Quantum degenerate mixtures of strontium and rubidium atoms

Benjamin Pasquiou,1 Alex Bayerle,1,2 Slava Tzanova,1,2 Simon Stellmer,1 Jacek Szczepkowski,1,3 Mark Parigger,1,2 Rudolf Grimm,1,2 and Florian Schreck1

1Institut für Quantenoptik und Quanteninformation (IQOQI), Österreichische Akademie der Wissenschaften, 6020 Innsbruck, Austria
2Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria
3Institute of Physics, Polish Academy of Sciences, 02-668 Warsaw, Poland

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We report on the realization of quantum degenerate gas mixtures of the alkaline-earth element strontium with the alkali element rubidium. A key ingredient of our scheme is sympathetic cooling of Rb by Sr atoms that are continuously laser cooled on a narrow linewidth transition. This versatile technique allows us to produce ultracold gas mixtures with a phase-space density of up to 0.06 for both elements. By further evaporative cooling we create double Bose-Einstein condensates of $^{87}$Rb with either $^{88}$Sr or $^{84}$Sr, reaching more than $10^5$ condensed atoms per element for the $^{84}$Sr,$^{87}$Rb mixture. These quantum gas mixtures constitute an important step towards the production of a quantum gas of polar, open-shell RbSr molecules.

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I. INTRODUCTION

Quantum degenerate gas mixtures of different chemical elements have opened up important new areas for the study of interacting quantum systems. The possibility to apply species-specific optical potentials [1] is a versatile tool and has for example been used to study the exchange of entropy between two gases [2] or mixed-dimensional systems [3]. The mass difference between the constituents of the mixture can lead to new few- and many-body phenomena [4-5], such as novel trimer states [6-8] or crystalline quantum phases [9]. Quantum gas mixtures of two elements have also attracted a great deal of attention because they are an ideal starting point for the coherent production of heteronuclear ground-state molecules, which can have large electric dipole moments [10-12]. The dipole interaction can dominate the behavior of a quantum gas of these molecules and lead to intriguing many-body phenomena [13-16]. Ultracold polar molecules also provide insights into chemistry at the quantum level and have the potential to be used as sensitive probes for variations of fundamental constants or as the basis of quantum computation schemes [11-17].

Most experimentally investigated quantum gas mixtures of two elements consist of two alkali metals [18-21]. Advances in producing quantum degenerate samples of Yb [22] and alkaline-earth elements [21,22] have led to efforts towards mixtures containing these elements and recently quantum degenerate Yb-Li mixtures were obtained [23,24]. A driving force behind these efforts is the interest in polar gases of polar molecules beyond alkali dimers, such as RbYb [31], LiYb [25,26], or RbSr [32]. Contrary to alkali dimers, these open-shell molecules possess an unpaired electron, which provides them with a rich spin structure and a magnetic dipole moment. This property will enable new ways to design and control few- and many-body systems and could prove very useful to implement lattice-spin models [33], to suppress inelastic collisions [34], to imprint geometric phases [35], or to study collective spin excitations [36].

In this Article, we present the realization of quantum gas mixtures composed of the alkali metal $^{87}$Rb and the alkaline-earth metal $^{88}$Sr or $^{84}$Sr. An essential ingredient of our experimental strategy is the use of sympathetic laser cooling [37-39] on a narrow linewidth transition, which allows us to reach a high phase-space density (PSD) for both elements before evaporative cooling. Strontium atoms are laser cooled on the narrow $^1S_0 \rightarrow ^3P_1$ intercombination line and act as a refrigerant for Rb confined in an optical dipole trap. During this sympathetic laser cooling stage, the PSD of Rb increases by a factor of more than 200, with only a 20% reduction of the Rb atom number. In less than 400 ms the PSD of both elements can reach 0.06. These very favorable conditions allow us to efficiently reach quantum degeneracy for both species by evaporative cooling and to create BECs with more than $10^7$ atoms per element. The ease of producing large quantum degenerate samples enabled by sympathetic narrow-line laser cooling, together with the large electric dipole moment of RbSr ground-state molecules of 1.5 Debye [40], make Sr-Rb quantum gas mixtures an ideal stepping stone towards the exploration of dipolar physics with open-shell molecules.

