An efficient magneto-optical trap of metastable krypton atoms

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(Received 5 October 2010; accepted 3 November 2010; published online 28 December 2010)

We report a magneto-optical trap of metastable krypton atoms with a trap loading rate of 3×10^{11} atoms/s and a trap capture efficiency of 3×10^{-5}. The system starts with an atomic beam of metastable krypton produced in a liquid-nitrogen cooled, radio-frequency driven discharge. The metastable beam flux emerging from the discharge is 1.5×10^{14} atoms/s/sr. The flux in the forward direction is enhanced by a factor of 156 with transverse laser cooling. The atoms are then slowed inside a Zeeman slower before captured by a magneto-optic trap. The trap efficiency can be further improved, possibly to the 10^{-2} level, by gas recirculation. Such an atom trap is useful in trace analysis applications where available sample size is limited. © *2010 American Institute of Physics*. [doi:10.1063/1.3520133]

I. INTRODUCTION

A magneto-optical trap (MOT) possessing simultaneously a high loading rate and a high efficiency is useful in many cold atom experiments. In atom trap trace analysis (ATTA) studies, a MOT is used to selectively capture and detect extremely rare trace isotopes. Upon the needs for radio-isotope dating applications in the earth sciences, ATTA method has been successfully developed to trap ^{81}Kr (Refs. 1 and 2) and it is also desired to analyze extremely rare (parts-per-quadrillion) isotope ^{39}Ar.[3] Here it is essential that the trap operates with a high efficiency to reduce the necessary sample size and, at the same time, with a high loading rate to maintain a reasonable measurement time. The apparatus reported here which was built in the University of Science and Technology of China (ATTA-USTC) can trap metastable krypton atoms with an efficiency at the 10^{-5} level together with a loading rate in the order of 10^{11} atoms/s.

II. EXPERIMENTAL RESULTS

The layout of the experimental setup is presented in Fig. 1. Sample Kr gas from the source chamber is cooled when flowing through a liquid nitrogen cooled aluminium nitride (AlN) tube with a 1 cm diameter. AlN is electrical insulating ceramic with a relatively high thermal conductivity. Kr atoms in the metastable level $5s[3/2]_2$, denoted as Kr*, are produced with a radio-frequency (RF) driven discharge inside the AlN tube. A platinum resistance thermal sensor attached on the AlN tube holder shows the working temperature of about 100 K. Following the discharge, two pairs of 15 cm long mirrors outside the vacuum chamber are used to implement two-dimensional multi-pass transverse cooling of the atomic beam. Laser power of 330 mW is divided to two perpendicular beams for two dimensional cooling with a beam size of 35 mm × 8 mm. The atomic beam is slowed inside a 1.2 m long Zeeman slower. The slowed atoms are trapped in a magneto-optic trap which is 2.3 m downstream from the discharge. The laser frequency for transverse cooling is set on resonance for the main isotope of ^{84}Kr (I.A. = 57%). The frequency detunings of the slowing and trapping laser beams are −80 MHz and −6 MHz, respectively.

Laser trapping and cooling of krypton atoms (or any noble gas elements) in the ground level is technically not possible due to the lack of suitable lasers in the vacuum ultraviolet region. Instead, it is implemented on krypton atoms in the metastable level $5s[3/2]_2$ by exciting the $5s[3/2]_2 \rightarrow 5p[5/2]_3$ cycling transition at 811.5 nm using either diode lasers or Ti:Sapphire lasers. There are quite a few ways to prepare metastable noble gas atoms, including: electron beam bombardment,[4–6] surface-wave-sustained plasma,[7] DC glow discharge,[8–10] radio-frequency (RF)[11] or microwave discharge,[12] or optical excitation.[13,14] Kr* beam flux density generally reaches 10^{14} atoms/s/sr. Here we apply the RF discharge method because it is relatively simple and can work at a pressure as low as 0.1 Pa. Low working pressure is essential in case that the sample size is limited.

Laser cooling in the transverse direction is an effective tool to producing an intense atomic beam, which is necessary for an efficient atom trap. In this work, simulation of individual atom trajectory was carried out to understand the transverse cooling process. For simplicity, all the atoms are supposed to have a forward speed of 178 m/s which is the most probable atomic speed measured in the beam. Moreover, all atoms were assumed to originate from a single point at the end of the AlN tube which is 5 cm upstream from the transverse cooling region. Trajectories of atoms with different initial transverse speed are shown in Fig. 2(a). The final transverse speed of the atoms leaving the TC region as a function of the initial speed is shown in Fig. 2(b). For illusion, a trajectory and its corresponding transverse speeds (initial and final) are marked on Figs. 2(a) and 2(b), respectively. The simulation shows the atomic beam becomes much

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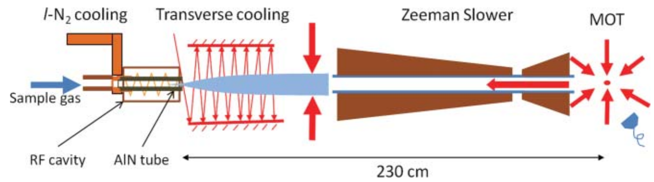

FIG. 1. (Color online) The schematic of the experimental setup.

collimated after transverse cooling because of significant decrease on the transverse speed for those atoms with moderate initial speed.

