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Developing Optical Traps for Ultra-Sensitive Analysis

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ABSTRACT

We describe the coupling of a magneto-optical trap to a mass separator for the ultra-sensitive detection of selected radioactive species. As a proof of principle test, we have demonstrated the trapping of ~6 million ^{82}Rb ($t_{1/2} = 75$ s) atoms using an ion implantation and heated foil release method of introducing the sample into a trapping cell with minimal gas loading. Gamma-ray counting techniques were used to determine the efficiencies of each step in the process. By far the weakest step in the process is the efficiency of the optical trap itself (0.3%). Further improvements in the quality of the nonstick dryfilm coating on the inside of the trapping cell and the possible use of larger diameter laser beams are indicated. In the presence of a large background of scattered light, this initial work achieved a detection sensitivity of ~4,000 trapped atoms. Improved detection schemes using a pulsed trap and gated photon detection method are outlined. Application of this technology to the areas of environmental monitoring and nuclear proliferation are foreseen.

Keywords: Magneto-optical trap, radioactive atoms, ultra-sensitive detection

1. INTRODUCTION

Since the development of the first magneto-optical trap¹ (MOT), great progress has been made in understanding and optimizing the cooling and trapping of atoms. Recently the 1997 Nobel Prize in physics was awarded to three scientists who played central roles in the development of these techniques. Today, as many of the talks in this session highlight, magneto-optical traps represent one of the most powerful tools used in the field of atomic physics. Herein, we explore the use of optical traps as a new tool for ultra-sensitive detection and analysis with applications to environmental monitoring and nuclear proliferation concerns.

Examining the capabilities of optical traps, one finds many desirable features which are well matched to the needs of ultra-sensitive detection. These include its high-selectivity, high-sensitivity, and large dynamic range. High selectivity results from the fact that the trapping process involves the repeated near-resonant absorption and fluorescent emission ("scattering") of thousands of photons within a fraction of a millisecond (the time it takes for an atom to traverse the trapping cell). High sensitivity results from the fluorescent detection of the trapped cloud of atoms where the signal is highly leveraged by the "scattering" of millions of photons per second per trapped atom. And finally, without the space charge limitations as in ion traps, neutral atom traps are capable of trapping large numbers of atoms (10^8 atoms or more) within a relatively small cloud size (~2 mm ϕ) making large dynamic range measurements possible. With the trapping of many different species (mostly alkali, alkali earth, and noble gas elements) already achieved and the ability to detect a single trapped atom already demonstrated², optical traps are a natural candidate for ultra-sensitive detection. The main challenge in applying this new technology is in obtaining high trapping efficiencies.

The problems associated with achieving high trapping efficiencies are multifold. They include: (1) the introduction of the sample without degrading the ultra-high vacuum of the trap; (2) enhancing the time the atoms of interest spend in the vapor state as compared to being "stuck" on the walls of the trapping cell; and (3) optimizing the trapping light field with respect to beam intensity, detuning, magnetic field, and geometry of the MOT. Given the relatively weak trapping potential of optical traps, atom-atom collisions with hot (room temperature) gas atoms or molecules represent a significant loss mechanism. In general, the trapping lifetime scales directly with the pressure in the trap. In the case of trapping rubidium atoms, a pressure in the 10^{-9} torr range is needed to achieve a trapping lifetime of ~10 seconds. As outlined below, our approach solves the sample introduction problem by using a mass separator to implant the species of interest directly into a small catcher foil located within the trapping cell itself. Upon subsequent heating of the catcher foil, the implanted atoms are

released and trapped with minimal gas loading. To address the second problem, we have adopted the approach of using a special nonstick coating on the inside of the trapping cell to reduce wall "sticking" times. Following the work of Stephens et al.³, we have used a dryfilm coating to increase the trapping efficiency. For stable cesium we have measured a trapping efficiency of 20% using such a coating⁴. Finally, there are several good studies^{3,5} that have investigated the trapping efficiency optimization of a MOT. Herein, we employ large diameter trapping beams and a cubic trapping cell geometry to obtain reasonably high trapping efficiencies.