The organization of this paper is as follows. In Sec. [1] we present an overview of our scheme. Section [11] describes the loading of a cloud of Rb into an optical dipole trap, followed by the loading of Sr atoms into a narrow-line magneto-optical trap (MOT). Section [1V] focuses on our sympathetic narrow-line laser cooling scheme. In Sec. [V] we describe the final evaporative cooling stage and the production of two different quantum degenerate mixtures, a $^{88}$Sr-$^{87}$Rb and a $^{84}$Sr-$^{87}$Rb double BEC.
II. OVERVIEW OF THE EXPERIMENTAL STRATEGY

To reach quantum degeneracy, most ultracold atom experiments rely on laser cooling followed by evaporative cooling. The latter process intrinsically leads to a loss of atoms. To minimize this loss, it is beneficial to develop laser cooling methods that are able to reach high PSDs. The main atomic transition for laser cooling of alkalis, such as Rb, is broad, on the order of several MHz. To achieve high PSDs by laser cooling of such species, one can apply sub-Doppler cooling techniques, such as polarization gradient cooling in optical molasses [41–46], velocity selective coherent population trapping of Rb with Sr atoms laser cooled on a narrow line and the formation of dual-species BECs by a consecutive evaporative cooling stage.

Our procedure to achieve quantum degeneracy can be divided into three main stages, see Fig. 1(a). During the first, “preparation” stage (Sec. III), we use well-established cooling and trapping techniques to prepare ultracold samples of Rb and Sr. We accumulate Rb atoms in a magneto-optical trap and transfer them into a single beam optical dipole trap, henceforth referred to as the “storage” trap. After having stored Rb, we operate a “blue” Sr MOT, thereby accumulating metastable Sr atoms in a magnetic trap. We then optically pump Sr back to the ground state and capture the atoms in a “red”, narrow-line MOT, see Fig. 1(b). During the second, “sympathetic laser cooling” stage (Sec. IV) we sympathetically cool the Rb cloud by $^{88}$Sr atoms that are continuously laser cooled to a few $\mu$K on a narrow linewidth transition. We then transfer Rb and either $^{88}$Sr or $^{4}$Sr into a second, “science” dipole trap, see Fig. 1(c). During the last, “evaporation” stage (Sec. V) we perform evaporative cooling, where Sr sympathetically cools Rb until quantum degeneracy is reached for both elements.

![Figure 1: (Color online) Timing of the experimental sequence and trap configurations used to produce a $^{88}$Sr-$^{87}$Rb double BEC. (a) Timing sequence. The central sympathetic laser cooling of $^{87}$Rb by $^{88}$Sr shaded in gray is characterized in Fig. 2. (b,c) Dipole trap configurations and atomic clouds at the end of the preparation stage (b) and during the evaporation stage (c) (not to scale).](image)

III. PREPARATION OF AN ULTRACOLD SAMPLE OF RUBIDIUM AND STRONTIUM

In this Section, we describe our experimental setup and the preparation of an ultracold mixture consisting of Rb contained in the storage trap and Sr stored in a narrow-line MOT, see Fig. 1(b).

