Pramana – J. Phys. (2019) 93:92
https://doi.org/10.1007/s12043-019-1852-x

Cooling of fermionic ^{83}Kr and bosonic ^{84}Kr isotopes in a magneto-optical trap

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MS received 1 February 2019; revised 12 April 2019; accepted 11 July 2019

Abstract. Simultaneous laser cooling of two isotopes of krypton, ^{83}Kr and ^{84}Kr, is reported here in a two-isotope magneto-optical trap (TIMOT). The number of cold metastable ^{83}Kr atoms in this TIMOT is dependent on the power of the repumping laser beams used, which is maximised for our set-up by varying the powers of repumping lasers. These studies may be useful to investigate cold collisions between fermionic ^{83}Kr and bosonic ^{84}Kr atoms in the metastable state.

Keywords. Metastable Kr atoms; laser cooling; magneto-optical trap.

PACS Nos **32.80.Pj; 37.10.De; 42.55.Px**

1. Introduction

Laser-cooled atoms are now being used for studying interesting atomic physics as well as for developing atom-optical devices for precision measurements [1,2]. The laser cooling of noble gas atoms (such as Kr) in the excited state provides an opportunity to study cold collisions, ionisation physics, nanolithography [3,4] and atom trap trace analysis (ATTA) [5,6]. Noble gas atoms are laser-cooled in the metastable state where the excitation to this state is commonly achieved by radiofrequency (RF) excitation [7] although direct current (DC) excitation is also possible [8,9]. In the case of Kr atom, the lowest excited metastable state ($4p^5 5s[3/2]_2$) has a lifetime of ∼40 s [10] which is longer than our experimental time. Laser cooling of the metastable state Kr (Kr*) atoms requires a wavelength of ∼811.5 nm to drive the cooling transition between the excited states $4p^5 5s[3/2]_2$ and $4p^5 5p[5/2]_3$. The natural linewidth of the $4p^5 5p[5/2]_3$ transition is $\Gamma = 2\pi \times 5.6$ MHz. The even isotopes (i.e. bosonic isotopes) of Kr, such as ^{82}Kr, ^{84}Kr and ^{86}Kr, have no hyperfine energy levels. This makes the laser cooling process simple like two-level system without the requirement of any repumping laser. However, the odd isotopes (i.e. fermionic isotopes) of Kr, such as ^{81}Kr, ^{83}Kr and ^{85}Kr, have multiple hyperfine levels in the lower ($4p^5 5s[3/2]_2$) and upper ($4p^5 5p[5/2]_3$) states involved in the cooling process. In these atomic systems, due to branching effect, atoms interacting with the cooling laser beam are pumped out of the cooling transition to the other hyperfine levels. Thus, for cooling these odd isotopes, in addition to the cooling laser beam, multiple repumping laser beams at suitable frequencies may be required [11,12]. In our experiments, we have used two repumping laser beams for the laser cooling of ^{83}Kr atoms and no repumping laser for the cooling of ^{84}Kr. The initial slowing of ^{83}Kr* atoms is performed in a Zeeman slower device with spatially varying longitudinal magnetic field [13–15], which also requires a cooling laser as well as two repumping lasers. These slowed down atoms are finally cooled and trapped in a magneto-optical trap (MOT). The sample of cold atoms, thus prepared with high internal energy (∼10 eV), is an ideal system to study Penning [3] and associative ionisations [16].

Here, we report the formation of a dual isotope MOT for a fermionic and bosonic mixture of ^{83}Kr* and ^{84}Kr* atoms, for the first time to the best of our knowledge. A large number of cold atoms in the MOT is a prerequisite for performing many experiments. Therefore, an effort was made to maximise the number of relatively lower abundant ^{83}Kr isotope in the MOT by optimising the power in the repumping laser beams for the MOT. We observed that the number of cold ^{83}Kr* atoms in the MOT depends considerably on the power of repumping laser beams used.

2. Experimental set-up

Figure 1 shows the schematic of the experimental set-up for laser cooling and trapping of ^{83}Kr* atoms. The set-up is similar to that used in our earlier reported works for trapping of even isotopes of Kr [17–19]. It consists of various vacuum chambers and a Zeeman slower tube. The vacuum level from the inlet chamber to the MOT chamber gradually varies from 10^{-3} to 10^{-9} Torr. An RF discharge (frequency ∼30 MHz) is used to produce metastable Kr (Kr*) atoms in the discharge tube (DT). The laser cooling of ^{83}Kr* is performed using the cooling transition between $4p^5 5s[3/2]_2$ and $4p^5 5p[5/2]_3$ at a wavelength of ∼811.5 nm. The cooling and repumping laser beams (CL, R1 and R2) are obtained from frequency-stabilised diode lasers with appropriate frequency shifting using acousto-optic modulators (AOMs).

