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Title: TRAPPING RADIOACTIVE ATOMS FOR BASIC AND APPLIED REAEARCH

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Trapping Radioactive Atoms for Basic and Applied Research

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We report on the trapping of radioactive atoms for a variety of nuclear, atomic, and applied physics investigations. To date we have trapped 5 different radioisotopes of rubidium and cesium ($^{82-84}$Rb + ^{135,137}Cs) using a magneto-optical trap (MOT) coupled to a mass separator. By optimizing the efficiency of this system, we have been able to trap as many as 6 million radioactive atoms and detect as few as 100. This technology is being applied in three different areas: (1) the parity-violating, beta-decay asymmetry measurement of polarized ^{82}Rb; (2) the study of ultracold fermionic ^{84}Rb atoms; and (3) the use of MOTs for the ultra-sensitive detection of selected radioactive species. Although all of these projects are in a formative stage of development, we highlight the progress that we have made in: (1) the trapping of ^{82}Rb atoms in double MOT system; (2) the hyperfine structure measurement of the $5P_{1/2}$ and $5P_{3/2}$ levels in ^{82}Rb; (3) the simultaneous trapping of ^{84}Rb and ^{87}Rb in overlapping MOTs; and (4) the first trapping and isotopic ratio measurement of ^{135}Cs and ^{137}Cs in a MOT.
Keywords: magneto-optical trap, radioactive atoms, hyperfine structure, laser spectroscopy, cold atomic collisions, ultra-sensitive detection.

1. Introduction

With the great advances in our ability to trap, cool and manipulate neutral atoms, we have a wonderful new tool with which to undertake high-precision and/or ultra-sensitive experiments. Herein we highlight the application of atom trapping technology to the trapping of radioactive atoms with experiments ranging from the study of electroweak interactions via beta-decay asymmetry measurements of spin-polarized ^{82}Rb and the investigation of ultracold Fermi-degenerate matter (^{84}Rb) to the ultra-sensitive detection of radioactive atoms (^{135}Cs/^{137}Cs). In a largely synergistic fashion, we have developed and refined a mass separator / magneto-optical trap (MOT) system which allows us to undertake these diverse experiments. A brief summary of our progress follows.

2. ^{82}Rb: Trapping, Transfer, and $5P_{1/2}$ and $5P_{3/2}$ Hyperfine Structure Measurements

Four decades have passed since the suggestion of Lee and Yang [1] that parity could be violated in the weak interaction, and the subsequent discovery of Wu *et al* [2] of parity violation in the beta decay of polarized ^{60}Co. Today the maximal violation of parity is incorporated into the standard model of electroweak interactions between leptons and quarks. Nonetheless, the origin of parity violation is unresolved and marks one of the central mysteries of modern physics. Consequently, low-energy physics experiments that exploit nuclear beta decay continue to offer a means to probe the fundamental origin of parity violation and, more generally, the helicity structure of electroweak interactions [3].

In Los Alamos, we are working to make an improved parity violation measurement using magnetically trapped and polarized ^{82}Rb ($t_{1/2}$ = 75 s). The basic approach is to first trap ^{82}Rb in a MOT, optically pump the atoms into a polarized state, and load them into a time-orbiting-potential (TOP) magnetic trap that will be used as a rotating beacon of spin-polarized nuclei to measure the parity violating positron-nuclear spin correlation coefficient (A). Our initial goal is to make a 1% measurement, but ultimately we hope to obtain a precision of ~0.1%.

