded after 38 ms of expansion for various points along the evaporation trajectory. At 2.7 s of evaporation, the distribution is fit well by a Boltzmann distribution, but at 3 s, the presence of a Bose-Einstein condensate is indicated by the emergence of a narrow peak at low velocity. Further evaporation to a beam power of 1.3 W at 4.35 s and trap depth of 600 nK yields a condensate with negligible discernible thermal fraction.

The areal density of expanded condensates is fit with the functional form [42]

\[
n(x, y) = \frac{5N_0}{2\pi} \left(1 - \frac{x^2}{R_x^2} - \frac{y^2}{R_y^2}\right)^{3/2} \theta \left(1 - \frac{x^2}{R_x^2} - \frac{y^2}{R_y^2}\right),
\]  

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The areal density of expanded condensates is fit with the functional form [42]
where $\theta$ is the Heaviside function, and $R_x$ and $R_y$ are the condensate radii. At 600 nK trap depth, fitting the areal density yields typical values of $N_0 = 3.0 \times 10^5$ for the largest condensates. The trap mean oscillation frequency at this point is $f = 70$ Hz and harmonic oscillator length $a_{ho} = (\hbar/(M\pi))^{1/2} = 1.3 \mu$m. The trap harmonic oscillator energy scale is $\hbar \omega/k_B = 3.3$ nK and the chemical potential, $\mu = \frac{\hbar}{2\pi a_{ho}} \left( \frac{15N\alpha}{a_{ho}} \right)^{2/5} = 90$ nK. $(N_0 \alpha)/a_{ho} = 1500$ is large, implying that the condensate is in the strong interaction regime and should be well described by a Thomas-Fermi density distribution, confirming that Eq. 2 is the appropriate description.

By releasing a pure condensate from the trap and varying the time of flight before recording an absorption image, we are able to characterize the expansion of the many-body wavefunction which is sensitive to the chemical potential and confinement of the trapped sample. Figure 3 shows a fit of the decay to an exponential, yielding a lifetime of $8 \pm 1$ s. No discernable thermal fraction was evident in these samples.

The radii show an inversion, as expected for an expanding condensate, but the effect is small because the trap is not highly asymmetric.

We fit the data using a numerical solution of the Castin-Dum model [43] for the free expansion of a Thomas-Fermi wavefunction [42]. The radii evolve according to

$$R_i(t) = R_i(0)b_i(t) = \sqrt{\frac{2\mu}{m(2\pi f_i)^2}} b_i(t)$$  \hspace{1cm} (3)

for $i = x, y, z$, where the scaling parameters obey $b_i(t) = (2\pi f_i)^2/(b_x b_y b_z)$. Using the well-known value of the scattering length [15] and our estimated trap parameters obtained from beam profiling and trap oscillation measurements, we obtain the dashed line in Fig. 4. Decreasing the frequencies by about 5% yields an improved fit (solid line), which is within our uncertainty in trap parameters.

If the trap is held constant after 4.5 s of evaporation, instead of releasing the condensate from the trap, the lifetime of the condensate can be measured. Figure 5 shows a fit of the decay to an exponential, yielding a lifetime of $8 \pm 1$ s. No discernable thermal fraction was evident in these samples.

The large number of condensate atoms and long lifetime indicate favorable conditions for many experiments. Of particular interest in the near future are the achievement of quantum degeneracy with other strontium isotopes and mixtures and the application of an optical Feshbach resonance to a quantum degenerate sample to modify the scattering length on small spatial and temporal scales.

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FIG. 5: (color online) Number of condensate atoms (filled circles) held in the optical dipole trap at constant depth versus time after the evaporation (see text). The solid line is an exponential fit of the data, yielding a condensate lifetime of $8\pm 1 \text{s}$.