Our experimental setup is based on our Sr BEC apparatus, which has been described in detail in [55, 56]. The basic principle of the apparatus is to capture a Zeeman slowed atomic beam in a MOT and to cool the gas to quantum degeneracy by evaporation out of a dipole trap. Here we will focus on the upgrades carried out to also trap and cool Rb with the apparatus. Copropagating atomic beams of each element are produced by two independent ovens, heated to 550 $^\circ$C for Sr and 200 $^\circ$C for Rb [56, 57]. The same Zeeman slower (ZS) is used to slow both beams. Since the magnetic fields required to slow Rb and Sr differ significantly, we perform a time-sequential loading scheme. The Rb ZS laser beam is superposed with the Sr ZS beam by a dichroic mirror, and uses 14 mW of light detuned by $-165$ MHz from the $^{2}$S$_{1/2}$-$^{2}$P$_{3/2}$, $|F = 2\rangle \rightarrow |F' = 3\rangle$ transition. A “re-pumping” beam with 4.5 mW of power, addressing the $|F = 1\rangle \rightarrow |F' = 1\rangle$ transition is overlapped with the ZS beam. All three laser beams have a waist of about 8 mm at the MOT position. Slowed atoms are captured by a 3D MOT. Producing an ultracold mixture of Rb and Sr requires the use of MOTs of three wavelengths, one for Rb and two for Sr. The Rb MOT uses 780-nm light, the blue Sr MOT is operated on the broad $^{1}$S$_{0}$ →
$^{1}P_{1}$ transition at 461 nm, and the red MOT on the $^{1}S_{0}$ → $^{3}P_{1}$ intercombination line at 689 nm. MOT beams of the three wavelengths are overlapped by dichroic mirrors on each of the three retro-reflected MOT beam paths. The Rb MOT beams have a waist of 9.8 mm, a power of 18 mW (25 mW) in the horizontal (vertical) direction, and are detuned by −16 MHz from the $^{2}S_{1/2}$→$^{2}P_{3/2}$, $|F = 2\rangle → |F' = 3\rangle$ transition. A repumping beam with a waist of 6 mm and a peak intensity of 130 $\mu$W/cm$^2$, on resonance with the $|F = 1\rangle → |F' = 2\rangle$ transition, is shone onto the MOT. The quadrupole magnetic field of the Rb MOT has a gradient of 12 G/cm along the vertically oriented coil axis.

The experimental sequence starts by operating the Rb MOT during 20 s to accumulate a cloud of $2 \times 10^7$ atoms at a temperature of 175 $\mu$K. We then compress the cloud in 140 ms by raising the gradient of the quadrupole field to 50 G/cm and increasing the MOT laser detuning to +30 MHz. After compression the $1/e$ cloud radius is $\sim 250 \mu$m. To decrease the temperature we use polarization gradient cooling in an optical molasses. After switching off the magnetic field, the MOT laser detuning is set to −110 MHz and the beam power is halved. After 3 ms of molasses, we obtain $1.8 \times 10^7$ atoms cooled to 15 $\mu$K with a peak density of $3 \times 10^{13}$ cm$^{-3}$.

We then transfer the Rb atoms into the storage trap. This trap consists of a horizontal beam with a waist of 40 $\mu$m propagating at a small angle to the x-direction, see Fig. 1(b). The beam is derived from a 100-W multimode fiber laser operating at a wavelength of 1070 nm (YLR-100-LP-AC-Y12 from IPG). It is linearly polarized in the vertical direction to minimize the light shift induced on the red Sr laser cooling transition [55]. Initially we use a power of 14 W for the storage trap, which results in a potential depth of $k_B \times 830 \mu$K and trap frequencies of $f_{\text{rad}} = 2.2$ kHz and $f_{\text{ax}} = 13$ Hz in the radial and axial directions respectively. To improve loading of the storage trap, we toggle the repumping beam to a path were a wire is imaged onto the trap region, creating a dark spot. The repumping beam power is reduced to a peak intensity of $8 \mu$W/cm$^2$ and in 500 ms we transfer 10% of the molasses atoms into the trap, pumping them at the same time into the $F = 1$ manifold. Up to $1.7 \times 10^6$ atoms are stored in the storage trap at a density of $2 \times 10^{13}$ cm$^{-3}$ and a temperature of $\sim 20 \mu$K.

Having stored Rb, we now capture Sr atoms. The loading and cooling of Sr is done in a manner similar to our previous work [27, 55]. We operate a blue MOT on the broad transition at 461 nm, which has a leak towards the metastable $^{3}P_{2}$ state. We accumulate $^{3}P_{2}$ atoms in the magnetic trap formed by the quadrupole field of the MOT. We typically load this reservoir in a few seconds with several million $^{88}$Sr atoms. For the data presented in Sec. III and IV we load for 0.5 s. The atoms are subsequently optically pumped back to the ground state using a flash of light on the $^{3}P_{2} \rightarrow ^{3}D_{2}$ transition at 497 nm. The atoms are captured by a red MOT operating on the $^{1}S_{0} \rightarrow ^{3}P_{1}$ intercombination transition and using a magnetic field gradient of 1.8 G/cm. The narrow, 7.4 kHz-linewidth intercombination transition allows us to cool Sr to less than 1 $\mu$K while keeping millions of atoms. The atoms settle in the lower part of an ellipsoid of constant magnetic field magnitude, see Fig. 1(b). The size and position of this cloud can be influenced by the magnetic field and the detuning of the MOT light. Varying these parameters facilitates the transfer of Sr into the optical dipole trap.