In order to introduce the desired sample with minimum gas loading into the MOT, we have developed a mass separator – internal catcher foil technique as shown in Fig. 1. For the trapping of ^{82}Rb, we used a hot-cavity type ion source loaded with ~10 mCi of ^{82}Sr ($t_{1/2}$ = 25 d). As ^{82}Sr decays, its more volatile daughter, ^{82}Rb, is vaporized and ionized in the source. A $^{82}Rb^+$ beam is then extracted, mass-separated, and implanted into a thin ytterbium catcher foil with an efficiency of ~35%. After a suitable accumulation period, a small heating coil inductively heats the foil to temperatures of 750-850 °C to release the implanted sample as neutral atoms into the quartz trapping cell (~30% are released within 5 s). The MOT is formed by three retro-reflected circularly polarized laser beams which enter through each surface of the 75 mm cubic trapping cell and a set of anti-Helmholtz coils not shown in the figure. A reasonable trapping efficiency (~0.3%) is obtained by using large-diameter, high-intensity

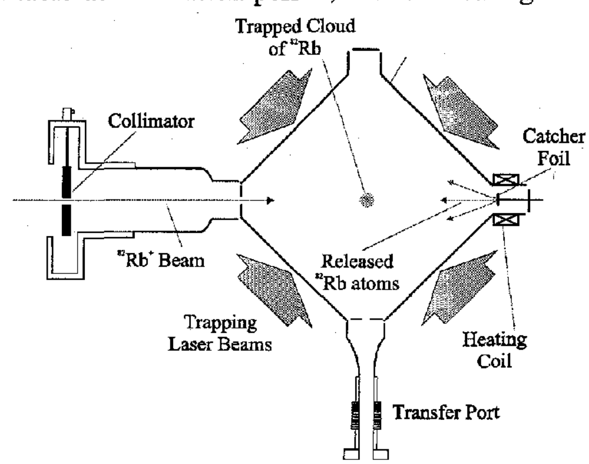

Figure 1. A schematic of the mass separator coupled MOT trapping cell.

trapping beams and by coating the inside of the trapping cell with a nonstick OTS dryfilm coating. In 1998 we reported [4] on the trapping of 6 million ^{82}Rb atoms in a MOT which broke existing records for the number of radioactive atoms trapped by two orders of magnitude.

By overlapping a separate probe beam with the trapped cloud, we measured the hyperfine structure of the $5P_{1/2}$ and $5P_{3/2}$ atomic levels as well as the isotope shift of the D_1 transition in ^{82}Rb (see Ref. [5] for details). This was accomplished by scanning the frequency of the probe laser across each transition which produced a modulation in the trapping signal. However because these measurements were done while the trap was on, careful measurements of the light shift (AC Stark shift) as a function of trapping light intensity were required (see Fig. 2). By extrapolating the data to zero trapping light intensity, we determined the $5P_{1/2}$ hyperfine constant to be A = 122.7 (1.0) MHz and the D_1 transition isotope shift of $\delta\nu_{82\text{-}85}$ = -150.8 (2.0) MHz. We also remeasured the $5P_{3/2}$ F=5/2 to F'=1/2 and 3/2 hyperfine splitting to be 90.3 (1.5) MHz in agreement with previous results of 89.3 (9.0) MHz [6]. (Note that because the splitting between the $5P_{3/2}$ F=1/2 and F=3/2 hyperfine levels is only 0.1 MHz [6], we were unable to resolve these two levels.) Not only do these measurements enhance our understanding of the ^{82}Rb atomic structure, but this spectroscopic information is needed for the optical pumping (polarizing) step and as part of the m-state population (polarization) determination in the β-asymmetry experiment.