Laser-induced-fluorescence (LIF) spectroscopy of the Kr* beam is measured with a laser beam perpendicular to the atomic beam in the MOT chamber 230 cm downstream from the source. The LIF spectra observed with and without transverse cooling are also shown in Fig. 2. The relative intensity of the LIF signal shows that cooling gives an enhancement factor of 156. The absolute flux of the ^{84}Kr* beam in the forward direction was measured to be 3.7×10^{12} atoms/s through an area of 10 cm^2. It corresponds to an equivalent ^{84}Kr* beam flux density of 2.0×10^{16} atoms/s/sr from the source, which is about two orders of magnitude higher than that given in Refs. 12 and 14.

The result of slowing of the atomic beam is illustrated with the LIF signal shown in Fig. 3. The LIF spectrum was observed with two crossing laser beams, one perpendicular to the atomic beam and another one at 45°. The peak on resonance is induced by the perpendicular laser beam. The Doppler shifted broad peak induced by the 45° crossing laser beam illustrates the distribution of the forward speed of the atoms in the beam. The observed spectrum was fitted according to Maxwell–Boltzmann distribution function given in Ref. 15. The fitting of the signal without slowing [Fig. 3(a)] gives the most probable velocity V_m of 178 m/s, corresponding to a temperature of 108 K for the atomic beam. The LIF signal with Zeeman slowing is shown in Fig. 3(b). The narrower distribution and less blue-shifted spectrum clearly shows the atomic beam is slowed down. The resulting speed V_m obtained from the fitting is 42 m/s and the equivalent temperature is 6 K. The very flat baseline on the blue side of the signal indicates that almost all the atoms were slowed down.

When the trapping laser beams are turned on, a large amount of atoms can be trapped in the MOT and a very strong fluorescence can be observed. The fluorescence intensity is applied to estimate the number of the trapped atoms. As many as 1.3×10^{10} ^{84}Kr atoms can be trapped within a volume of about 0.5 mm diameter, at a cold Kr* atom density of 2×10^{14} atoms/cm^3. The loading process can be adequately described in the following equation:

$$\frac{dN}{dt} = L - \alpha N - \beta N^2, \tag{1}$$

where L is the loading rate of the trap, N is the number of atoms in the trap, α and β are the coefficients describing loss of trapped atoms due to trap-background collisions and trap–trap collision, respectively. By fitting the decay curve of the fluorescence signal of trapped ^{84}Kr atoms when the MOT loading is suddenly turned off, we can retrieve the loading rate of the trap, which is 1.5×10^{11} s^{-1}. Taking into account that

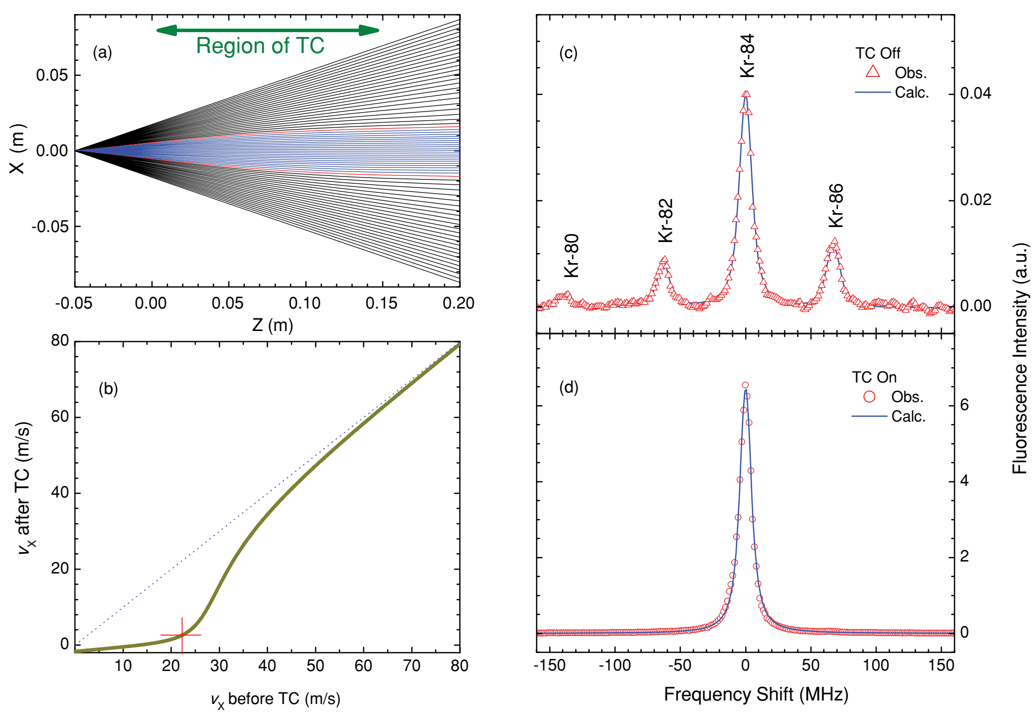

FIG. 2. (Color online) (a) Trajectories of metastable atoms bend by the transverse cooling (TC) laser beams. Atomic beam forward direction is along the Z axis. TC region covers $Z = 0 \sim 0.15$ m. (b) Transverse speed (along the X axis) of a metastable Kr atom leaving the TC region as a function of the transverse speed before entering the TC region. The one emphasized with a cross corresponds to the trajectory highlighted on panel (a). (c) and (d) show LIF signal of the metastable Kr atomic beam observed at 230 cm downstream when TC laser beams was off and on, respectively.

