The Progress of Strontium Optical Clock at NIM

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ABSTRACT

We report the experimental realization of ^{88}Sr magneto-optical trap (MOT) operating at the wavelength of 461 nm and 689nm. The blue MOT is loaded via a 32 cm long spin-flip type Zeeman slower which enhances the MOT population by a factor of 44. We have trapped 1.6×10^{8} 88Sr atoms with the use of 679nm and 707nm repumping laser. The ^{88}Sr cloud has a temperature of about 2.3 mK, measured by recording the time evolution of the absorption signal. The 689nm laser used in our experiment has a line width of about 200Hz. To optimize the transfer efficiency, the laser spectrum is broadened by frequency modulation technique to about 2 MHz. The transfer efficiency from blue MOT to red MOT is about 20%.

INTRODUCTION

Recently, laser-cooled alkaline-earth metals have been the subject of active research in the fields spanning from fundamental study of Doppler cooling, precision optical frequency metrology and ultra cold collisions [1-5]. Much of the interest relies on the versatile internal level structure, the two valence electrons can couple together anti-parallel to form a singlet state or parallel to make a triplet state. The upper state of the $^1S_0$- $^1P_1$ 461nm transition has a life-time of 5.22ns (32 MHz) which allows efficient cooling of the atom to mill Kelvin stage, while the natural width of the intercombination transition is only 7.5 kHz which allows the sample to be cooled to several micro Kelvin. In this letter, we report the cooling and trapping of about 10^8 ^{88}Sr atom at temperature of 2.3mk with 461nm laser, then the atom cloud was further cooled by 689nm laser utilizing the narrow intercombination transition. To achieve a high loading rate, Katori et al. have used laser spectrum, broadened by frequency modulation. Thus the velocity capture range of the 689 nm MOT matches the typical velocity in the 461 nm MOT. The transfer efficiency from blue MOT to red MOT is about 20%.

EXPERIMENTAL SETUP

The experimental setup was shown in Fig1. The atomic beam is generated by an effusive oven which is heated to 590℃. An array of tube-pinholes with dimensions of 100μm diameter and 2mm length is put on the front of the oven to collimate the atomic beam. The heated atom beam is further collimated by a two-dimension optical molasses detuned from the $^1S_0$- $^1P_1$ transition by -10 MHz. The heated atom beam has an average velocity of more than 500m/s, so a Zeeman slower is inserted between the oven and MOT. A single coil spin-flip type Zeeman slower whose shape is optimized by a computer program was used to reduce the hot atom's velocity from 500 meters per second to less than 50 m/s. The Zeeman slower is made of hollowed brass pipe of about 32cm long, with water cooling on both ends of the slower. The outer diameter of the pipe was about 37mm. The wire used to construct the slower has a diameter of 1mm, which allowing maximum current of 5 A. The 461nm Zeeman slower cooling laser, red detuned from $^1S_0$- $^1P_1$

