Journal of the Optical Society of Korea, Vol. 9, No. 3, September 2005, pp. 87-91

Investigation of Isotope Selective Characteristics of the Strontium Magneto-optical Trap by the Fluorescence Detection

Kwang-Hoon Ko*, Do-Young Jeong, Gwon Lim, Taek-Soo Kim, Yong Ho Cha and Hyung Ki Cha

Laboratory for Quantum Optics, Korea Atomic Energy Research Institute, Yusong, Daejeon, KOREA, P.O.Box 105

You-Kyoung Lim

Department of Physics, Chungbuk University, 12 Gaesin-dong, Cheongju, Chungbuk, KOREA

(Received August 22, 2005 : revised September 20, 2005)

The strontium magneto optical trap followed by a Zeeman slower has been demonstrated. The isotope selective characteristics of the trap have been investigated. The fluorescence spectrum of the MOT was compared with those of other high resolution spectroscopic methods. The red detuned deflection beam is also considered for a more selective spectrum.

OCIS codes : 300.6210

I. INTRODUCTION

A trace isotope analysis has played an important role in many areas, such as basic research, environmental science, biochemistry and archaeological dating [1,2]. Especially, the detection of a trace radio isotope such as ^{90}Sr, which is a fission product, has been of interest in the nuclear industry and an environmental assessment. The radiochemical analysis is a general method to analyze rare radio isotopes [3]. However, it doesn't only need a long measurement time but also a high toxic material treatment. Therefore, several spectroscopic techniques have been developed and studied for a direct fast detection of ^{90}Sr isotopes [4,5].

Recently, the neutral atom trap has been applied for analyzing ultra trace isotopes, such as ^{81}Kr, ^{85}Kr and ^{41}Ca [6]. This method is not only free of contamination from different isotopes or isobars, but it also has a higher selectivity than that of the other laser based methods [6,7]. Moreover, other enrichment processes for handling the neutral atoms such as an atomic beam collimation and a Zeeman slowing technique are able to be applied to obtain a higher enrichment factor for the interested isotope. The relative abundance of ^{90}Sr reaches down to the $<10^{-10}$ of the dominant isotope, so only one group has been achieved the selectivity by the laser based method because of the small isotope shifts and broad natural line width [4]. The sufficient selectivity may not be obtained by only MOT. However, MOT which has the isotope selective characteristics can be applied to the combined method with the mass spectrometer as a former separation stage. To develop a higher and faster isotope selective analytical system to detect rare ^{90}Sr, MOT (magneto optical trap) can be one of the best candidates as an isotope selective excitation method. Therefore, the isotope selective characteristics of strontium MOT has to be studied before applying MOT as an excitation method.

In the present work, the strontium MOT was demonstrated with the Zeeman slower and the isotope selective characteristics were investigated when the strong 460.7 nm cycling transition ($5s^2\ ^1S_0$ - $5s5p\ ^1P_1$) was used for a trapping and slowing. The fluorescence spectrum of MOT was compared with the Doppler limited and the Doppler free spectrums. The isotope selective characteristics have been studied as a function of the trap light intensity. In addition, the red detuned pushing beam effect for the elimination of other isotopes was also discussed.

II. EXPERIMENTAL SETUP

The atomic structure of the strontium is shown in Fig. 1. The strong 460.7 nm cycling transition ($5s^2\ ^1S_0$ - $5s5p\ ^1P_1$) is used for slowing down and trapping the strontium atoms. There is the $5s4d\ ^1D_2$ leak (decay rate of $3.9 \times 10^3 s^{-1}$) which strongly governs the performance of the strontium MOT. Atoms that decay from the $^1D_2$