At the end of the preparation stage, we obtain $7 \times 10^9$ $^{88}$Sr atoms at a temperature of 2.5 $\mu$K in a red MOT. The storage trap contains $1.6 \times 10^9$ Rb atoms at a temperature of 30 $\mu$K and a phase-space density of $2.5 \times 10^{-4}$, which is slightly worse than before loading the Sr atoms. The 1/e lifetime of the Rb cloud in the storage trap in presence of the blue $^{88}$Sr MOT is 5.0(5) s. To detect the influence of Sr atoms on the Rb cloud in the storage trap, we perform the same experimental sequence, but shutter the atomic beam off after loading the Rb MOT. Under these conditions, the lifetime of the Rb sample in the storage trap is 30(1) s. This value does not change if also the Sr laser cooling beams are off.

IV. SYMPATHETIC NARROW-LINE LASER COOLING

The following, sympathetic laser cooling stage is crucial in our approach to obtain a Sr-Rb double BEC. We make use of laser cooled Sr to further cool Rb and increase its PSD. To this aim, we overlap the cloud of $^{88}$Sr atoms with the focus of the storage trap. This overlap is achieved by moving the magnetic field center upwards, while keeping the MOT laser frequency red detuned by 200 kHz from resonance. At this point, the Sr density is so low that the influence on the Rb cloud is negligible on a timescale of 500 ms. To increase the density of the Sr cloud, the magnetic field together with the MOT detuning and intensity are changed over 200 ms such that the cloud is compressed while remaining at the same position.

The Sr atoms are loaded into the storage trap during this compression phase. The loading process is strongly influenced by the light shift induced on the red MOT transition by this trap. At the center of the trap, the light shift is $\sim +500$ kHz, which is almost 70 times the linewidth. In order to laser cool Sr atoms in the storage trap we tune the MOT laser frequency 350 kHz to the blue of the unshifted atomic transition in a 200 ms ramp, while reducing the peak beam intensity to 6 $\mu$W/cm$^2$. The part of the Sr cloud that does not spatially overlap with the dipole trap is thereby expelled from the MOT, leading to a loss of 60% of the Sr atoms. This loss could be reduced by canceling the light shift of the transition, for example by inducing a light shift on the excited state of the laser cooling transition [55]. Since $^{88}$Sr has a high natural abundance, leading to a high atom number in the MOT, we here simply tolerate the loss. The temperature of the Sr cloud in the storage trap increases to 15 $\mu$K before reducing to below 5 $\mu$K during the compression
Figure 2: (Color online) Sympathetic laser cooling of $^{87}\text{Rb}$ by $^{88}\text{Sr}$. During the compression phase the density of the red Sr MOT is increased and the Sr atoms are loaded into the storage dipole trap by changing magnetic field and both the MOT laser detuning and intensity. During the hold phase these parameters are held constant. (a,b) Evolution of the Rb and Sr atom numbers (a) and temperatures (b) as determined from time-of-flight absorption images. During a part of the compression phase the Sr cloud separates into two components, one being heated out of the system, the other remaining trapped and being transferred into the storage trap. We only show the number of trapped Sr atoms and the Sr temperature if we can determine them reliably from bimodal fits to the absorption images. (c) PSD of Rb, calculated from trap parameters and Rb atom number and temperature.

phase and a subsequent 200 ms hold phase. This temperature increase results from MOT dynamics in presence of the light shift induced by the dipole trap and would also occur in absence of Rb atoms. The Rb cloud thermalizes with laser cooled Sr by elastic collisions. During this process, the Rb PSD increases dramatically, by a factor of more than 200, reaching $0.062(6)$, while only $20(5)$% of the Rb atoms are lost. From the thermalization behavior we can deduce a minimum absolute value of the interspecies scattering length of $30\ a_0$ between $^{87}\text{Rb}$ and $^{88}\text{Sr}$.

