Bose-Einstein condensation of $^{86}\text{Sr}$

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We report on the attainment of Bose-Einstein condensation of $^{86}\text{Sr}$. This isotope has a scattering length of about $+800a_0$ and thus suffers from fast three-body losses. To avoid detrimental atom loss, evaporative cooling is performed at low densities around $3 \times 10^{12}\text{cm}^{-3}$ in a large volume optical dipole trap. We obtain almost pure condensates of $5 \times 10^{13}$ atoms.

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Quantum degenerate gases of atoms with two valence electrons are an exciting field of research. The electronic structure of these atoms is the basis for applications like ultraprecise optical clocks [11, 12]. Quantum degenerate samples open new possibilities such as the study of unique quantum many-body phenomena [8–11] and novel schemes of quantum computation [12–15]. They are also an ideal starting point for the creation of molecules of two-electron atoms [16, 17] and molecules of two-electron atoms with alkali atoms [18, 19], which have applications in precision measurement [20] or quantum simulations with spin-dependent anisotropic long range interactions [21]. The first two-electron atom cooled to quantum degeneracy was ytterbium [22, 23], followed by calcium [24] and strontium last year. Quantum degenerate samples of bosonic $^{84}\text{Sr}$ and $^{88}\text{Sr}$ [26, 27], as well as of fermionic $^{87}\text{Sr}$ [28, 29] have been created, but Bose-Einstein condensation (BEC) of $^{86}\text{Sr}$ has so far been elusive [30].

The success of evaporative cooling with the goal to reach quantum degeneracy depends largely on the ratio of elastic to inelastic collisions of the atomic species used [32]. The four isotopes of strontium differ significantly in this respect. Despite its low natural abundance of 0.56%, $^{84}\text{Sr}$ was the first to be Bose condensed as it offers ideal scattering properties [26, 27]. $^{88}\text{Sr}$, which has a scattering length close to zero, and spin-polarized fermionic $^{87}\text{Sr}$ barely collide at ultralow temperatures. They could only be cooled to quantum degeneracy using mixtures with other isotopes or spin states [28, 30]. $^{86}\text{Sr}$ poses the opposite challenge: its large scattering length of $+800a_0$ [33] leads to a large three-body loss rate constant [31].

Previously reported conditions of $^{86}\text{Sr}$ in a dipole trap led to an elastic to inelastic collision ratio that was insufficient for evaporative cooling [31]. Magnetic tuning of the scattering properties, as was an essential ingredient to circumvent similar difficulties on the way to BEC of cesium [34], is not available in alkaline-earth elements. Another approach to increase the ratio of elastic two-body collisions and inelastic three-body collisions is to lower the density. This approach was important for BEC of $^{40}\text{Ca}$, which is also an isotope with large scattering length [27], as well as for BEC of cesium.

In this Rapid Communication, we show that it is indeed possible to create $^{86}\text{Sr}$ BECs by performing evaporation at comparatively low densities around $3 \times 10^{12}\text{cm}^{-3}$. To obtain sizeable atom numbers at these low densities, we implement a large volume optical dipole trap.

Our experimental procedure initially follows the one used for Bose condensation of $^{84}\text{Sr}$ [20]. Zeeman slowed atoms are captured and cooled by a “blue” magneto-optical trap (MOT) operating on the $5\text{s}\,^1\text{S}_0 - 5\text{s}\,^1\text{P}_1$ transition at a wavelength of 461 nm. A weak leak of the excited state of the cooling cycle continuously populates the $5\text{s}\,^3\text{P}_2$ metastable state. Weak-field seeking atoms in this state can be trapped in a magnetic trap formed by the quadrupole magnetic field used for the MOT. Metastable state atoms are accumulated in the magnetic trap for 1 s. Further cooling and density increase is achieved by operating a “red MOT” on the 7.4 kHz linewidth $^1\text{S}_0 - ^3\text{P}_1$ intercombination line at 689 nm. To increase the capture velocity of the red MOT, we frequency modulate the light, producing sidebands, which cover a detuning range from a few ten kHz to a few MHz to the red of the transition. To load the red MOT, the metastable-state atoms in the magnetic trap are optically pumped to the $^1\text{S}_0$ ground state using the $5\text{s}\,^3\text{P}_2 - 5\text{s}\,^5\text{D}_2$ transition at 497 nm. After loading, the MOT is compressed by reducing the MOT beam intensity and ramping off the frequency modulation, resulting in a colder and denser sample. At this point the MOT contains $2 \times 10^7$ atoms at a temperature of 1 µK.

The following evaporative cooling stage significantly differs from our previous experiments on $^{84}\text{Sr}$. The atoms are transferred into a crossed-beam optical dipole trap, which is much larger than the one used before. The trapping geometry consists of a horizontal and a nearly vertical beam, derived from a broadband ytterbium fiber laser operating at 1075 nm. The horizontal beam has an elliptic beam shape with a horizontal waist of 300 µm and a vertical waist of 33 µm. The vertical beam is circular with a waist of 290 µm and is used to provide additional confinement along the weak direction of the horizontal beam towards the end of evaporation. Initially, only the horizontal dipole trap beam is used and set to a power of 2 W. The resulting trap is oblate with horizontal trap oscillation frequencies of 3 Hz and 30 Hz, a vertical trap oscillation frequency of 260 Hz and a potential depth of...
3.7 µK, taking into account gravitational sagging. This oblate trap geometry combines the requirement of strong enough confinement against gravity in the vertical direction with the requirement of a large trap volume.

