Magneto optical trapping of Barium

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First laser cooling and trapping of the heavy alkaline earth element barium (Ba) has been accomplished based on the strong 6s2 1S0 - 6s6p 1P1 transition for the main cooling. Due to the large branching into metastable D-states several additional laser driven transitions are required to provide a closed cooling cycle. A total efficiency of 0.4(1)·10^{-2} for slowing a thermal atomic beam and capturing atoms into a magneto optical trap was obtained. Trapping lifetimes of more than 1.5 s were observed. This lifetime is shortened at high laser intensities by photo ionization losses. The developed techniques will allow to extend significantly the number of elements that can be optically cooled and trapped.

The heavy alkaline earth element barium (Ba) has been laser cooled and captured in a magneto-optical trap (MOT). Of particular interest is the trap loading efficiency from a thermal atomic beam because the developed technique is essential to trap short lived isotopes of the chemical homologue radium for searches for peculiarities of their atomic level structure. To date, the list of optically trapped elements includes all alkaline metals [3], noble gases in metastable symmetries. To date, the list of optically trapped elements includes all alkaline metals [3], noble gases in metastable symmetries. To date, the list of optically trapped elements includes all alkaline metals [3], noble gases in metastable symmetries. T o date, the list of optically trapped elements includes all alkaline metals [3], noble gases in metastable symmetries.

In Ba or Ra the strong ns2 1S0-nsp 1P1 transitions, n=6, 7, offer large optical forces. However, in both cases the substantial branching fractions of 0.3% of the nsp 1P1 states to metastable D-states require quantita-

The ns2 1S0-nsp 1P1 transitions, n=3...5, are used for laser cooling and trapping of lighter alkaline earth elements, where the branching to metastable D-states is much smaller than for Ra and Ba. On average, an atom is transferred to one of the metastable D-states after scattering of only A^{Ba}_{peak}=330(30) photons at wavelength \lambda_1 for Ba (Fig. and Tab. D). This corresponds to a velocity change of 1.8(2) m/s only. The largest loss from a cooling cycle of previously trapped elements of A^{Cr}_{peak}= 2500 was given for Cr [8]. Because of its lighter mass Cr could be loaded into a magneto optical trap without repumping, however, the efficiency increased by two orders of magnitude with repumping from the D-states. In contrast, for Ba no trapping can be expected without effective repumping from all three low-lying D-states, i.e. 6s5d 1D2, 6s5d 3D1 and 6s5d 3D2 (Fig. I).

Two different repumping schemes were investigated, where repumping was implemented via low lying states to minimize the transfer of atomic population into additional states. The first scheme uses the 6s6p 1P1 level as an intermediate state. This constitutes a closed five-level manifold (6s2 1S0, 6s6p 1P1, 6s5d 1D2, 6s5d 3D2 and 6s5d 3D1) involving infrared transitions at the wavelengths \lambda_{ir1}, \lambda_{ir2} and \lambda_{ir3} (Tab. 1). The common excited state for the cooling transition and the repumping transition leads to multiple coherent Raman resonances [14]. In the limit of high intensities the population in all five states is equal. This reduces the maximum optical force by a factor of 2/5 compared to an ideal closed two level

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FIG. 1: Low lying energy levels of atomic Ba relevant for laser cooling. Full lines indicate laser driven transitions and dashed lines show spontaneous decay channels.
TABLE I: Vacuum wavelengths and experimental transition rates for barium.

| Upper Level | Lower Level | Label | Wavelength [nm] | $\lambda_{ik}$ [$10^8$ s$^{-1}$] |
|-------------|-------------|-------|-----------------|----------------------------------|
| 6s6p $^1P_1$ | 6s$^2$ $^1S_0$ | $\lambda_1$ | 553.7 | 1.19(1)$^a$ |
|             | 6s5d $^1D_2$ | $\lambda_{ir1}$ | 1500.4 | 0.0025(2)$^a$ |
|             | 6s5d $^3D_2$ | $\lambda_{ir2}$ | 1130.6 | 0.0011(2)$^a$ |
|             | 6s5d $^3D_1$ | $\lambda_{ir3}$ | 1107.8 | 0.000031(5)$^a$ |

| 5d6p $^3D_1^0$ | 6s$^2$ $^1S_0$ | $\lambda_3$ | 413.3 | 0.013(1)$^b$ |
|                | 6s5d $^3D_2$ | $\lambda_2$ | 667.7 | 0.17(2)$^a$ |
|                | 6s5d $^3D_1$ | $\lambda_3$ | 659.7 | 0.38(2)$^a$ |
| others         | $\geq$ 3000  |              |      | 0.011(2)$^b$ |

$^a$ from reference [17] and $^b$ this work [18].

system. In atoms with nuclear spin different states of the hyperfine manifold can be employed for cooling and repumping. The second scheme alternatively repumps the 6s5d $^3D_1$-state through the 5d6p $^3D_0^0$ state using light at wavelength $\lambda_3$. This strong transition exhibits only a 2.0(4)% leak to further states. The main contribution arises from the 5d$^2$ $^3F_2$-state, which cascades to 94(3)% down to one of the states of the cooling manifold according to a recent calculation [16].