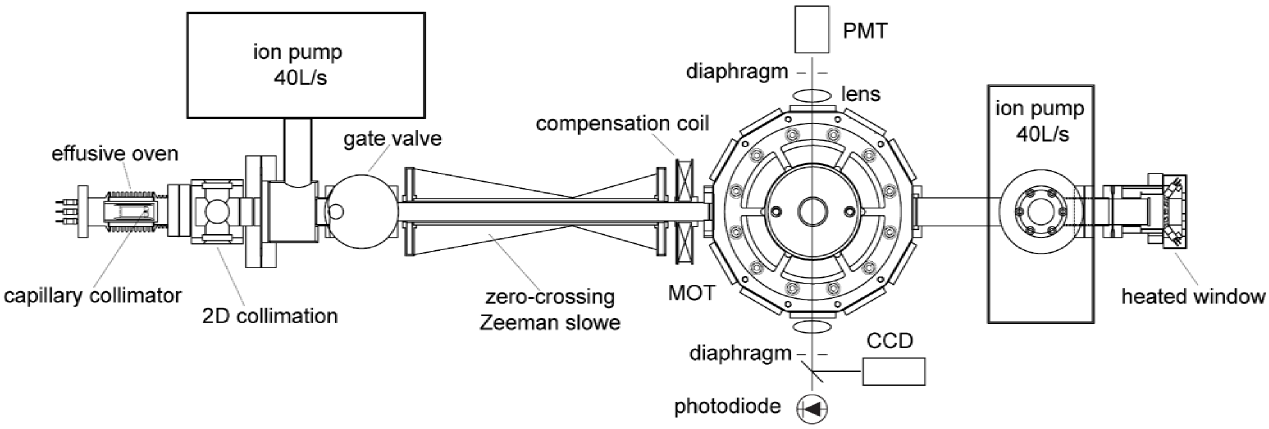

Fig.1. Schematic of experiment apparatus

resonance by 440 MHz contains 66mw of power which means the atoms are decelerated with 0.45 times the maximum acceleration. To combat the transverse heating effect during slowing process, the slowing laser is weakly focused to match the atom beam's divergence. The MOT chamber is a cylindrical dodecagon with twelve 1.5-inch windows in horizontal plane and two 6-inch ones along the vertical direction. All windows are made of fused silica and broadband AR coated with AR coating optimized for transmission of 461nm and 689nm. The MOT anti-Helmholtz coils running 16A current can produce a field gradient of dBz=50 gauss/cm in the gravity direction. The window for Zeeman slower laser is heated to 160°C to prevent the formation of Strontium coating. All the vacuum system is evacuated by two 40L/s ion pumps at both side of the gate valve. The vacuum level is better than 3×10^{-8} Pa in MOT chamber and a little less in oven region.

BLUE MOT

The 461nm laser in our experiment is produced by two independent frequency doubling cavity while the fundamental waves are from the same source. One is a commercial Toptica TA SHG 110 system which uses $KNbO_3$ as frequency doubling crystal. Although it gives a relatively high output power (180mw), its beam profile is poor. We use its output to perform Zeeman slowing, frequency locking, and two-dimension cooling experiments. A home made PPKTP frequency doubler can output 120mw laser power with very good beam profile. The PPKTP laser serves for the MOT and probing operation. The frequencies of the two lasers were simultaneously locked to the absorption line of $^1S_0$-$^1P_1$ transition by sending 2mw of 20 MHz phase modulated 461nm laser through a heated strontium beam. The locking is achieved by feeding the error signal back to the 922nm ECDL laser. The MOT beams are in retro-reflection configuration and the cooling beams are expanded to 20mm diameter with total power of 20mw. The frequency is red detuned 40 MHz with respect to the $^1S_0$- $^1P_1$ resonance.

In fact the $^1S_0$- $^1P_1$ transition is not closed indeed [6]. The atoms in $^1P_1$ state can decay to $^3P_2$ state via the low lying $^1D_2$ state. This losing mechanism limits the blue MOT life time to about several tens of milliseconds without using Repumping_laser. To repump the $^3P_2$ state atom back to $^1S_0$, we drive the $^3P_2$-$^3S_1$ transition (707nm) to pump the atom to $^3P_1$ state, which eventually decays to ground state [7]. To prevent optical pumping to $^3P_0$ state, another Repumping_laser that drives $^3P_0$- $^3S_1$ is also used. In our experiment, the two Repumping lasers are external cavity diode laser with Littrow configuration. The 707nm laser has a maximum output power of 30mw and a mode hop free tuning range of