A schematic of the mass separator-MOT system that we have recently assembled is shown in Fig. 1. A chemically concentrated and purified sample is placed in the ion source where it is vaporized and ionized. The ion beam is then extracted from the ion source and passed through a mass separator where a single mass line is selected, focused and implanted into a small catcher foil located inside the trapping cell. The catcher foil is inductively heated to release the implanted species as neutral atoms that bounce around in the dryfilm coated cell where they are trapped by a magneto-optical trap. The fluorescent signal from the trapped cloud of atoms is modulated and imaged onto a photo-detector. The trapping signal is then demodulated using a lock-in amplifier to reject (at least partially) the intense laser scattered light coming from the surfaces of the trapping cell to determine the number of trapped atoms. In more advanced detection schemes it may be advantageous to transfer the trapped species to a second MOT where the amount of scattered light can be greatly reduced.

Figure 1. Layout of the Los Alamos magneto-optical trap (MOT) system coupled to a mass separator.

In this work we have concentrated on the trapping of ^{82}Rb ($t_{1/2} = 75$ s) because a convenient mother source of ^{82}Sr (25 d) was readily available, gamma-ray counting techniques could be used to characterize the efficiency of each step in the process, the possibility of long-term contamination of our system was eliminated, and the efficient trapping of ^{82}Rb was synergistic with a beta-asymmetry experiment that we are currently mounting⁶. In the future we are interested in extending this technique to the trace detection of ^{135}Cs , ^{137}Cs , and possibly ^{90}Sr as these long-lived radioactive species are of high importance to environmental monitoring and nuclear proliferation concerns. Ultimately, our goal is to demonstrate the utility of optical traps as a new ultra-sensitive analysis tool with the capability of making quantitative measurements at the 10^4 atom level – two orders of magnitude better than existing techniques.

2. TRAPPING AND DETECTION OF ^{82}Rb

To understand the ^{82}Rb trapping experiment, we now describe each step in the process. The ^{82}Sr source is produced at the isotope production facility of the Los Alamos Neutron Scattering Center (LANSCE) by 750-MeV proton irradiation of a molybdenum target. Handled within a hot cell, the target is dissolved in hydrogen peroxide and the strontium fraction extracted using an ion exchange column. The strontium sample containing both ^{82}Sr (~9 mCi) and ^{85}Sr (~50 mCi) is coprecipitated as SrCO_3 and loaded into a tantalum crucible. The crucible is then installed into a thermal ion source of the hot-cavity type⁷ and heated to a temperature where the ionization efficiency is low for strontium, but high for rubidium. A collimated NaI counter looking at the ion source region monitors the gamma-rays emitted by ^{85}Sr ($E_\gamma = 514$ keV, branching ratio = 96%) and ^{82}Rb (776 keV, 13%). Under appropriate operating conditions, we observe a 42% drop in the ^{82}Rb gamma-count rate while the ^{85}Sr gamma-count rate remains essentially constant. Once ionized, the ions are electrostatically extracted from the ion source, accelerated to 20 keV, and separated using a high transmission mass separator. ^{82}Rb ions are mass selected and refocused by a quadrupole triplet through a stainless steel collimator located just before the entrance of the trapping cell (see Fig. 2). The ions then enter the quartz trapping cell through a 5 mm diameter opening and are implanted into a small yttrium catcher foil. Final focusing and steering of the beam onto the foil is achieved by maximizing the current

Figure 2. Schematic of the ^{82}Rb trapping cell. The mass separated ^{82}Rb ion beam passes through a collimator (5 mm I.D.) and the opening (5 mm ϕ) of the OTS dryfilm coated quartz cell (a 75 mm cube) and is implanted into a yttrium catcher foil (6 mm ϕ). The heating coil inductively heats the foil to temperatures of 750-850 $^{\circ}\text{C}$ to release the implanted ^{82}Rb atoms into the cell where they are trapped by a MOT. Not shown are the anti-Helmholtz coils (170 mm ϕ) located above and below the plane of view.

measured on the foil while minimizing the current measured on the collimator. Typical ion beam intensities of $\sim 1 \times 10^8$ ions/s are measured with a picoammeter. A second, collimated NaI γ -counter viewing the foil region monitors the ^{82}Rb activity collected on the catcher foil. By comparing the 776 keV count rates at the source and foil positions, we find that $\sim 35\%$ of the ^{82}Rb produced in the source is ionized, separated, and implanted into the foil. A small rf-coil that surrounds the catcher foil, but located outside the cell, is used to inductively heat the foil to temperatures of 750 to 850 $^{\circ}\text{C}$ to release the implanted ^{82}Rb as a vapor within the cell. The cell is coated with a nonstick coating of octadecyltrichlorosilane (OTS) dryfilm. The dryfilm coating allows the atoms to "bounce" many times in the trapping cell, rethermalizing with the wall on each bounce, such that there are multiple chances to trap the atoms in the light field of the magneto-optical trap and enhance the trapping probability.