After the hold phase the Sr laser cooling beams are switched off. We observe that complete thermal equilibrium between Rb and Sr can only be reached in absence of the cooling light.

To prepare for the creation of a quantum degenerate sample, we transfer both elements into the science dipole trap, which has been described in detail in Ref. [55] and will be especially important for the creation of a large $^{84}\text{Sr}$-$^{87}\text{Rb}$ double BEC (see Sec. V B). This crossed-beam dipole trap is composed of an elliptical beam propagating in the $x$-direction with waists of $w_x = 17\ \mu m$ and $w_y = 300\ \mu m$, crossed by a nearly vertical beam with a waist of $90\ \mu m$, see Fig. 1(c). The center of this dipole trap is overlapped with the center of the storage trap, and the horizontal beams of the two traps intersect at an angle of $17^\circ$. Individual laser sources are used for each science trap beam (5-W, 1065-nm multimode fiber lasers, YLD-5-LP from IPG). At the wavelength of 1065 nm the polarizability of Rb is 2.9 times the polarizability of Sr [60, 61]. The ratio of trap depths is even higher because of gravitational sagging. Initially the science trap has a depth of $k_B \times 25\ \mu K$ for Rb and $k_B \times 7\ \mu K$ for Sr. The reduction of the Rb cloud volume and temperature by sympathetic laser cooling allows us to transfer Rb from the storage trap into this much shallower trap in 500 ms with a nearly perfect transfer efficiency (more than 95% of the atoms). The $^{88}\text{Sr}$ transfer efficiency is 30%. After transfer we typically obtain $1.25 \times 10^6$ Rb atoms and $1.6 \times 10^8$ Sr atoms at a temperature of 1.2 $\mu K$. The Rb PSD is 0.5(2) and the Sr PSD is 0.10(3). We attribute the increase in PSD to evaporation of Sr during the transfer process.

