Cooling and trapping of ultra-cold strontium isotopic mixtures

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We present the simultaneous cooling and trapping of an isotopic mixture in a magneto-optical trap and we describe the transfer of the mixture into a conservative, far-off resonant dipole trap. The mixture is prepared with a new technique that applies to intermediate and heavy alkaline earth like atoms. In this work, $^{86}$Sr and $^{88}$Sr are simultaneously loaded first into the magneto-optical trap operated on the $^{1}S_{0}-^{3}P_{1}$ spin-forbidden line at 689 nm, and then transferred into the dipole trap. We observe fast inter-species thermalization in the dipole trap which allows one to set a lower bound on the $^{88}$Sr-$^{86}$Sr elastic cross section.

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Recently laser cooled atomic strontium has been the subject of active researches in various fields spanning from all-optical cooling towards quantum degeneracy for bosonic and fermionic isotopes, cooling physics, continuous atom laser, detection of ultra-narrow transitions, multiple scattering, and collisional theory.

As a result of the efficient second stage Doppler cooling, strontium is a promising candidate to reach quantum degeneracy. Second stage Doppler cooling working on the $^{1}S_{0}-^{3}P_{1}$ intercombination transition (see figure 1) combined with optical dipole trapping was proven effective to directly reach phase space densities of $\rho = 0.1$. Further increase of $\rho$ seems to be limited by light assisted collisions and direct evaporative cooling was not reported so far. Alternative cooling techniques are offered by mixtures of different atomic species or different isotopes. Mixtures offer a way to exploit collisional physics not applicable in single species samples. They also offer additional degrees of freedom such as sympathetic cooling in order to achieve the degenerate quantum regime with atoms for which evaporative cooling is not efficient.

In this article we present the simultaneous cooling and trapping of isotopes of atomic strontium in a magneto-optical trap (MOT) and we describe the transfer of the mixture into a conservative, far-off resonant dipole trap (FORT). The isotopic mixture is prepared with a new technique based on sequentially loading different isotopes into a magnetic trapped metastable state through the leakage of a MOT operating on a single isotope. Afterwards the magnetically trapped mixture is optically pumped down to the ground state for further cooling close to the recoil limit on the intercombination $^{1}S_{0}-^{3}P_{1}$ transition. Then the mixture is loaded into a FORT.

The advantage of this method comparing with previous works based on simultaneous optical cooling and trapping of two species, is the drastic simplification of the laser source and the elimination of possible interferences between the simultaneous loading into the MOTs. For the sake of clarity we start by describing the production of a single-isotope sample, then we explain how we extend the procedure to the production of isotopic mixtures.

In the experimental setup we use a thermal source of strontium atoms as described in [8]. The strontium is evaporated in an oven heated to 500°C. The atomic beam is collimated through a bundle of capillaries which limits the geometric divergence to 50 mrad full width. After the capillaries, the atomic beam brightness is increased by a factor 4 with a transverse cooling stage realized with multipass beams in two orthogonal planes, with a frequency offset by 20 MHz to the red of the $^{1}S_{0}-^{1}P_{1}$ transition ($\Gamma/2\pi=32$ MHz). After the collimation stage the atomic beam is slowed to a few tens of m/s in a 30-cm long Zeeman-slower based on a two stage tapered coil with zero crossing magnetic field and a counterpropagating laser beam tuned 15 GHz to the red of the $^{1}S_{0}-^{1}P_{1}$ transition.

FIG. 1: Relevant energy levels and optical transitions for laser cooling and trapping of strontium.

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1 transition. The light beam is typically 18 mW, has a 7 mm $e^{-2}$ radius at the MOT and is focused on the capillaries, 85 cm away from the MOT. The slowed atoms are then further cooled and trapped in a MOT working on the $^{138}\text{Sr}-^{131}\text{P}$ transition red detuned by 40 MHz from the resonance. The MOT is formed by three retro-reflected beams with a $e^{-2}$ radius of 5 mm crossing almost orthogonally, with the vertical beam collinear with the magnetic quadrupole axis of an anti-Helmholz pair of coils. The total 461 nm light incident on the MOT region amounts to 46 mW/cm$^2$, and the magnetic gradient is 56 G/cm. The atom number, spatial density and temperature are derived in time-of-flight by imaging on a CCD camera the atomic absorption of a 70 μs probe beam resonant on the $^{138}\text{Sr}-^{131}\text{P}$ transition. The 461 nm light source for the first cooling stage, as described in Fig. 2, is based on frequency doubling of a semiconductor laser. It routinely delivers 150 mW at 461 nm in a 4 MHz linewidth FWHM. The source is frequency stabilized with saturated spectroscopy on a strontium vapor cell [21].