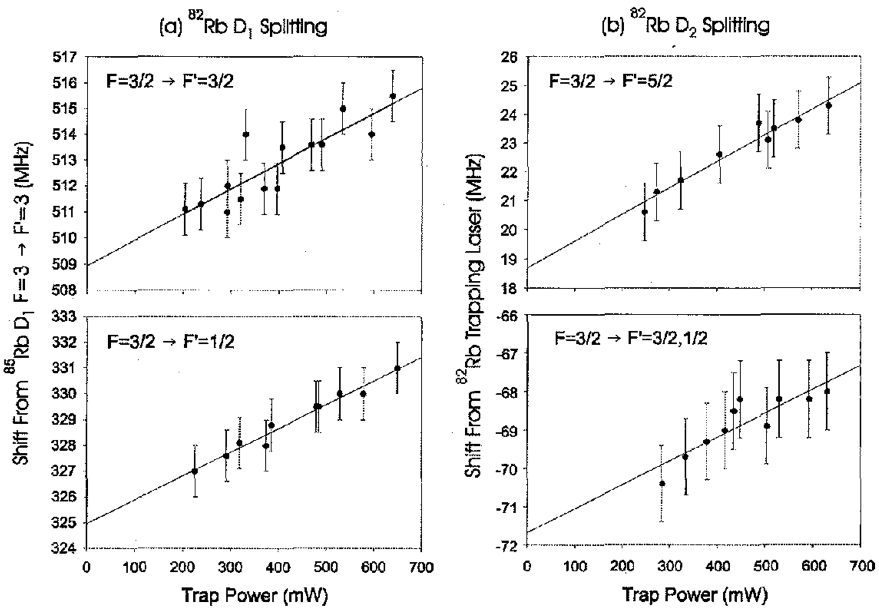

Figure 2. The ^{82}Rb light shifts for (a) the $5S_{1/2}$, F=3/2 -> $5P_{1/2}$, F' = 3/2 and F'=1/2 D_1 transitions and (b) the $5S_{1/2}$, F=3/2 -> $5P_{3/2}$, F' = 5/2 and F'=3/2+1/2 D_2 transitions as a function of trapping laser power.

Good progress has also been made in assembling and testing a double MOT + TOP trap system. In particular, we have been successful in transferring ^{82}Rb from one MOT to a second MOT with an efficiency of ~30% using a laser push beam / magnetic guide approach. And because the pressure in the second MOT was superior to that of the first, atoms could be accumulated in the second MOT by running in multi-shot transfer mode [7]. Once trapped in the second MOT, the next step is to load the atoms into the TOP trap. Using stable ^{85}Rb and a sequence of MOT trapping/fluorescence measurement, optical molasses cooling, magnetic trapping using either a quadrapole (Quad) field or a quadrapole + rotating bias field (TOP) configuration, and then MOT retrapping/fluorescence measurement, we obtained preliminary magnetic trap loading efficiencies of ~20% (Quad) and ~15% (TOP) with trap lifetimes of ~100 s (Quad) and ~70 s (TOP), respectively. By implementing the optical pumping step and further optimizing the TOP conditions and molasses cooling step, we hope to achieve loading efficiencies approaching 50% with trap lifetimes in excess of 150 s. These optimization studies and initial measurements with a first-generation β-telescope are currently underway.

3. ^{84}Rb: Trap Lifetime Measurements With and Without ^{87}Rb

With the exciting developments involving dilute alkali Bose-Einstein condensates (BECs), there is a growing interest in cooling dilute Fermi-Dirac (half integer total spin F) systems to the quantum degenerate regime. For fermionic atoms in identical spin states, s-wave collisions are forbidden by antisymmetry and p-wave collisions vanish at low temperatures, which eventually limits the effectiveness of evaporative cooled. One method of avoiding these limitations, sympathetic cooling using two different spin states, has already shown promising results in ^{40}K [8]. However, there are only two fermionic alkali isotopes, ^{6}Li and ^{40}K, that are stable and a wider set of systems to study is desired. An intriguing alternative is the possibility of trapping radioactive atoms and cooling them sympathetically with cold source of bosonic atoms. Recent calculations [9] show that ^{84}Rb ($t_{1/2}$ = 33 d) is a good fermionic candidate because of its large and positive scattering length with ^{87}Rb which should enable efficient sympathetic cooling. Consequently, we have begun an investigation to trap ^{84}Rb and sympathetically cool them down to the Fermi degenerate regime with a ^{87}Rb BEC.

Using the same method as outlined for ^{82}Rb, we have demonstrated the trapping of ^{84}Rb [10]. Trap lifetimes have been measured to explore trap loss mechanisms and their consequences in the magnetic trap loading and cooling sequence. When more than 10^5 ^{84}Rb atoms are initially trapped, we measure a double exponential decay for the trap lifetime. The short-lived component (τ_1 ~ 13 s) is interpreted in terms of light-assisted collisional losses, while the long-lived component (τ_2 ~ 60 s) is limited by collisions with the hot background gas.

