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 $+800 a_0$ and thus suffers from fast three-body losses. To avoid detrimental atom loss, evaporative cooling is performed at low densities around $3 \times 10^{12}$ cm$^{-3}$ in a large volume optical dipole trap. We obtain almost pure condensates of $5 \times 10^3$ 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 such as ultrasprecise optical clocks [1–7]. Quantum degenerate samples open up possibilities, such as the study of quantum many-body phenomena [8–11] and schemes of quantum computation [12–15] not accessible with alkali-metal atoms. 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-metal 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 [22–24], followed by calcium [25] and strontium. Quantum degenerate samples of bosonic $^{84}\text{Sr}$ and $^{88}\text{Sr}$ [26–28], as well as of fermionic $^{87}\text{Sr}$ [29,30], have been created, but Bose-Einstein condensation (BEC) of $^{86}\text{Sr}$ has so far been elusive [31].

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 with a horizontal waist of 300 $\mu$m and a vertical waist of 290 $\mu$m. The vertical beam is circular with a waist of 290 $\mu$m. The horizontal beam has an elliptic beam shape derived from a broadband ytterbium fiber laser operating at 1075 nm. The horizontal beam geometry consists of a horizontal and a nearly vertical beam, initially only the horizontal dipole trap beam is used and set to a power of 2 W. The resulting trap is oblate with horizontal waist of 300 $\mu$m and a vertical waist of 33 $\mu$m. The vertical beam is circular with a waist of 290 $\mu$m and is used to provide additional confinement along the weak direction of the horizontal beam toward 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 and 30 Hz, a vertical trap oscillation frequency of 260 Hz, and a potential depth of 3.7 $\mu$K, 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, $2.5 \times 10^8$ atoms at a temperature of 500 K 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 2 compared to the zero-temperature value. The elastic collision rate is 380 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 downward 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 s$^{-1}$ before condensation. At this point the temperature is $\sim 30$ 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 and 18 Hz, the vertical trap oscillation frequency is $f_{\text{vert}} = 115$ 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 $2\pi f_{\text{vert}}$ [35].

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 [36]. The condensate fraction $N_0/N$ as a function of temperature, scaled by the transition temperature of a noninteracting gas in the thermodynamic limit $T_0^0$ is shown in Fig. 2. From this data we extract a critical temperature of $T_c/T_0^0 = 0.9(1)$, where the error is dominated by uncertainties in $T_0^0$ resulting from the uncertainty in the atom number of about 25%. The phase transition occurs at a temperature of 30(2) nK with $3.7 \pm 1 \times 10^4$ atoms. The theoretically expected critical temperature $T_c$ is reduced by 14% compared to $T_0^0$ by interaction effects. Finite-size effects add a minor reduction of 1%. These effects give a theoretically expected transition temperature of $T_c = 0.85T_0^0$ [37], which is within the uncertainty of our data.

After 4.8 s of evaporation, a nearly pure BEC of $5 \times 10^3$ atoms is produced in a trap with oscillation frequencies of 5 and 16 Hz in the horizontal plane and 70 Hz in the vertical direction. The peak density of the BEC is $3 \times 10^{12} \text{ cm}^{-3}$ and the chemical potential is 7 nK. The BEC has an oblate shape with calculated in situ Thomas-Fermi radii of 40 and 12 $\mu$m in the horizontal plane and 3 $\mu$m in the vertical direction. After release from the trap, the BEC undergoes a mean-field driven expansion, with the strongest expansion in the vertical direction, resulting in an inversion of ellipticity as shown on the absorption images in Fig. 3.

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 $N_0^{-1}dN_0/dt = 3(1)$ 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 $dN_0/dt = -(1/6)K_3 \int n_3 dV$, 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 $K_3 = 210ha^4/m = 5 \times 10^{-25} \text{cm}^6/\text{s}$, 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 $^{86}$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. Our present data are insufficient to distinguish these different loss scenarios and further studies are needed to resolve this issue.

In conclusion, we have produced a Bose-Einstein condensate of $^{86}$Sr containing $5 \times 10^3$ atoms. With this achievement all stable isotopes of strontium have been cooled to quantum degeneracy. The large scattering length of $^{86}$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 $^{86}$Sr enriches the possibilities opened up by strontium quantum gases. The large scattering length of $^{86}$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 $^{86}$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-metal mixtures suitable for molecule creation [18].

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[36] To determine if a BEC is present, we also fit single Gaussian distributions to the images. If the fit residue of such a fit is comparable to that of a bimodal fit, we consider the distribution as purely thermal and extract temperature and atom number from the single Gaussian fit, otherwise from the bimodal fit. The temperature is determined from the size of the Gaussian component in the vertical direction, in which the cloud has expanded far enough beyond its initial size to show the momentum distribution.