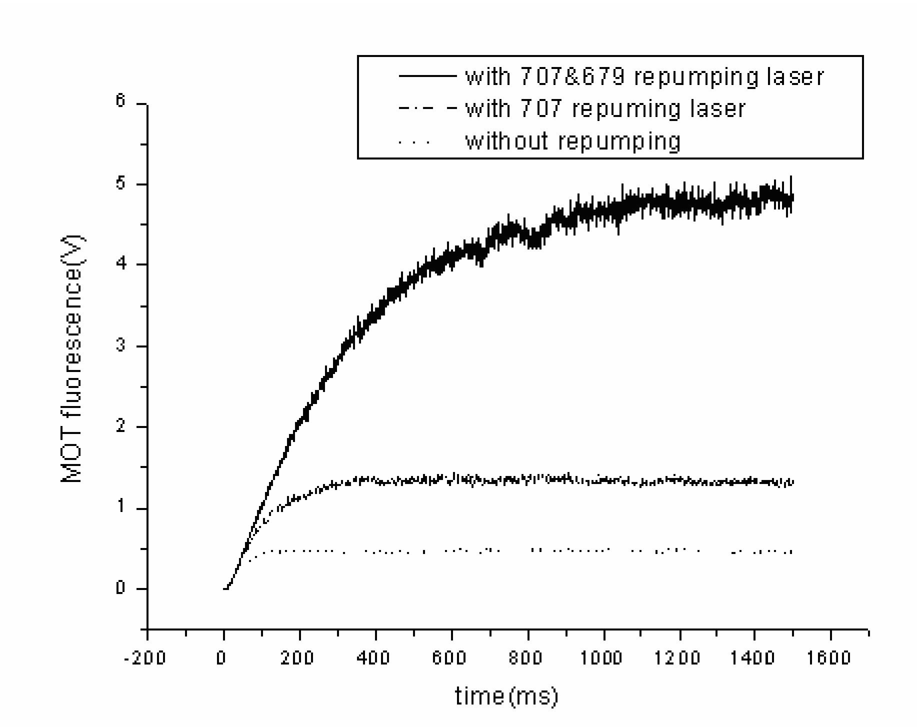

Fig.2. loading curve of 461nm MOT

5 GHz. The 679nm laser has a maximum output power of 16mw and a mode hop free tuning range of 4 GHz. The frequencies of the two Repumping lasers are not locked in our experiment. We can see from figure 2 that using Repumping lasers can enhance both the population and life time of the blue MOT by a factor of about 10.

The atom number in 461nm MOT was estimated by means of measuring fluorescence level with calibrated photo diode taking factors of solid angle, laser power and detuning etc. into account. The result shows that we have trapped 1.6×10^{8} ^{88}Sr atoms. The in-trap atomic cloud size was measured by imaging the MOT fluorescence with a high resolution commercial CCD camera as shown in Fig.3. A total number of 1024*1024 pixels were distributed evenly on a chip with the size of 13mm×13mm. we measured the cloud sizes in two directions: one in gravity, the other in horizontal. We assume the cloud have rotation symmetry along gravity direction. We fit the fluorescence signal with Gaussian function, which shows the e^{-1} radiuses of the cloud in the vertical and horizontal direction were 1.63mm and 1.43mm respectively. So the average radius of the cloud, defined as $r_a=(r_x r_y r_z)^{1/3}$, is 1.5mm.

To perform the MOT temperature measurement, a 100-µm-diamter resonant 461nm probe beam with several micro watts power was sent through the center of the cloud. The evolution of the probe absorption signal was recorded on a photo diode as the MOT and Zeeman slower laser were turned off suddenly. Fig.4 shows a typical result of our measurement. The data are then fitted with [8]:

$$f(t) = a\exp\left(-\frac{b}{r_a^2 + 2k_B T t^2 / m}\right) \tag{1}$$

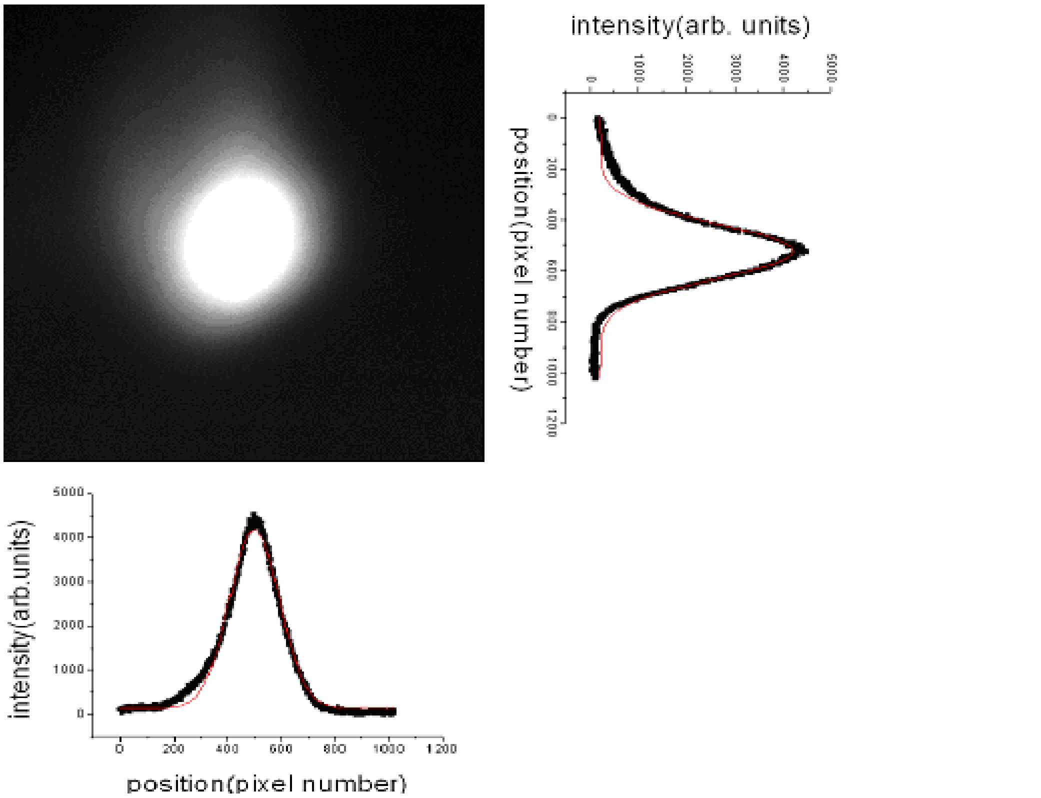

Fig.3. fluorescence image of trapped atoms on CCD chip

where a, b, and T are three fitting parameters, r_a is the averaged e^{-1} radius of the cloud, k_B=1.38×10^{-23}J/k is Boltzman constant, m=1.47×10^{-25} kg is mass of ^{88}Sr atom. The fitting gives a result of T=2.3mk. We also measured the cloud temperature by time of flight (TOF) method, which also give a temperature of 2～3mk.