In the experiment, an Ba atomic beam is produced from an isotopically enriched sample of $^{138}$BaCO$_3$ which is mixed with Zr powder as a reducing agent in a resistively heated oven at 780(40) K temperature (Fig. 2). The beam enters a straight section, where it is overlapped with counter-propagating deceleration laser beams at wavelengths $\lambda_1$, $\lambda_{ir1}$ and $\lambda_{ir2}$ from one dye-laser and two diode lasers. The laser beams are spatially overlapped and focussed into the 1 mm diameter oven orifice. The divergence of the laser beams is typically 5 mrad, their diameter 600 mm downstream of the oven is 3 mm and the typical laser powers are 12 mW at wavelength $\lambda_1$, 5 mW at $\lambda_{ir1}$ and 35 mW at $\lambda_{ir2}$. The detunings from the resonances are -290(2) MHz, -60(10) MHz and -90(10) MHz, respectively. These parameters permit slowing of atoms with velocities up to 150 m/s. Additional repumping from the 6s5d $^3D_1$ state allows for even larger velocity changes.

At the end of the slowing region three mutually orthogonal beams of 12 mm diameter of up to 15 mW power at wavelength $\lambda_1$ are retro-reflected into themselves. The required circular polarizations for a MOT are produced by a set of $\lambda/4$-plates. The six beams are overlapped in the minimum of a magnetic field produced by a pair of coils in anti-Helmholtz configuration, which creates a field gradient along the axis between the two coils of up to 36 G/cm. The frequency detuning from resonance $\delta_{trap}$ of the trapping light can be adjusted between -200 MHz and 50 MHz by acousto optical modulators (AOM’s). Three custom-made fiber lasers (Koheras) at the wavelengths $\lambda_{ir1}$ (5 mW), $\lambda_{ir2}$ (25 mW) and $\lambda_{ir3}$ (60 mW) of typically 5 mm diameter are overlapped with the central region of the trap. The detuning from resonance is small compared to the linewidth of 18 MHz of these transitions to achieve optimal repumping for the trapped atoms. For the second repumping scheme a laser beam at wavelength $\lambda_3$ of 10 mm diameter and 5 mW light power is co-propagating with the MOT beams.

The fluorescence from the central region of the trap is collected by a 60 mm focal length plano-convex lens. An aperture of 2.0(5) mm diameter in the image plane allows to select the field of view. Fluorescence at the wavelengths $\lambda_1$ and $\lambda_3$ are detected by two photomultiplier tubes (PMT’s) equipped with interference filters of 10 nm spectral bandwidth.

The detected fluorescence increases for small negative
FIG. 3: Signals from trapped atoms as a function of detuning of the trapping laser light at wavelength $\lambda_1$. (a) Fluorescence at wavelength $\lambda_1$. The black points is the Doppler-free fluorescence signal arising from the MOT laser beam which is orthogonal to the atomic beam. (b) Fluorescence at wavelength $\lambda_1$ detected simultaneously. The trap lifetime was $\tau_{\text{MOT}}=0.15(4)$ s.

frequency detunings $\delta_{\text{trap}}$ of the trapping laser beams at wavelength $\lambda_1$ (Fig. 3(a)). The vertical MOT-beam, which is orthogonal to the atomic beam, produces a Zeeeman broadened fluorescence signal which can be used to estimate the flux of atoms in the atomic beam. A comparison of the signal rates for these two conditions yields the fraction of the atomic beam, which is captured in the MOT. The scattering rate from the MOT laser beams is about the same for trapped atoms and from the beam. With this assumption the collection efficiency is

$$\epsilon = \frac{R_1}{R_{\text{beam}}} \cdot \frac{\Delta t}{\tau_{\text{MOT}}},$$

where $R_1$ and $R_{\text{beam}}$ are the fluorescence rates from trapped atoms and from the Doppler-free signal of the beam and $\Delta t$ is the average time of flight of thermal atoms through the light collection region. An efficiency of $\epsilon=0.4(1)\cdot10^{-2}$ is determined. A trap population $N_{\text{MOT}}$ of up to $10^6$ atoms and a lowest temperature for the trapped cloud of 5.4(7) mK were achieved.