The magneto-optical trap is formed by six circularly-polarized laser beams (45 mm ϕ , 100 mm $1/e^2$ width) which enter the cubic cell through each surface. Each beam has a power of 200 mW. A set of anti-Helmholtz coils generates the quadrupole magnetic field gradient of 7 G/cm in the axial direction. A Ti:Sapphire laser tuned to the D_2 line of Rb at 780 nm forms the trapping beams. The laser frequency is locked to the $5S_{1/2}, F=3 \rightarrow 5P_{3/2}, F'=3,4$ cross-over transition of ^{85}Rb using a FM sideband technique⁸. The related energy levels and transitions are shown in Fig. 3. A double-pass acoustic optical modulator (AOM) driven at 268 MHz provides the 536 MHz frequency shift needed to excite the $5S_{1/2}, F=3/2 \rightarrow 5P_{3/2}, F'=5/2$ cycling trapping transition in ^{82}Rb ⁹. In order to repump atoms which fall into the $5S_{1/2}, F=1/2$, sidebands are added to the trapping beam by using an electro-optical modulator (EOM) tuned to 1.470 GHz which excites the $5S_{1/2}, F=1/2 \rightarrow 5P_{3/2}, F'=3/2$

^{82}Rb ($I=1, t_{1/2} = 75$ s)

^{85}Rb ($I=5/2$, stable)

$$f_T - f_4 = 536. \text{ MHz}$$

$$f_T - f_R = 1470. \text{ MHz}$$

Figure 3. The atomic energy levels of ^{82}Rb and ^{85}Rb relevant to their trapping and detection.

transition. For trapping ^{85}Rb , however, the EOM is tuned to 1.463 GHz and the second harmonic generates the repump light. Trapped atoms are detected by chopping the EOM on and off at 4 kHz modulating the trap fluorescence signal. A 58 mm $f/1.4$ lens images the trap fluorescence onto a photomultiplier tube (PMT) or a photodiode through a 10 nm interference filter and a 2 mm pinhole; a lock-in amplifier is then used to demodulate the trapping signal. Because of the intense laser scattering background coming from the cell surfaces, this scheme has a sensitivity of ~ 4000 atoms. In addition, a CCD camera with a $f/1.2$ lens provides an image of the trapped cloud.

Due to the low pressure in the cell ($\sim 10^{-10}$ torr) and a corresponding long trapping lifetime (30 s with the foil on and 90 s with the foil off), ^{82}Rb can be accumulated either in the foil (pulsed mode) or in the trap by continuous heating of the foil (continuous mode). Shown in Fig. 4 is the pulsed release and trapping signal for ^{82}Rb after implanting 3 mCi of ^{82}Rb into the catcher foil. In the top half of Fig. 4, we show the temperature of the foil (a) as measured with an optical pyrometer upon excitation of the heating coil; (b) shows the count rate for the 776 keV γ -rays coming from the decay of ^{82}Rb as a function of time. The drop in count rate indicates that $\sim 35\%$ of the ^{82}Rb atoms are released from the foil and leave the region viewed by the collimated γ -counter upon heating. Measurements with and without -300 V applied to the foil indicate that essentially all of the activity is released as neutral atoms. The $1/e$ release time from the foil is measured to be 5 seconds.

Figure 4. Pulsed release and trapping of ^{82}Rb . The top figure shows the foil temperature (a), and 776 keV γ -count rate (b) of ^{82}Rb accumulated and then released from the foil upon heating. The modulated fluorescence trapping signal as measured with a photomultiplier and a lock-in amplifier is shown in the bottom of the figure (c). The lock-in amplifier has an integration time constant of 3 s.

In the bottom half of Fig. 4, the lock-in trapping signal (c) is plotted as a function of time. A strong trapping signal is evident with a risetime consistent with the release profile of ^{82}Rb . Additional measurements with shorter foil heating times indicate that the trapping signal decays with a $1/e$ lifetime of 50 s, corresponding to a 90 s trap lifetime and the 75 s half-life of ^{82}Rb . No trapping signal is observed if: (1) the foil is not heated; (2) the foil is heated, but no ^{82}Rb is implanted into the foil; or (3) the magnetic field of the MOT is reversed. All of these cross-checks are consistent with the signal being attributed to the trapping of ^{82}Rb .