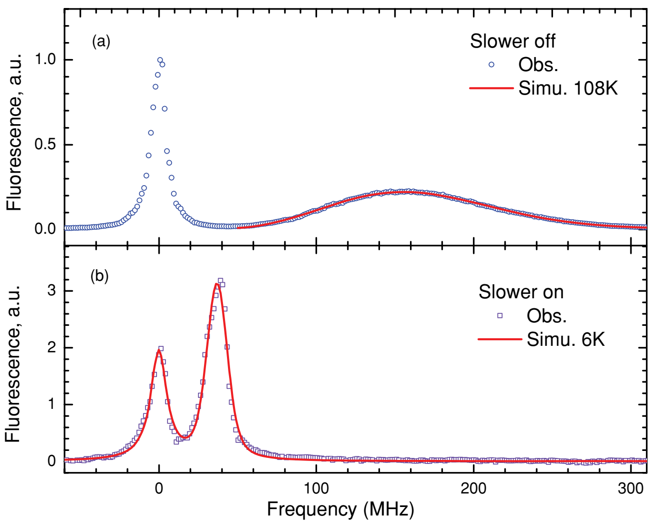

FIG. 3. (Color online) LIF signal observed 230 cm downstream in the MOT chamber. The slower beam was off for (a) and on for (b).

the flow rate of the Kr sample gas is about 0.8 μl/s (STP), or 1×10^{16} ^{84}Kr atoms/s, we derive that the overall trapping efficiency is 1.5×10^{-5}, which is about 150 times of that reported in Ref. 1.

III. DISCUSSION

As shown above, liquid-nitrogen cooling used in present apparatus has effectively decreased the Kr gas temperature to about 108 K. With a low atomic beam temperature, both the forward and transverse speeds of Kr* atoms decrease. It leads to a better efficiency on both transverse cooling and Zeeman slowing. In addition, liquid-nitrogen cooling also helps to take away the heat produced in the discharge, thus avoiding over heating the discharge tube. In order to quantitatively determine the significance of liquid-nitrogen cooling, we also carried out measurements without liquid nitrogen cooling. By removing liquid nitrogen, we observed that the atomic beam temperature increased from 100 K up to over 350 K; the average atomic speed almost doubled; the transverse cooling enhancement factor dropped from 156 to 90; and the efficiency of the Zeeman slower also decreased. Typically, the loading rate is 2–4 times smaller without the liquid nitrogen cooling. However, it is not always the lower temperature, the better. If the temperature of the discharge source becomes too low, even when the Kr gas pressure is still high enough to support the discharge (the Kr vapor pressure is 1 Pa at 59 K), there will be considerable amount of sample gas adsorbed onto the cold surface. This is to be avoided if the sample size is limited.

Since the optimized excitation rate (Kr*/Kr) in the RF discharge can be about 10^{-3},[16] there is still considerable loss from the source to the trap. Our simulation of the atomic beam trajectories shows that about 90% of the atoms are lost while traveling through the Zeeman slower tube due to beam divergence. Even among those atoms reaching the MOT chamber, there is still a significant fraction escaping the trap. The reason may be that the atomic beam divergence gets larger when the forward speed of the atoms decreases in the slower. In this case, using a two-dimensional magneto-optic trap (2D-MOT) after the transverse cooling to give a slight focusing of the atomic beam may reduce the divergence loss. A preliminary 2D-MOT inserted between the transverse cooling and the Zeeman slower in our apparatus has increased the loading rate with a factor of two, resulting in a MOT loading rate of 3×10^{11} atoms/s. It also doubled the trapping efficiency. Further optimization of the 2D-MOT with larger laser beam size is under construction.

It is also worth noting that since the pressure in the source chamber needed to sustain the RF discharge is low (~ 0.1 Pa), the sample gas can be recirculated by directly connecting the foreline of the turbopumps to the source chamber. Such method has been successfully applied by Du *et al.* to increase the trapping efficiency with a factor of 2000.[16] Applying sample recirculation to the present setup, the overall efficiency would be potentially raised to the 10^{-2} level. Such a high-efficiency atom trap would be very attractive for trace analysis applications.

ACKNOWLEDGMENTS

We thank Z.-T. Lu for numerous suggestions and discussions. This work is jointly supported by National Natural Science Foundation of China (Grant Nos. 90921006 & 10728408), by Chinese Academy of Science (YZ200765), and by Chinese Ministry of Science and Technology (2006CB922001, 2007CB815203).

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