After the initial capture in the blue MOT, and following the approach described in Fig. 1, the atoms are further cooled in a MOT operating on the $^{138}\text{Sr}-^{131}\text{P}$ intercombination line at 689 nm. The 689 nm light is provided by a master-slave semiconductor laser system which is frequency narrowed by locking to an optical cavity which is, in turn, steered to the $^{138}\text{Sr}-^{131}\text{P}$ transition by saturation spectroscopy in a second strontium heatpipe [8]. The red beam is mode-matched to the 461 nm MOT beam and it is overlapped to it on a dichroic mirror. From this point the two beams share the same broad-band optics up to the atoms.

As discussed in the following, the atoms leak from the blue MOT to the metastable $^3\text{P}_2$ due to the $2 \times 10^{-5}$ branching ratio of the $^3\text{P}_1$ excited state to the low-lying $^3\text{D}_2$ and the subsequent decay to the $^3\text{P}_2$ state. This loss channel is eliminated with a single optical pumping process which involves the $^3\text{P}_2-^3\text{D}_2$ transition at 497 nm. For this purpose we developed an anti-reflection coated laser-diode stabilized in the Littrow ECL configuration which delivers 25 mW at 994 nm. This light is frequency doubled on a 17 mm long KNbO$_3$ crystal placed in a resonant cavity for improved conversion efficiency resulting in 4 mW at 497 nm. The KNbO$_3$ is b-cut for non-critical phase matching at a temperature of 54°C. The 497 nm beam is sent to the MOT region with a 1.5 cm $e^{-2}$ diameter, it is retroreflected, and its frequency is tuned in order to maximize the blue MOT fluorescence.

Without the 497 nm repumper the blue MOT lifetime is limited to 10 ms and typically we trap $10^7$ $^{88}\text{Sr}$ atoms at 3 mK. By applying the green repumper the blue MOT lifetime increases by more than one order of magnitude, resulting in up to $3 \times 10^8$ atoms loaded into the $^{88}\text{Sr}$ blue MOT at a density of $6 \times 10^9$ cm$^{-3}$. These values are comparable to the alternative optical pumping scheme [22] in which two lasers at 707 and 679 nm couple the $5p^3\text{P}_2$ and the $5p^3\text{P}_0$ states to the $6s^3\text{S}_1$ state (see Fig. 1).

As described in Fig. 1, the transfer from the blue to the red MOT is done in two steps: For the first 200 ms the red laser is frequency modulated at 50 kHz, spanning 2 MHz (FM red MOT), to recapture the atoms moving faster than the capture velocity on the $^3\text{S}_1-^3\text{P}_1$ transition. In the following 40 ms the red laser is set single frequency at the intensity that determines the desired final temperature of the sample. Working at 350 kHz below resonance and reducing the total light intensity on the MOT to 70 μW/cm$^2$, we obtain about 10% of the initial atoms from the blue MOT cooled below 1 μK.

For simultaneous trapping of multiple isotopic samples previous experiments employed laser sources delivering the necessary frequency components for each isotope involved [14, 15]. This approach in the case of the blue MOT may be difficult to apply because of the complexity of the laser sources, the limited optical access, the frequency offsets involved, and the limited laser power. An alternative solution is presented by the use of the magnetically trapped $^3\text{P}_2$ state as a dark atom reservoir [23]. During the blue MOT phase without the repumper, the small branching ratio of the excited $^3\text{P}_1$ state towards the metastable $^3\text{P}_2$ state, provides a continuous loading of atoms into the potential given by the MOT’s magnetic quadrupole [24]. Figure 2 reports the lifetime of the magnetically trapped metastable isotopes. Then, using the same blue source, one can sequentially load different isotopes into the magnetic potential just by stepping the laser frequency to the different resonances.

The trapping sequence for collection of a $^{88}\text{Sr}-^{86}\text{Sr}$ mixture is reported in Fig. 3. We start collecting $^{86}\text{Sr}$ for 3 s, then we tune the blue laser on resonance to $^{88}\text{Sr}$ for 2 s. Once the isotopic mixture is prepared in the $^3\text{P}_2$ state, the blue light is switched off, and the FM red MOT is switched on as well as the repumping beam. The isotopic shift on the repumping transition is smaller than the resonance width of the $^3\text{P}_2-^3\text{D}_2$ transition ob-

![FIG. 2: Metastable $^3\text{P}_2$ state decay when trapped in a 56 G/cm magnetic quadrupole. The data are taken for the individual isotopes with the $^3\text{S}_1-^3\text{P}_1$ MOT switched off (circles: $^{86}\text{Sr}$, lifetime $\tau = 4.7$ s. Squares: $^{88}\text{Sr}$, $\tau = 6.6$ s), and with the $^3\text{S}_1-^3\text{P}_1$ MOT operating on the undetected isotope (diamonds: $^{86}\text{Sr}$ with $^{88}\text{Sr}$ MOT, $\tau = 4.7$ s. Triangles: $^{88}\text{Sr}$ with $^{86}\text{Sr}$ MOT, $\tau = 4.9$ s). The measurements are taken after red MOT recapture and the $e^{-1}$ lifetimes are reported.](image-url)
served on the blue MOT fluorescence, which results in efficient, simultaneous optical pumping of $^{86}$Sr and $^{88}$Sr on a timescale short with respect to red MOT capture time [24]. The loading of a single isotope into the magnetic potential was already described in [24] and we did not observe significant differences in the behavior when loading two isotopes. Figure 2 shows the measurement of the lifetime for each isotope, both when individually trapped and in presence of the blue MOT working on the other isotope. All the lifetimes are on the order of 5 s, close to the background pressure limited lifetime of 8 s.