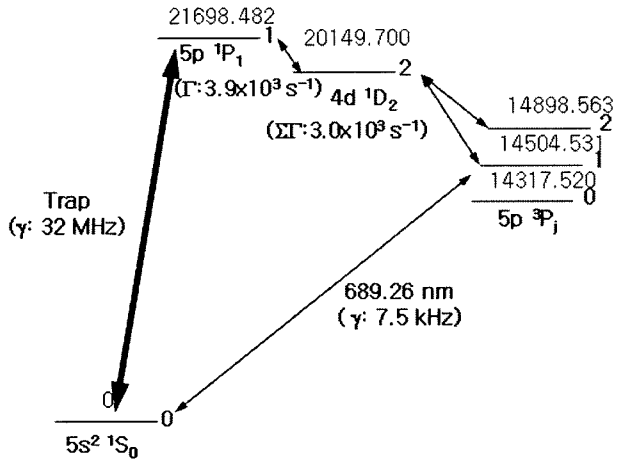


FIG. 1. Strontium level diagram showing relevant transition wavelengths.

state to the long-lived $^3P_2$ state are lost from the trap. This leakage shortens the trap lifetime of the strontium MOT.

The strontium consists of four stable isotopes ^{88}Sr, ^{87}Sr, ^{86}Sr and ^{84}Sr and their abundances in nature are 82.56, 7.02, 9.89 and 0.56, respectively. The shifts in the corresponding trapping transition line ($5s^2$ $^1S_0$ - 5s5p $^1P_1$) of the ^{87}Sr, ^{86}Sr and ^{84}Sr isotopes from the ^{88}Sr isotope are 49.2 MHz, 124.5 MHz and 270.6 MHz, respectively [8].

The MOT system schematic is shown in Fig. 2. The strontium atoms were extracted from the atomizer operating at about 600°C and collimated with two slits. The divergence of the atomic beam was about 2 mrad. The Zeeman slowing technique was used to longitudinally slow down the atomic beam to the capture velocity. Two anti-Helmholtz coils created the magnetic field gradient of 50 G/cm in the trap center. The single mode laser beam was split into two parts; one was used for the slowing beam and the other for the trapping beam after being shifted by +130 MHz to the blue side by an acousto-optic phase modulator. The laser power of about 100mW was applied for the trapping beam, the slowing beam and the saturated absorption spectroscopy for the frequency locking onto the transition line. The trap beam

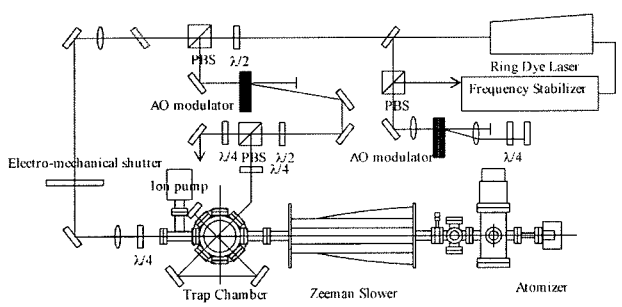


FIG. 2. Experimental setup for trapping and slowing the strontium atoms.

intensity was controlled from 0 mW to 20 mW by varying the supplied rf powers to an acousto-optic phase modulator and the slowing beam was turned on and off by an electro-mechanical shutter which had rise and falling times of less than 10 ms. The pulse delay generator provided the electric signal to synchronize the laser beam intensity control and the measurement times. The fluorescence from the trapped atoms was measured by a photomultiplier (hamamatsu Inc., R928) and stored in an oscilloscope.

The saturated absorption spectroscopy setup was composed of one atomic heat oven and two counter propagated beams and it was also used for obtaining the Doppler free spectrum on the $5s^2$ $^1S_0$ - 5s5p $^1P_1$ line. The Doppler limited LIF (laser induced fluorescence) experiment was also achieved on the collimated atomic beam (divergence : 2 mrad) in the trap chambers without the slowing and the trapping beams. In the LIF experiment, the fluorescence was detected at an arm of the trap chamber by using the photomultiplier tube.