For optimum loading of the dipole trap, we adjust the intensity and detuning of the red MOT beams before switching them off. After 1 s of plain evaporation, 2.5 \times 10^9 atoms at a temperature of 500 nK remain in the trap. The peak density is 3 \times 10^{12} \text{cm}^{-3} and the peak phase-space density is 0.05. Even at the temperature of 500 nK, unitary limitation leads to a reduction of the thermally averaged elastic scattering cross section by a factor of two compared to the zero temperature value. The elastic collision rate is only one tenth of 2 \times 10^{-12} \text{cm}^{-3} \text{s}^{-1}.

After the plain evaporation stage, forced evaporation is performed over 4.8 s. The power of the horizontal dipole trap beam is reduced nearly exponentially to 740 mW, with a longer time constant during the last 1.5 s. During the first 2.3 s of forced evaporation, the vertical dipole trap beam is increased to a power of 0.5 W, at which it stays for the rest of the evaporation sequence. The vertical beam increases the confinement along the weak direction to 5 Hz and does not provide any confinement along the vertical direction. The potential depth of the vertical beam in the radial directions is 200 nK. During evaporation atoms escape the trap mainly downwards by leaving the trap over the potential barrier formed by the horizontal beam and gravity. It is beneficial for evaporation that the vertical trap oscillation frequency remains higher than the elastic collision rate, so that high energy atoms produced by collisions can quickly move out of the trap. During evaporation the peak density slightly drops to 10^{12} \text{cm}^{-3} and the elastic collision rate drops to 70 \text{s}^{-1} before condensation. At this point the temperature is \sim 30 \text{nK} and the thermally averaged scattering cross section is very close to the zero-temperature value.

The phase transition from a thermal cloud to a BEC becomes evident in the appearance of a bimodal distribution, as clearly visible in time-of-flight absorption images and in the corresponding linear density profiles shown in Fig. 1. At higher temperature the distribution is thermal, exhibiting a Gaussian shape. Cooling below the critical temperature $T_c$ leads to the appearance of an additional, narrower and denser, elliptically shaped component: the BEC. The phase transition occurs after 4 s of evaporative cooling, when the power of the horizontal beam is 820 mW. At this point, the horizontal trap oscillation frequencies are 5 Hz and 18 Hz, the vertical trap oscillation frequency is $f_{vert} = 115$ Hz and the trap depth is about 110 nK, taking into account gravitational sagging. Note that despite the large scattering length, we are not in the collisionally hydrodynamic regime since the elastic scattering rate is only one tenth of $2\pi f_{vert}$.

In order to analyze the phase-transition precisely, we fit bimodal distributions to the time-of-flight absorption images. The bimodal distributions consist of a Gaussian for the thermal part of the cloud and an inverted paraboloid integrated along one direction for the BEC. We extract the amount of condensed atoms $N_0$, the total amount of atoms $N$ and the temperature $T$ of the sample from the fits. The condensate fraction $N_0/N$ as a function of temperature, scaled by the transition temperature of a non-interacting gas in the thermodynamic limit $T_0$ is shown in Fig. 2. From this data we extract a critical temperature of $T_c = 29(2)$ nK = 0.90(5) $T_0$. The atom number at the onset of BEC is $3.5 \times 10^4$. Interaction effects reduce the critical temperature $T_c$ by 14% compared to $T_0$, whereas finite-size effects add only a minor reduction of 1%. These effects give a theoretically expected transition temperature of $T_c = 0.85 T_0$.

After 4.8 s of evaporation, a nearly pure BEC of $5 \times 10^4$ atoms is produced in a trap with oscillation frequencies...
We extract an upper bound for the three-body loss rate constant from the lifetime measurement of a nearly pure BEC. The initial atom loss rate per atom from the BEC is $N_0^{-1} dN_0/dt = 3(1) \text{s}^{-1}$. This value is determined from the initial slope of an exponential fit to 500 ms of decay data. Assuming only three-body loss, the loss of atoms is described by $dN_0/dt = -(1/6)K_3 \int n_0^3 dV$, where $n_0$ is the density distribution of the BEC and the factor $1/6$ takes into account the difference of three-body correlations of a thermal gas and a BEC. The resulting upper bound for the three-body loss rate constant is $K_3 = 6(3) \times 10^{-24} \text{cm}^6/\text{s}$. This value is about six times higher than the value measured by Ferrari et al. 31. Moreover it is an order of magnitude higher than the maximally expected loss rate constant, which is $K_3 = 210\hbar a^4/m = 5 \times 10^{-25} \text{cm}^6/\text{s}$, assuming that three atoms are lost during each three-body loss event 38,39. Here $a$ is the scattering length and $m$ is the mass of $^{86}\text{Sr}$. Several explanations are possible for the unusually large measured value. More than three atoms might be lost per three-body loss event resulting from secondary collisions, possibly augmented by an enhanced atom-dimer scattering cross section 40,41. Evaporation of atoms heated by technical noise of the dipole trap is an example for an explanation other than three-body loss. Further studies are needed to resolve this issue.

In conclusion, we have produced a Bose-Einstein condensate of $^{86}\text{Sr}$ containing $5 \times 10^6$ atoms. With this achievement all stable isotopes of strontium have been cooled to quantum degeneracy. The large scattering length of $^{86}\text{Sr}$ leads to a very large three-body loss rate coefficient, which poses a challenge for evaporative cooling. We have shown that performing evaporation at low density in a large volume trap is a possible way to overcome this problem. The BEC of $^{86}\text{Sr}$ enriches the possibilities opened up by strontium quantum gases. The large scattering length of $^{86}\text{Sr}$ originates from a weakly bound state in the molecular potential. This state will influence the properties of optical Feshbach resonances 42,43. The BEC of $^{86}\text{Sr}$ increases the options for quantum degenerate mixtures of different Sr isotopes or of mixtures of Sr with other elements. This wider choice can be important, for example in the search for magnetic Feshbach resonance in Sr-alkali mixtures suitable for molecule creation 18.

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