The laser source for the operation of the two-isotope red MOT is composed of two slave lasers injected from the same frequency-stabilized master with a frequency offset corresponding to the isotopic shift of 163 817.3 kHz [5]. Subsequently, the frequency and the intensity of the two beams are controlled by double pass AOMs driven by the same RF, the beams are superimposed on a polarizing beam splitter, and then they are overlapped to the blue MOT beams as described previously.

Comparing the two-isotope red MOT with the single isotope one, with the same atom numbers we do not observe any effect in the transfer efficiency and final temperature due to the presence of the second isotope. In this way, we obtain samples with up to $10^7$ ($10^6$) atoms of $^{88}$Sr ($^{86}$Sr) at a temperature 2 µK (1 µK). We attribute the difference in the loading with respect to the natural abundances to minor differences in the red MOT parameters. By varying the order of loading and the loading times of the two isotopes we can vary almost arbitrarily the final ratio of populations.

The cloud is then transferred into a FORT realized by focusing a far detuned 922 nm laser beam on the center of the trap. For this application we employ a semiconductor tapered amplifier seeded from the same 922 nm source used for the 461 nm laser. At this wavelength, setting the optical field polarization orthogonal to the magnetic field, the differential Stark shift between the $^1S_0$ and $^3P_1$ levels is small with respect to the transition linewidth, allowing precision spectroscopy and laser cooling even on optically confined atoms [26]. The light from the amplifier is spatially filtered through a polarization-maintaining single-mode optical fiber and is focused on the atoms to a waist of 15 µm. At maximum power, we measure the radial oscillation frequency $\nu_{\text{rad}}=2$ kHz and the axial oscillation frequency $\nu_{\text{ax}}=26$ Hz. These values are consistent with our peak intensity of 160 KW/cm$^2$ which corresponds to a trap depth of 90 µK.

As shown in figure 3, the transfer between the $^1S_0-^3P_1$ MOT and the FORT is done by adding the 922 nm light 60 ms before switching off the MOT. Figure 4 shows the transfer of the mixture from the red MOT to the FORT as a function of the overlap time. The loading dynamics of $^{86}$Sr is slightly faster than for $^{88}$Sr while the losses at overlap time longer than 100 ms are attributed to the balance of light assisted collisions [6]. The maximum transfer efficiency of 40 % is observed by overlapping the FORT beam waist on the red MOT, and then displacing the the FORT waist 500 µm in the direction of the FORT beam. This displacement corresponds to 2/3 of Rayleigh range, or equivalently 2 red MOT $e^{-2}$ radii. The effects of this displacement are the increase of the overlap volume between the final red MOT and the FORT, and the reduction of the light assisted collisional losses at the bottom of the dipole potential. Finally we load into the FORT up to $3 \times 10^5$ ($10^6$) atoms typically at 15 µK (20 µK) for the individual $^{86}$Sr (${^{88}}$Sr) isotope. The difference in the final temperature is in agreement with the density dependent heating reported in [6]. When loading the isotopic mixture we do not observe any reduction of the transfer efficiency from the red MOT into the FORT. Surprisingly in the optical trap we always find thermal equilibrium among the two species. The interspecies thermalization is fast on the timescale of the loading into the FORT and allows us to set a lower bound for the interspecies elastic cross section $\sigma > 3.5 \times 10^{-12}$ cm$^2$. Equivalently, the modulus of the inter-species scattering length is $|a| = \sqrt{\frac{\sigma}{\pi}} > 70$ Bohr radii.

In conclusion we presented the simultaneous cooling and trapping of $^{88}$Sr and $^{86}$Sr isotopes into a MOT operating on the spin-forbidden $^1S_0-^3P_1$ transition, and we described the transfer of the mixture into a conserva-
tive, far-off resonant, dipole trap working near the “magic wavelength” for the $^{1}\text{S}_0$–$^{3}\text{P}_1$ transition\textsuperscript{21}. The method, which is demonstrated with strontium isotopes, can be applied to all the atoms with similar level structure and transitions, to load an arbitrarily large number of isotopes. The realization of the strontium isotopic mixture and the observed strong inter-species thermalization will allow the implementation of additional cooling mechanisms based sympathetic cooling. This seems very promising towards the realization of a Bose-Einstein condensate of an alkali-earth atom.

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