A little amount of the slowing beam was provided to the atomic beam at a 90° direction as a pushing beam to deflect the other isotopes out of the beam line before a slowing down. The side beam power was delivered in a multi-mode fiber and its power was about 4 mW

III. EXPERIMENTAL RESULT

The slowing beam and the Zeeman slower were used for increasing the loading rate. Then, when the Zeeman slower was used, the numbers of the trapped atoms became 10 times higher than those of the slowing case with only the slowing beam. The atom number was about 10^4 - 10^5 atoms which was obtained from the measured electric signal and the photomultiplier gain corresponding to the applied voltage. When the trap beam was turned on at t = 0, the fluorescence intensity from the trapped atoms increased with an exponential loading time τ. In this experiment, the observed loading time (the loss rate can be measured from the loading curve) was about 20 ms as shown in Fig. 3. The loading rate is equal to the trap lifetime in the approximation with no cold collision (it is a reasonable approximation in our atom number) [9]. The short trap lifetime is due to the 5s4d $^1D_2$ leak, as mentioned above.

The magneto optical trap has the enrichment characteristics of the isotope of interest by the repetitive processes of emission and absorption on the corresponding trap transition line, while there is just one selection process in the isotope selective excitation, such as the LIF experiment. The fluorescence spectrum is, then, expected to show well separated fluorescence peaks which originated from the trapped isotopes [8]. The two typical high resolution spectroscopic methods were represented here together with the trap fluorescence for a comparison.

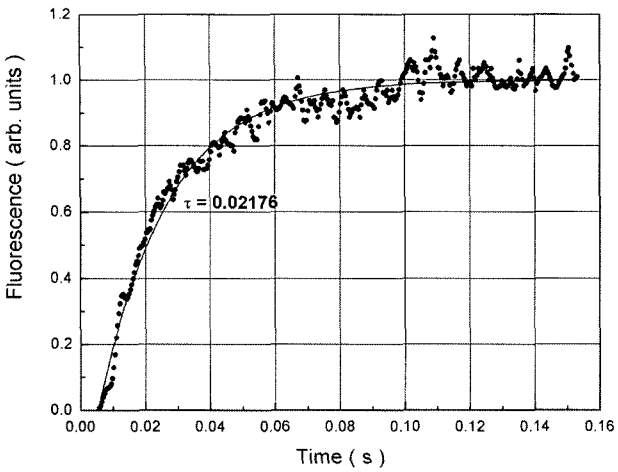
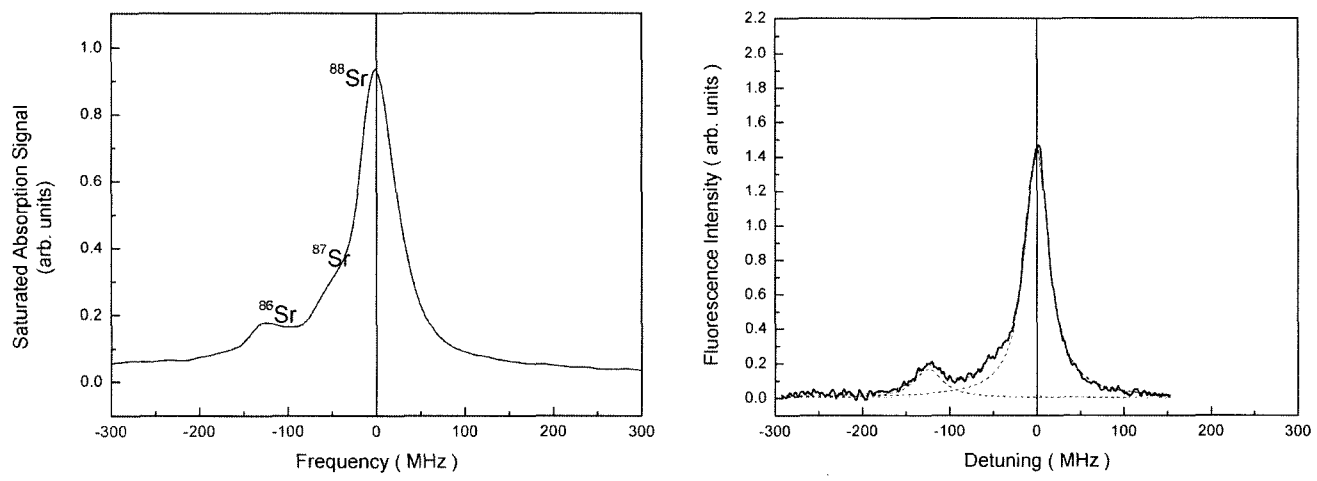


FIG. 3. Trap Loading time.