V. EVAPORATION TO ALKALI/ALKALINE-EARTH DOUBLE BECS

In this Section we present the creation of quantum degenerate mixtures of $^{87}\text{Rb}$ with either $^{88}\text{Sr}$ (Sec. V A) or $^{84}\text{Sr}$ (Sec. V B). These two Sr isotopes have markedly different properties, which we take into account in our experimental strategy. The $^{88}\text{Sr}$ isotope has a high natural abundance and provides us with an ideal coolant for sympathetic narrow-line laser cooling of $^{87}\text{Rb}$. Since the $^{88}\text{Sr}$ scattering length is negative (-2$a_0$), the $^{88}\text{Sr}$ BEC atom number is limited to a few thousand atoms. By contrast, $^{84}\text{Sr}$ has a convenient scattering length of +123$a_0$, allowing us to create BECs with high atom number. Unfortunately this isotope has a low natural abundance (only 0.56%), which renders it less favorable for sympathetic laser cooling. To overcome this drawback, we employ both isotopes in the production of a $^{84}\text{Sr}$-$^{87}\text{Rb}$ double BEC, using $^{88}\text{Sr}$ for sympathetic laser cooling of $^{87}\text{Rb}$ and $^{84}\text{Sr}$ for evaporative cooling to quantum degeneracy.
Rb cloud consists of a mixture of all three $m = -2, 0, +2$ and Sr BECs with low atom number immersed in ther-
times deeper for Rb than for Sr, Rb is sympathetically
thermalized. Since the trap depth is more than three
interspecies thermalization. Note that by itself
$^88\text{Sr}$ scattering cross section is sufficient for in-
cooling by lowering the trap depth exponentially over
$^88\text{Sr}$ to $^87\text{Rb}$ expansion time [64]. The distribution for
during the evaporation stage [64, 65]. The lifetime of the MOT
has a radius of about 1 mm and a low density, which re-
fluence the various operations on the other
by using two frequencies for the red MOT laser
operation stage to obtain a $^{88}\text{Sr}^{87}\text{Rb}$ BEC. Nonetheless we have developed an improved strategy,
which requires less time, makes optimal use of the
precious $^84\text{Sr}$ atoms, and leads to much larger numbers
of condensed atoms. Because of its high natural abun-
dance, we use $^88\text{Sr}$ as the refrigerator for sympathetic
cooling of Rb. We then use $^84\text{Sr}$ during the evap-
oration stage to obtain a $^{88}\text{Sr}^{87}\text{Rb}$ BEC.
We adapt the scheme of our experiment to this new
strategy, see Fig. 4(a). During the Sr blue MOT stage we
load both Sr isotopes, $^{88}\text{Sr}$ and $^{84}\text{Sr}$. This double-isotope
loading is achieved by accumulating one isotope after the
other in the metastable state reservoir. In between, the
frequency of the 461-nm cooling laser source is changed
by the isotope shift [55, 69]. We first accumulate $^{88}\text{Sr}$ for 500 ms and then add
$^{84}\text{Sr}$ during 10 s. The lifetime
of Rb atoms in the storage trap in presence of the
$^84\text{Sr}$ blue MOT is 23(1) s. Afterwards both isotopes are opti-
cally repumped into the electronic ground state. The
two isotopic clouds are captured simultaneously by two
narrow-line red MOTs, which contain $4 \times 10^9$ atoms of
$^{88}\text{Sr}$ and $9 \times 10^9$ atoms of $^84\text{Sr}$ respectively, see Fig. 4(b)
[55, 69]. The different isotopes are addressed independ-
ently by using two frequencies for the red MOT laser
beams, separated by the isotope shift. Changing one of
the MOT laser frequencies, vertically displaces the cor-
responding isotopic cloud and changes its radial size.
We proceed as described in Sec. IV with the sympa-
thetic laser cooling of Rb by $^{88}\text{Sr}$ and the transfer of the
$^{88}\text{Sr}^{87}\text{Rb}$ mixture into the science trap. In the mean-
time we keep the $^84\text{Sr}$ cloud about 0.7 mm below the
center of the dipole traps. At this position the red MOT
has a radius of about 1 mm and a low density, which re-
duces light-assisted collisions. The lifetime of the MOT
is independent of the various operations on the other
species and we lose only 10% of the $^84\text{Sr}$ atoms during
the sympathetic laser cooling stage. Reciprocally, the

A. $^{88}\text{Sr}^{87}\text{Rb}$ double BEC

To obtain a $^{88}\text{Sr}^{87}\text{Rb}$ double BEC, we prepare as be-
fore a $^{88}\text{Sr}^{87}\text{Rb}$ mixture in the science trap. Compared
with the previous sections, we here increase the number of
ultracold $^{88}\text{Sr}$ atoms by increasing the Sr MOT loading
time to 5 s. Then we perform forced evaporative
cooling by lowering the trap depth exponentially over
11 s to 0.5 $\mu$K for Sr. As demonstrated in Sec. IV, the
interspecies scattering cross section is sufficient for in-
terspecies thermalization. Note that by itself $^{88}\text{Sr}$ does
barely thermalize because of its small scattering length of
$-2 a_0$ [62, 63] and only the presence of Rb ensures proper
thermalization. Since the trap depth is more than three
times deeper for Rb than for Sr, Rb is sympathetically
cooled by evaporating Sr.

At the end of the evaporation stage, we obtain Rb
and Sr BECs with low atom number immersed in ther-
al clouds (see Fig. 3). The Sr cloud contains $2.3 \times 10^5$
condensed atoms and $6.5 \times 10^4$ thermal atoms. The
Rb cloud consists of a mixture of all three $m_F$ states of
the $F = 1$ manifold, as confirmed by Stern-Gerlach
measurements. The spin state distribution can be influ-
enced by applying a magnetic field offset and gradient
during the evaporation stage [64]. The distribution for
zero offset and gradient is 38%, 25%, and 37% for the
$m_F = -1, 0, +1$ states after evaporation. In total
the Rb cloud consists of $1.3 \times 10^4$ atoms in the spinor
BEC and $5 \times 10^4$ thermal atoms. The temperature of
both elements is 190(30) nK. The low $^{88}\text{Sr}$ BEC atom
number is expected since the negative scattering length
of $^{88}\text{Sr}$ leads to a collapse of the BEC for higher atom
numbers [55, 63, 68].