The number of trapped atoms is deduced from the trapping signal using a calibrated photodiode, yielding 6×10^6 and 3×10^6 trapped ^{82}Rb atoms for the pulsed and continuous operation, respectively. These numbers are approximately two orders of magnitude larger than any previous work with radioactive atoms¹⁰⁻¹⁵. From CCD image measurements of the cloud size, we obtain a density of $\sim 10^{10}$ atoms/cm³, consistent with re-radiation limited densities reported in the literature¹⁶. Calculating the overall trapping efficiency as $\eta_{\text{total}} = N_{\text{trap}} / \tau_{\text{trap}} A_{\text{Rb}}$, where $N_{\text{trap}} = 3 \times 10^6$ is the number of trapped atoms, $\tau_{\text{trap}} = 30$ s is the lifetime of the trap, and $A_{\text{Rb}} = 3 \times 10^8$ disintegration per second is the ^{82}Rb activity in the ion source, we obtain an overall efficiency of $\sim 3 \times 10^{-4}$ which is comparable with previous work¹⁰⁻¹⁵. Breaking this down stepwise, we obtain an ionization and separation efficiency of $\sim 35\%$, a catcher foil release efficiency of $\sim 30\%$ at 750°C and a trapping efficiency of $\sim 0.3\%$.

Using a third collimated NaI counter, we attempted to measure the number of trapped ^{82}Rb atoms directly through the detection of 776 keV gamma rays. This measurement failed, yielding a constant count rate with or without a ^{82}Rb cloud present, indicating that a large portion of the ^{82}Rb sticks to the cell walls. This is supported by a calculation that predicts that ~ 30 "bounces" (i.e., collision and release from the wall) are required to account for our measured trapping efficiency. When compared to the ~ 600 bounce pump-out estimate from the ratio of entrance/exit area to total surface area of the cell, we conclude that the dryfilm coating performance is less than optimal when compared to previous work^{3,4}. We suspect that improvements in the cell coating could lead to a sizable gain in the trapping efficiency. To this end, we are using the gamma-ray monitoring technique to select the best type of dryfilm coating for future use.

To further improve the sensitivity of the detection system, we propose to implement a MOT with two different trapping beams – one with large diameter (> 5 cm) and high intensity (> 200 mW) and the other with small diameter (< 1 cm) and low intensity (< 2 mW). Once the atoms are trapped, the high-intensity trapping beams will be shut off by a mechanical shutter leaving only the low-intensity beams to hold the atoms. Using an AOM, the low-intensity beams will be chopped on and off at a frequency of 1-2 kHz. At this chopping rate, the cold atoms will remain trapped by the low-intensity beams (falling less than 100 μm under the influence of gravity when the laser beams are off). Using a counter propagating probe beam (< 5 mm ϕ , ~ 250 μW) to continuously illuminate the trapped atoms and a PMT to measure the time-gated trap fluorescence signal, we hope to dramatically increase our detection sensitivity by reducing the scattered light background. We estimate that this method will have single atom detection sensitivity with a photon counting rate of ~ 1000 counts/sec/atom. An alternate approach is to develop a double MOT system where the first MOT is optimized for trapping efficiency and the second MOT is optimized for high detection sensitivity. Recently we have setup such a double MOT system and demonstrated the transfer of stable ^{85}Rb to the second MOT with a efficiency of $\sim 50\%$ using a push beam / magnetic guide approach¹⁷.

3. SUMMARY & OUTLOOK

We have demonstrated the trapping of 6 million ^{82}Rb radioactive atoms by optimizing the efficiency of each step in the trapping process. This represents two orders of magnitude improvement in the number of trapped radioactive atoms over previous work. Using gamma-ray and phase-sensitive fluorescence detection, we have obtained an overall efficiency of 3×10^{-4} which breaks out into an ionization and separation efficiency of $\sim 35\%$, a catcher foil and neutral atom release efficiency of $\sim 30\%$, and a trapping efficiency of $\sim 0.3\%$. Since we have obtained much higher trapping efficiencies in the past with stable species, these results indicated that the dryfilm coating used in this experiment was less than optimal. Further work is planned to improve the dryfilm coating and to increase the trapping efficiency by using larger diameter trapping beams. Other efforts will concentrate on improving our detection sensitivity beyond the $\sim 4,000$ atom level report by dramatically reducing the amount of scattered light. This developments will lead to the ultra-sensitive detection of ^{135}Cs and ^{137}Cs at the 10^4 atom level.

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