Fig. 4 shows the saturated absorption signal in the heat oven (Doppler free spectroscopy) (a) and the LIF (laser induced fluorescence) signal in the atomic beam (Doppler limited spectroscopy) (b), respectively. Their spectral resolutions are limited to the intrinsic natural linewidth of the transition lines. The saturated absorption spectroscopy has been performed in the typical experimental geometry [7]. The LIF signal was detected in the trap chambers while all the lasers and magnetic fields were turned off except for one excitation laser. Even small residual Doppler broadening, the isotopes ^{86}Sr, ^{87}Sr and ^{88}Sr could not be completely resolved by the two high resolution methods, because of the small isotope shifts comparing to the natural linewidth [8].

In the case of a trapping, the selectivity is increased by repeating the absorption and the emission processes on the trap transition line. The fluorescence spectrum of strontium MOT as a function of the laser frequency is shown in Fig. 5. The fluorescence peaks are positioned at the red side of the resonance lines due to the trap characteristics. The frequency has to be scanned slowly for the trap to be in a steady state. If not, the spectrum becomes asymmetric and distorted. Fortunately, the trap lifetime is a little bit short, therefore the scan speed could be increased more than that of the other conventional trap experiments. In this experiment, the scan speed was maintained at less than 50 MHz/s. This speed was correspondent to 1MHz per the trap lifetime (20 ms) which was sufficiently slow to be a steady state during a scanning. In this spectrum which includes the isotope selection effect by the Zeeman slowing, the three peaks which originated from the three isotopes are completely resolved. However, there is the background which may come from the neutral atomic beam. The spectrum profiles have not been analyzed so far due to the complexity of simulating the trap and the slowing processes. Instead of measuring the isotope selectivity by analyzing the fluorescence spectrum, we compared the sum of the two isotopes (^{87}Sr and ^{88}Sr) in the LIF experiment and the total signal including the background of the trap fluorescence at the frequency position of -90 MHz(A) from the ^{88}Sr peak as shown in Fig. 5. The sum of the two isotopes(^{87}Sr and ^{88}Sr) in the LIF experiment could be calculated by a fitting with three Lorentzian shapes. The ratio of the two isotopes (^{87}Sr and ^{88}Sr) in the LIF and the total signal in the trap was about 10, even when the background fluorescence was included in the trap fluorescence.

Fig. 6 shows that the spectral width of the fluorescence decreases as the trap laser power decreases. The narrowing results from a weak restoring force on the cooled atoms. This narrowing may affect the improvement of the isotope selectivity at the fluorescence maximum, but a direct measurement of the isotope selectivity was not performed



(a) (b)

FIG. 4. Saturated absorption signal in the heat oven (a); laser induced fluorescence signal in the atomic beam (b). The dashed lines in (b) are the fitted curves with three Lorentzians. The divergence of the atomic beam is less than 2 mrad.

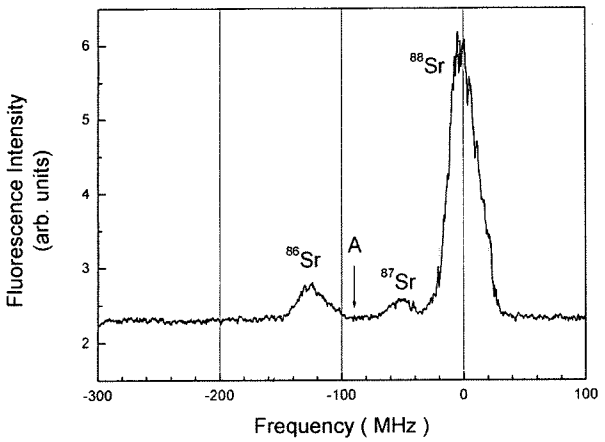


FIG. 5. Fluorescence from the trapped atoms as a function of the laser frequency. The fluorescence peaks are positioned at the red side of the corresponding resonance lines. The x-axis shows the relative frequency from the ^{88}Sr peak.