B. $^{84}\text{Sr}^{87}\text{Rb}$ double BEC

Figure 3: (Color online) $^{88}\text{Sr}^{87}\text{Rb}$ double BEC. The ab-
sorption images have been recorded after an expansion time
of 26 ms. The lower panels show density profiles obtained by
vertical integration of the absorption images. Bimodal fits
consisting of a Gaussian and a Thomas-Fermi distribution
are shown as red, solid lines. The Gaussian part of the fit
corresponds to the thermal fraction of the cloud and is shown
as blue, dotted line.

To obtain quantum degenerate samples with higher
atom numbers, we now turn to the $^{84}\text{Sr}$ isotope. This
isotope has a scattering length of $+123 a_0$ [62, 63], which
is well-suited for evaporative cooling. Despite the small
$^{84}\text{Sr}$ natural abundance of only 0.56% the production of
large $^{84}\text{Sr}$ BECs with $10^7$ atoms has been demonstrated
[55]. The low abundance can be compensated for by a
longer blue MOT duration compared to the one used
for the highly abundant $^{88}\text{Sr}$ isotope, leading to nearly
the same atom number accumulated in the metastable
state reservoir. By simply replacing $^{88}\text{Sr}$ with $^{84}\text{Sr}$ and
operating the blue MOT for 20 s, we can prepare a $^{84}\text{Sr}^{87}\text{Rb}$
double BEC with essentially the same scheme as
the one used for the production of a $^{88}\text{Sr}^{87}\text{Rb}$ double
BEC. Nonetheless we have developed an improved strategy,
which requires less time, makes optimal use of the
precious $^{84}\text{Sr}$ atoms, and leads to much larger numbers
of condensed atoms. Because of its high natural abun-
dance, we use $^{88}\text{Sr}$ as the refrigerator for sympathetic
laser cooling of Rb. We then use $^{84}\text{Sr}$ during the evap-
oration stage to obtain a $^{84}\text{Sr}^{87}\text{Rb}$ BEC.

We adapt the scheme of our experiment to this new
strategy, see Fig. 4(a). During the Sr blue MOT stage we
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other in the metastable state reservoir. In between, the
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of Rb atoms in the storage trap in presence of the
$^{84}\text{Sr}$ blue MOT is 23(1) s. Afterwards both isotopes are opti-
cally repumped into the electronic ground state. The
two isotopic clouds are captured simultaneously by two
narrow-line red MOTs, which contain $4 \times 10^9$ atoms of
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[55, 69]. The different isotopes are addressed independ-
ently by using two frequencies for the red MOT laser
beams, separated by the isotope shift. Changing one of
the MOT laser frequencies, vertically displaces the cor-
responding isotopic cloud and changes its radial size.
presence of the $^{84}$Sr red MOT does not affect the sympathetic laser cooling of Rb.

It is advantageous to expel the refrigerant $^{88}$Sr after it has fulfilled its role. Without the removal of $^{88}$Sr, the large scattering length between $^{84}$Sr and $^{88}$Sr of about 1700 $a_0$ would lead to strong three-body loss as soon as $^{84}$Sr is loaded into the science trap. We expel $^{88}$Sr by adiabatically lowering the science trap depth in $300$ ms. Including gravitational sagging the trap is about ten times shallower for Sr than for Rb at the end of the ramp, leading to a removal of all $^{88}$Sr atoms without affecting the Rb atom number. We then raise the trap back to its former depth in 100 ms.

At this point we load $^{84}$Sr into the science trap, see Fig. 4(c). We shift the red MOT upwards by changing the cooling laser frequency until the MOT overlaps with the science trap. Now 70\% of the $^{84}$Sr atoms are loaded into the dipole trap, compared to 40\% when transferring into the storage trap as in Sec. IV. The reasons for this increased transfer efficiency are that the much shallower science trap induces a negligible light shift on the red Sr laser cooling transition and that the horizontally extended science trap is well adapted to the pancake shape of the red MOT. The $^{84}$Sr cloud is slightly colder than the Rb sample, which again leads to sympathetic laser cooling of Rb. When choosing the final red MOT parameters, we have to compromise between attainable temperature and remaining Rb and Sr atom numbers. We chose a temperature of 1 $\mu$K, for which we
obtain $4.0(1) \times 10^6$ Sr atoms and $5.2(1) \times 10^5$ Rb atoms, both elements at a PSD of 0.4(1). At this point the cooling laser beams are switched off.