Extended cavity diode laser (ECDL) systems (Models: DL-100 and TA-Pro, TOPTICA, Germany) are used for cooling and repumping purposes for Zeeman slower and MOT with appropriate detuning and frequency lock. Saturated absorption spectroscopy (SAS) in krypton cells with RF discharge is used to generate the required frequency locking signal. The relevant energy levels for the laser cooling of ^{84}Kr* and ^{83}Kr* are shown in figure 2. The cooling laser beam frequency (ν_{CL}) for ^{83}Kr* is ∼6 MHz red-detuned from the cooling

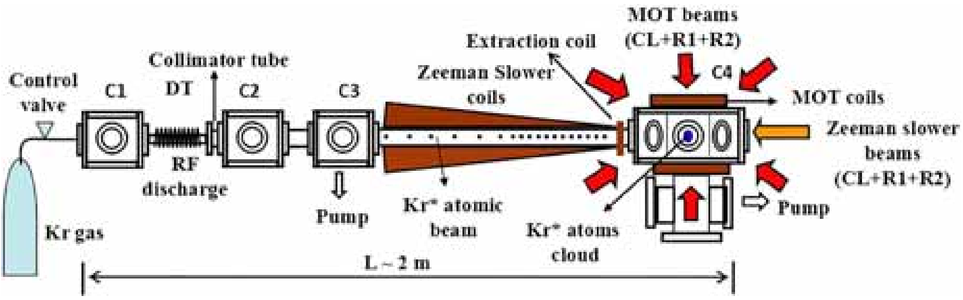

Figure 1. Schematic of the experimental set-up for the cooling and trapping of ^{83}Kr* atoms. The chambers C1, C2, C3 and C4 are respectively the gas inlet chamber, analysis chamber, pumping chamber and MOT chamber. DT is the discharge tube, CL is the cooling laser beam, R1 and R2 are the repumping laser beams for ^{83}Kr* atoms.

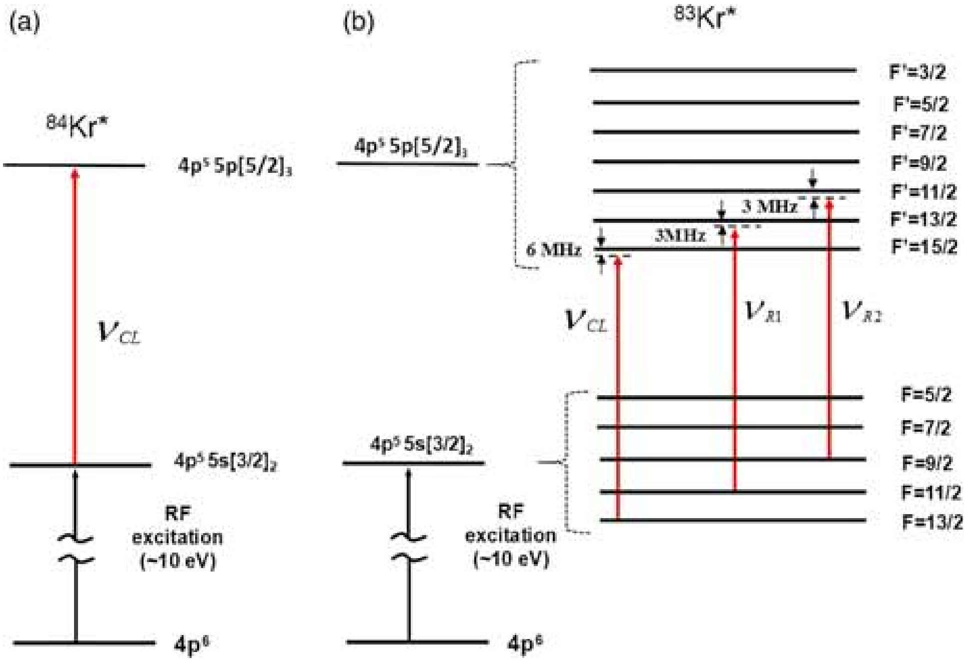

Figure 2. (**a**) Energy levels for laser cooling of ^{84}Kr* and (**b**) energy levels for laser cooling of ^{83}Kr*. Here ν_{CL}, ν_{R1} and ν_{R2} denote the frequencies of cooling and repumping lasers.

transition (i.e. $F = 13/2 \rightarrow F' = 15/2$). The repumping laser beams R1 and R2 for the MOT are ~3 MHz red-detuned from the repumping transitions $F = 11/2 \rightarrow F' = 13/2$ and $F = 9/2 \rightarrow F' = 11/2$ respectively. A part of the cooling laser beam was split into three beams to transmit into the chamber from three ports, which upon retroreflection resulted in six beams required for MOT formation. These three beams had ~5 mW power in each beam. The repumping laser beams (~3 mW power in each) were mixed in one of the cooling beams going into the chamber. The remaining parts of cooling and repumping laser beams were combined to make a Zeeman slower beam. This combined Zeeman slower beam (cooling and repumping beams) was passed through an AOM to shift its frequency to further red side by ~60 MHz before injection into the Zeeman slower tube. In the final Zeeman slower beam, before injection into the chamber, each of the repumping laser beam had ~3 mW power and cooling beam had ~30 mW power.