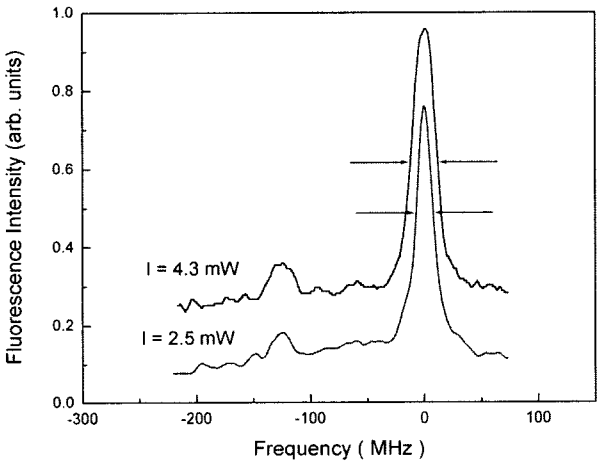


FIG. 6. Fluorescence spectrum from the trapped atoms for the trapping laser powers 4.3 mW(a) and 2.5 mW(b).

due to its complexity.

As mentioned above, the manipulation of the neutral atoms by lasers, such as the atomic beam deflection and the atomic beam collimation, gives us a better selectivity. We considered eliminating the unwanted isotopes by providing several laser beams on to the atomic beam at a right angle. To obtain the depletion of unwanted isotope in this report, a part of the slowing beam was applied to the atomic beam at a right angle before a slowing in the Zeeman slower. The deflection beam intensity was measured at about 4 mW and delivered with a multi-mode fiber. When the frequency of the carrier beam is swept, the isotopes which are resonant or nearly resonant on the deflection beam are able to be eliminated, while other isotopes proceed to the trap region through the Zeeman slower. The experimental result is shown in Fig. 7. Fig. 7(a) and (b) show the fluorescence spectrum of MOT without and with the

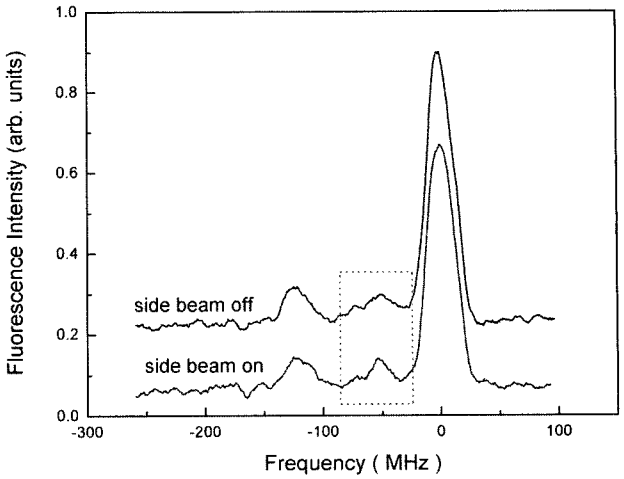


FIG. 7. Fluorescence spectrum from the trapped atoms as a function of the laser detuning with and without the deflection beam. The depletion beam power was measured about 4 mW.

deflection beam. The fluorescence spectrum with the deflection beam shows little a more sharp spectrum. Even the deflection beam frequency was to far from the neighboring isotope, it can interact with the atoms at the wing of the naturally broadened line of neighboring isotope. If the frequency is tuned to the line center of the neighboring isotope such as ^{87}Sr, the trapped number of ^{88}Sr could also be decreased, but the selectivity may be improved.

IV. CONCLUSION

In this paper, we report on the characteristics of the strontium MOT with the Zeeman slower and its spectrum. The strontium MOT with the Zeeman slower has been demonstrated for the strontium isotope analysis. The Zeeman slower increased the trapped atoms by up to 10 times that of a slowing with no magnetic field. The observed atoms was up to 10^4 atoms and the trap lifetime was about 20 ms from the trap loading curves.