Starting with these excellent conditions, we perform evaporative cooling by lowering the science trap depth exponentially over 8.8 s to $k_B T = 150$ nK for Sr. Strontium is evaporated, sympathetically cooling Rb, and a double BEC is formed (see Fig. 5). At the end of evaporation we obtain a pure $^{84}$Sr BEC of $2.3 \times 10^5$ atoms and $1.3 \times 10^5$ quantum degenerate Rb atoms accompanied by $6.5 \times 10^4$ thermal Rb atoms at a temperature of $\sim 70$ nK. The Rb cloud again contains a nearly equal mixture of the three $F = 1$ $m_F$ states. The trapping frequencies in the x-, y-, and z-direction are at this point 40 Hz, 37 Hz, and 190 Hz for Sr and 67 Hz, 63 Hz, and 400 Hz for Rb. For the lowest values of the science trap depth, the gravitational sagging of the Sr cloud is $\sim 3.5 \mu m$ larger than the gravitational sagging of the Rb cloud. For comparison, the Thomas-Fermi radii, calculated neglecting the interspecies mean-field, is $2.5 \mu m$ for the Sr BEC in the vertical direction and $2 \mu m$ for the Rb BEC. The two elements are barely overlapping, which reduces interspecies thermalization. The differential gravitational sag between Sr and Rb could be compensated for the magnetic Rb $F = 1$, $m_F = +1$ or $m_F = -1$ state by using a magnetic field gradient in the vertical direction, which does not influence the non-magnetic Sr. The peak density of the Sr BEC and of each $m_F$-state component of the Rb BEC is $1.5 \times 10^{14}$ cm$^{-3}$. The $1/e$ lifetime of the BECs is about 10 s. The atom number of the Sr BEC can be increased at the expense of the Rb BEC atom number by reducing the MOT loading time of Rb. On absorption images of $^{84}$Sr-$^{87}$Rb double BECs taken after 24 ms of expansion, we observe that the position of the Sr BEC is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field expansion, we observe that the position of the Sr BEC is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number. This observation hints at a positive mean-field is shifting downwards for an increasing Rb BEC atom number.

VI. CONCLUSION AND OUTLOOK

We have presented the production of $^{88}$Sr-$^{87}$Rb and $^{84}$Sr-$^{87}$Rb double BECs. Crucial to our success are the favorable interaction properties of the two mixtures. For both mixtures we observe efficient thermalization. At the same time the mixtures do not suffer from large inelastic three-body losses. These interaction properties cannot be predicted by ab-initio calculation and were completely unknown prior to our work.

A central stage in our scheme is sympathetic narrow-line laser cooling of Rb by Sr. This powerful technique will also be useful to cool other species besides $^{87}$Rb, including fermions, and should work if one of the four Sr isotopes has good interspecies scattering properties with the target species. It might even be possible to sympathetically laser cool the target species to quantum degeneracy without using evaporation [58]. This goal will be facilitated by selectively increasing the density of the target species with a species-specific dipole potential [1] or by using a target species of low mass, which leads to a high critical temperature or Fermi temperature for a given density.

Our next goal is the creation of RbSr molecules. We plan to associate atoms to weakly-bound molecules by either magneto-association [70] or stimulated Raman adiabatic passage (STIRAP) [71, 72]. These molecules will then be transferred into the ro-vibrational ground-state by STIRAP [73, 74]. We are currently performing photoassociation spectroscopy of the $^{84,88}$Sr-$^{87}$Rb mixtures, in order to precisely determine the interspecies scattering lengths of all Sr-Rb isotopic combinations, the magnetic field values of Sr-Rb magnetic Feshbach resonances, and STIRAP paths for molecule association and ground-state transfer. The optimal Sr-Rb isotopic mixture for our task will depend on these properties, especially the interspecies scattering length, which determines the miscibility of the Rb and Sr quantum gases.

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