A pair of anti-Helmholtz magnetic coils provided a magnetic field gradient of ~15 G/cm for MOT formation. The number of cold atoms (N) in the MOT was estimated by collecting the fluorescence from the MOT cloud on a CCD camera [20].

3. Results and discussion

The optimisation of a ^{83}Kr*-MOT is challenging due to the use of multiple cooling and repumping laser beams for the MOT as well as for the Zeeman slower. The important parameters which affect the number of cold atoms (N) and their temperature in MOT include power and detuning of the cooling laser beams used in MOT and Zeeman slower, power and detuning of the repumping laser beams used in MOT and Zeeman slower, gradient of the magnetic field for MOT, etc.

First, we optimised the frequency shifting of Zeeman slower beam (cooling and repumping beams) using AOM. The optimum shifting was ~60 MHz towards the red side, which makes the effective cooling beam detuning ~66 MHz (red) from cooling transition of ^{83}Kr* and the effective repumping beams detuning ~63 MHz (red) from repumping transitions respectively.

Then, the power and detuning of the cooling beam for MOT were optimised for fixed values of power and detuning of the repumping beams used in the MOT. It was observed that the number of cold atoms in the MOT was maximum at the cooling laser beam detuning of ~6 MHz (red) for ~5 mW power in each of the six cooling beams. The number of atoms in the MOT was found to vary linearly with the cooling beam power, upto the maximum available power of 8 mW in each cooling beam.

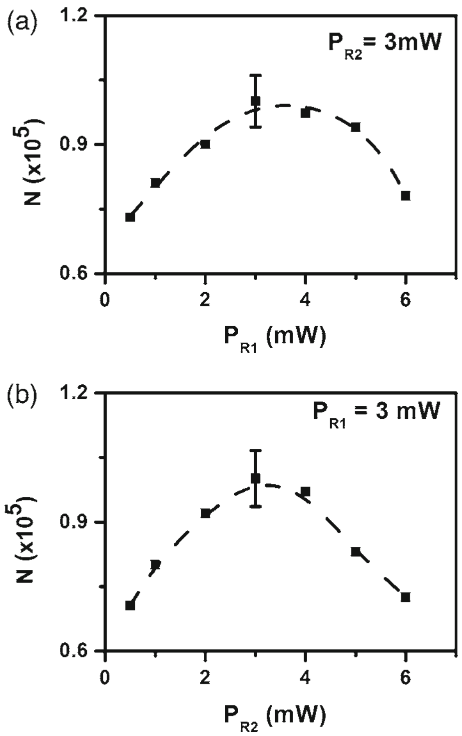

Figure 3. Measured variation in the number of cold atoms (N) with the power of (**a**) repumping laser beam (P_{R1}) and (**b**) repumping laser beam (P_{R2}) for $P_{CL} = 5$ mW. The error bars are determined from scatter in the values obtained in repeated measurements. The dashed curves are guides to eye.

The repumping laser beam parameters play an important role in maximising the number of cold atoms in the MOT [21,22]. In order to maximise the number of cold atoms in the MOT, the power of repumping laser beams were varied independently keeping the power and detuning of the cooling laser fixed (~5 mW in each beam and 6 MHz red-detuned). We have studied the dependence of the number of cold atoms on the power of both the repumping laser beams. The detuning of both the repumping laser beams (R1 and R2) was kept at 3 MHz (red). Figures 3a and 3b show the measured variation in the number of cold atoms with the power of the first and the second repumping laser beams respectively. As shown in the figure, number of cold atoms in the MOT initially increases with the repumping power and reaches a maximum value. Further increase in the power of the repumping beams results in a decrease of the number of cold atoms. Initial increase in the repumping laser power leads to an increase in the transfer of atoms back into the cooling cycle, which results in an increase in the number of cold atoms in the MOT. However, a decrease in the number of cold atoms with further increase in the repumping laser beam power is possibly due to the light-induced collisional losses in the MOT [23]. At higher repumping power, the power broadening of the repumping transition could also reduce the repumping efficiency. The power of both the repumping laser beams was varied from 0.5 to 6 mW and the optimum was found at ∼3 mW for the maximum number of cold ^{83}Kr* atoms in the MOT. The maximum number of cold atoms in MOT for ^{83}Kr* was estimated to be around 1×10^5, which can be further enhanced by increasing the power of the cooling beams in the MOT.