In addition, we investigated the selective characteristics of the trapping from a comparison with the spectrums. The linewidth of the $^1S_0$ - $^1P_1$ transition is broader than the corresponding isotope shifts so conventional high resolution techniques can not resolve the isotopes completely. However, the trap process, the repetitive processes of absorption and emission, makes it possible to resolve them. In this experiment, we observed a higher selective spectrum by the trap method while the conventional high resolution spectroscopies (SAS and LIF) could not resolve them. The trap spectrum depends on the trap parameters such as the trap laser intensity, the frequency detuning, the laser beam diameter, the magnetic field gradient and the loading rate from the Zeeman slower.

Therefore, we didn't measure the isotope selectivity but only compared the spectrum to those of other spectroscopic methods. The trap fluorescence includes the background fluorescence which lowers the isotope selectivity and it may come from the fast atoms which were not slowed. We are sure that it can be removed by applying the atomic beam deflector after the Zeeman slower. Instead of the slow beam deflector, we applied a part of the slowing beam as the deflection beam to the atomic beam at a right angle before the Zeeman slower. We, then, observed a sharper spectrum when it was applied. Our results are so qualitative that they require a direct measurement for the quantitative results of the application. Therefore, an experiment is going to be performed for a quantitative analysis of the selective process.

*Corresponding author : khko@kaeri.re.kr

REFERENCES

[1] X. Du, R. Purtschert, K. Bailey, B.E.Lehmann, R.Lorenzo, Z.T. Lu, P. Mueller, T. P. O'Connor, N.C. Sturchio, L. Young, "A New Method of Measuring 81Kr and 85Kr Abundances in Environmental Samples," Geophysical Research Letters, vol. 30, p. 2068 (2003).

[2] C. Y. Chen, Y. M. Li, K. Bailey, T. P. O'Connor, L. Young, Z.-T. Lu, "Ultrasensitive Isotope Trace Analyses with a Magneto-Optical Trap," Science, vol. 286, pp. 1139-1141 (1999).

[3] K. H. Hong, Y.H. Choi, S.B. Kim, M.H. Lee, H.G. Park, K.S. Choi, S.R. Kim and C.W Lee, "Analysis of 89Sr, 90Sr in Soil Sample Using Crown Ether/Chloroform Solvent Extraction Method, Radio-chemical analysis," J. Korean Asso. Radiat Prot., vol. 21. p. 9 (1996).

[4] K. D. A. Wendt, C. Geppert, M. Miyabe, P. Mueller, W. Nortershaeuser, and N. Trautmann, "Ultratrace isotope determination in environmental, bio-medical and fundamental research by high resolution laser-mass spectrometry." J. Nucl. Sci. Technol. vol. 39, pp. 303-307 (2002).

[5] M. Sankari, P. V. K. Kumar, and M. V. Suryanarayana, "Investigations on the $^1S_0$ -> $^1P_{01}$ -> $^1S_0$ -> M^+ photoionization pathway for selective ionization of rare calcium and strontium isotopes," vol. 21, no. 7, p. 1369 (2004).

[6] S. Hoekstra, C. van Ditzhuijzen, J. Mulder, R. Morgenstern and R. Hoekstra," Ultra-sensitive Atom Trap Trace Analysis of 41Ca" the conferences on laser and probing 2002(2002).

[7] Alan Corney, *Atomic and Laser Spectroscopy*, (Clarendon Press, Oxford, 1977) p. 377.

[8] F. Buchinger, R. Corriveau, E. B. Ramsay, D. Berdichevsky and D. W. L. Sprung, "Influence of the N=50 shell closure on mean square charge radii of strontium," Phys. Rev. C, vol 32, p. 2058 (1985)

[9] K. H. Ko, D. Y. Jeong, J. Han and J. Lee, Magneto-Optical Trap of Slowed Sodium Atoms by using a Zeeman Slower and the Characteristics of trapped atoms," Hankook Kwanghak Hoeji, vol. 12, no. 5, p.347 (2001).