The fraction of atoms in the metastable D-states $\rho_D$ can be determined from the fluorescence rates $R_B$ at wavelength $\lambda_B$ produced by the repumping the 6s5d $^3D_1$ state via the 5d6p $^3D_2$-state (Fig. 3(b)). The detected rate $R_B$ is

$$R_B = \epsilon_B \cdot B_B \cdot B_{ir3} \cdot \gamma_1 \cdot N_{\text{MOT}},$$

where $\epsilon_B$ is the detection efficiency for a photon at wavelength $\lambda_B$, $B_B=2.2(2)\%$ is the decay branching fraction of the 5d6p $^3D_2$-state to the ground state, $B_{ir3}=4.2(4)\cdot10^{-5}$ is the decay branching fraction of the 6s5p $^1P_1$-state to the 6s5d $^3D_1$-state and $\gamma_1$ the scattering rate at wavelength $\lambda_1$. Similarly the rate $R_1$ at wavelength $\lambda_1$ is

$$R_1 = \epsilon_1 \cdot \gamma_1 \cdot N_{\text{MOT}} \cdot (1 - \rho_D).$$

The ratio of the detection efficiencies was measured to $\epsilon_B/\epsilon_1=1:0.8(1)$. The observed rather large fraction of $\rho_D=0.5(1)$ is due to the strong coherent Raman transitions in the cooling scheme.

The number of trapped atoms depends on the intensity of the slowing beam at wavelength $\lambda_1$ (Fig. 4). The detuning of the slowing laser beam was $\delta_s=-260$ MHz, corresponding to a velocity class of 145 m/s. The number of trapped atoms is proportional to the loading rate. The loading rate increased up to a cooling beam power of about 11 mW which corresponds to 2.7 saturation intensities. A further increase of the cooling beam power does not increase the flux into the MOT. This is caused by stopping of atoms before they have reached the trapping region. Thus, the velocity change in $l=600$ mm length is larger than 150 m/s. The average deceleration exceeds $1.7\cdot10^4$ m/s$^2$. The flux at low velocities can be significantly improved by a weak laser beam at wavelength $\lambda_1$ co-propagating with the atomic beam, which would define a finite end velocity [19].

The lifetime $\tau_{\text{MOT}}$ of the trapped sample depends strongly on the intensity of the trapping laser beams at wavelength $\lambda_1$ (Fig. 5). A 3rd-order process is observed for the losses as a function of laser intensity $I$ with a rate constant of $\beta=0.20(3)$ s$^{-1}$ I$^{-3}$, where $I_s=14.1$ mW/cm$^2$ is the saturation intensity. This could be explained by three-photon ionization. The MOT lifetime $\tau_{\text{MOT}}^0$ of up to 1.5 s depends on the intensity in the repumping laser beams. The overlap of all laser beams in the trap region is crucial. Atoms in the metastable states can escape from the trap, since they do not experience any trapping force. Similar effects have been observed in Ca [20].

We have realized laser cooling of Ba in a closed five-
level subsystem and a six-level system with a small leak. These are the minimal subsets of levels for laser cooling of Ba in the ground state. Efficient deceleration of the atomic beam is achieved with counter-propagating lasers at high intensities. Further improvements can be expected from frequency broadening of the deceleration lasers, e.g. with electro-optical modulation. This would enlarge the velocity acceptance of the deceleration and a larger fraction of the atomic beam velocity distribution can be stopped. As a note, a Zeeman slower is not applicable in such multilevel atomic laser cooling systems, for which repumping during slowing is required, because the changing Doppler shifts cannot be compensated by single magnetic field for all transitions at the same time.

In particular, some of the repumping transitions in Ba have a negative value for the g-factor $g_F$.

The demonstrated laser cooling with a complex cooling cycle appears particularly well suited for efficient collection of rare isotopes in a MOT with similar level schemes, i.e. Ra isotopes. The strong motivation for trapping Ra arises because such samples allow for novel precision measurements within the Standard Model in particle physics and searches for physics beyond it such as they are under way at the KVI TRIP facility. Recent computations show that Ra offers an enhancement of about 500 times due to nuclear effects and 40000 times due to the unique atomic level structure for nucleon or electron EDM’s 1. In addition, APV induced effects are 100 times larger for the weak charge and 10$^8$ times larger for the nuclear anapole moment than in other systems 2. All Ra isotopes with nuclear spin $I$$\neq$0 have short lifetimes (e.g. $^{225}$Ra, $\tau$ = 14.8 d) and are only available in small quantities and require experiments in the proximity of an isotope production facility. Sensitive experimental searches for EDM’s, which would establish CP violation without strangeness, and measurements of APV in Ra require the developed trapping techniques.

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