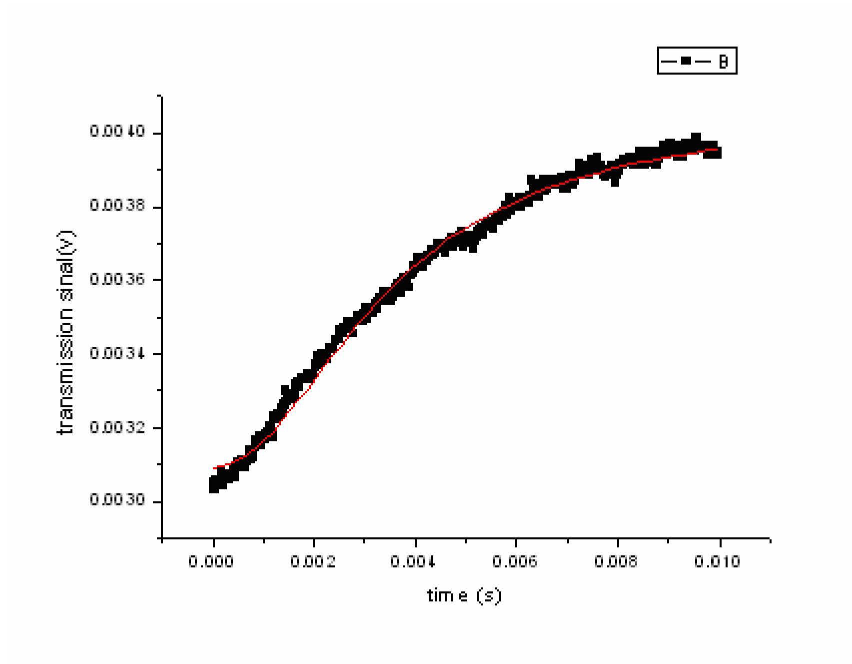

Fig.4. the evolution of the probe absorption

RED MOT

To perform the second stage cooling requires a laser system whose short-term linewidth is small compared to the 7.5 kHz transition natural width [9]. However to matches the typical velocity in the 461 nm MOT, the spectrum of the laser should be broadened by frequency modulation to several Mega Hertz. The 689 nm laser system consists of a master-slave ECDL, a temperature stabilized and vibration isolated passive optical reference cavity. The linewidth of the master ECDL is first narrowed by locking the laser to a stable optical reference cavity via the Pound-Drever-Hall technique. The cavity consists of high reflectivity ULE substrate mirrors that are optically contacted to a ULE spacer. The measured cavity finesse (free spectral range) at 689 nm is 10000(1.5 GHz), giving a linewidth for the TEM00 mode of 150 kHz. When the lock is engaged, the master laser has linewidth of 200Hz measured by beating two similar laser. A portion of the 689 nm master ECDL output is next used to injection lock a 689 nm slave diode laser after double-passing through two AOMs used for frequency shifting and broadband modulation. The slave laser has an output power of about 20mw and then is coupled into a single-mode polarization-maintaining optical fiber. Upon exiting the fiber, the 689 nm light, containing up to10 mW of power, is expanded to a $1/e^2$ diameter of 6 mm and divided into three equal intensity trapping beams. The trapping beam waveplates are $3\lambda/4$ at 461 nm and $\lambda/4$ at 689 nm. Figure 5 shows the red MOT loading procedure. At first, 10^8 atoms are first cooled to 2-3 mK in a 461nm MOT. At time t = 0, the 461 nm light and the atomic beam shutter are switched off, the gradient of magnetic field is rapidly lowered from50 G/cm to 3 G/cm. During the process, the red-detuned, broadband frequency modulated 689 nm trapping beams are always on. At time t = 10 ms and for the following 50 ms, the gradient of magnetic field is linearly increasing to 10 G/cm. The laser frequency is modulated at 40 kHz with modulation depth of 1MHz. The image for the red MOT is taken with probe pulse at the wavelength of 461nm. Although the transfer efficiency from blue MOT to red MOT is estimated as 20% by recording the level of the fluorescence, the red MOT is not finished yet. Now we are working to optimize the temperature and to improve the space density of our red MOT.

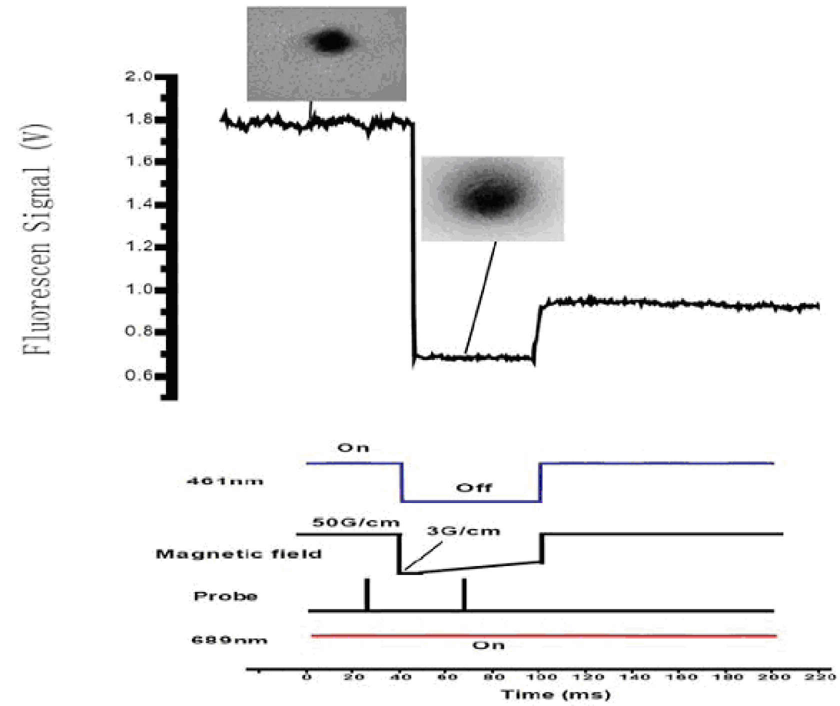

Fig.5. the time sequence and image of red MOT

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