The temperature (T) of the cold atom cloud was estimated from the trap parameters by using the relation [24],

$$\frac{1}{2}\kappa_i \rho_i^2 = \frac{1}{2}k_{\mathrm{B}}T, \tag{1}$$

where κ_i is the spring constant of the MOT, ρ_i is the rms radius of the cold atom cloud in the ith direction, k_{B} is the Boltzmann constant and $i = x$, y and z. The spring constant for the MOT along the z-axis is given as [24]

$$\kappa_z = \mu_{\mathrm{B}} \frac{2\pi}{\lambda} \frac{\mathrm{d}B}{\mathrm{d}z} \frac{[8(\Delta_{\mathrm{L}}/\Gamma)/(I/I_{\mathrm{s}})]}{\left[1 + 6(I/I_{\mathrm{s}}) + (\Delta_{\mathrm{L}}/\Gamma)^2\right]^2}, \tag{2}$$

where μ_{B} is the Bohr magneton, $2\pi/\lambda$ is the wave vector, $\mathrm{d}B/\mathrm{d}z$ is the magnetic field gradient, Δ_{L} is the cooling laser beam detuning, $\Gamma = 2\pi \times 5.6$ MHz is the linewidth, I is beam intensity of each MOT beam and I_{s} is the saturation intensity. Using typical values of intensity and detuning for our MOT, the temperature of the cold atom clouds in ^{83}Kr*-MOT is $\sim 400\ \mu$K.

Further, we have demonstrated the working of a two-isotope MOT (TIMOT) for simultaneous cooling and trapping of ^{83}Kr* and ^{84}Kr* atoms. In order to cool and trap both isotopes simultaneously, the corresponding cooling and repumping laser beams for the MOT as well as Zeeman slower were aligned and overlapped in the set-up. A similar experimental set-up has been made operational for the TIMOT of ^{84}Kr* and ^{86}Kr* isotopes, which was used to study the homonuclear and heteronuclear cold collisions in bosonic–bosonic (^{84}Kr* and ^{86}Kr*) mixture of Kr* atoms [18].

Figure 4 shows the result with two isotopes of krypton (^{83}Kr* and ^{84}Kr*) trapped simultaneously in the TIMOT. In order to observe the cold atom clouds separately for the two isotopes, we slightly misaligned the MOT beams for two isotopes with respect to each other. Figure 4a shows the CCD images of the separated and overlapped clouds and figure 4b shows the probe absorption spectrum of the TIMOT when clouds of both isotopes ^{83}Kr* and ^{84}Kr* are overlapped. In future, we plan to use this cold mixture of fermionic and bosonic isotopes for studying cold collisions.

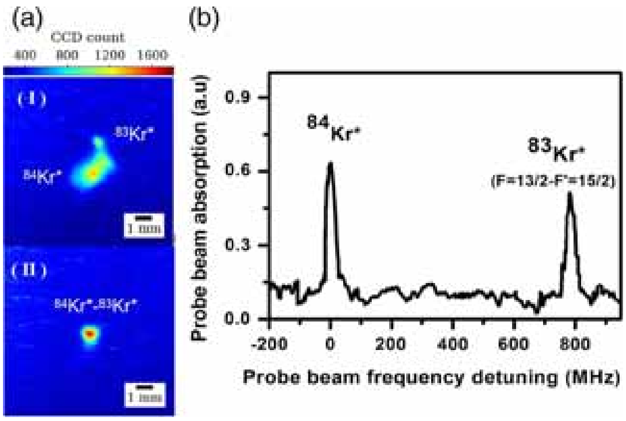

Figure 4. (**a**) Separated (I) and overlapped (II) CCD images of the TIMOT atom clouds for ^{83}Kr* and ^{84}Kr* atoms and (**b**) probe absorption signal from the TIMOT with probe beam frequency detuning from ^{84}Kr* transition frequency.

4. Conclusion

We have demonstrated the operation of a two-isotope magneto-optical trap (TIMOT) for the simultaneous cooling of ^{83}Kr and ^{84}Kr isotopes of krypton in the metastable state. The effect of various experimental parameters for ^{83}Kr*-MOT, such as cooling laser detuning and repumping lasers power, on the number of atoms trapped has been studied. This TIMOT is useful for studying cold collisions in fermionic–bosonic mixture of ^{83}Kr and ^{84}Kr isotopes.

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