By overlapping two MOTs, one trapping ^{84}Rb and the other trapping ^{87}Rb, we have also investigated mixed-isotope light-assisted losses (see Fig. 3). From the lifetimes of the short-lived component measured with and without an overlapping cloud of ^{87}Rb, we determined a homonuclear light-assisted collisional loss rate of $\beta_{84,84}$ = 3 (1) x 10^{-12} cm^3s^{-1} and a mixed-isotope loss rate of $\beta_{84,87}$ = 5 (3) x 10^{-13} cm^3s^{-1} under our particular trapping conditions [10]. The homonuclear loss rate is similar to those measured for ^{85}Rb or ^{87}Rb under similar conditions [11], however, the mixed isotope loss rate is 6x smaller. This can be understood in terms of the lower light field used to trap ^{87}Rb which decreases the probability that ^{87}Rb would be found in an excited state. Consequently, we have demonstrated a trapping solution for which there is negligible additional trap loss for ^{84}Rb due to the presence of ^{87}Rb, proving that a ^{84}Rb/^{87}Rb mixture can be readily loaded for the sympathetic cooling experiment.

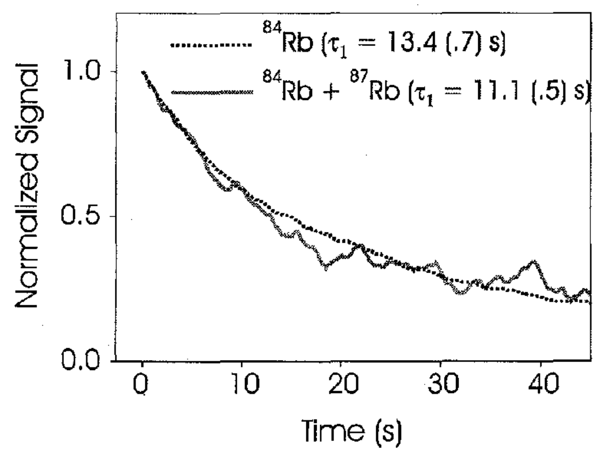

Figure 3. Normalized trap lifetime measurements for ^{84}Rb without (dotted line) and with (solid line) an overlapping cloud of ^{87}Rb. Numerical fits of the data yield the short-lived components (τ_1) for each case.

4. ^{135}Cs / ^{137}Cs: Ultra-Sensitive Detection

Examining the capabilities of magneto-optical traps, one finds many desirable features which are well matched to the needs of ultra-sensitive detection. These include its high-selectivity (trapping involves multi-photon, near-resonant absorption), high-sensitivity (each trapped atom scatters ~10^7 photons/s), and large dynamic range (up to ~10^9 atoms can be trapped). With the trapping of many different species already achieved (and others under development) and with the ability to detect a single trapped atom demonstrated [12], magneto-optical traps are a natural candidate for ultra-sensitive detection. As a good test case with practical applications in environmental and nonproliferation monitoring, we have applied the mass separator / MOT technique described above for the ultra-sensitive detection of ^{135}Cs and ^{137}Cs.

Shown in Fig. 4 are the trapping signals that we have obtained after implanting, releasing and trapping ^{135}Cs and ^{137}Cs. Through a set of sequential implantation, release, trap and detect measurements using a known amount of implanted atoms (as measured by current integration) for each isotope, we have demonstrated our first isotopic ratio measurement. By averaging five ~20,000 trapped atoms "shots", we obtained a normalized isotopic ratio $^{135}Cs/^{137}Cs = 1.21$ $(0.10)^{stat}$ $(0.30)^{sys}$. With improvements in the laser frequency and power stabilization and automated switching between isotopes, we will be able to reduce our systematic errors to the ~5% level. Moreover, we will greatly improve our sensitivity and statistical limitations by using a zirconium implantation foil that gives better release efficiency (~60%), a more efficient SC-77 dryfilm coating and by transferring atoms to a second measurement MOT where scattered light problems are effectively eliminated. Magneto-optical traps hold great promise as a new tool for ultra-sensitive detection.

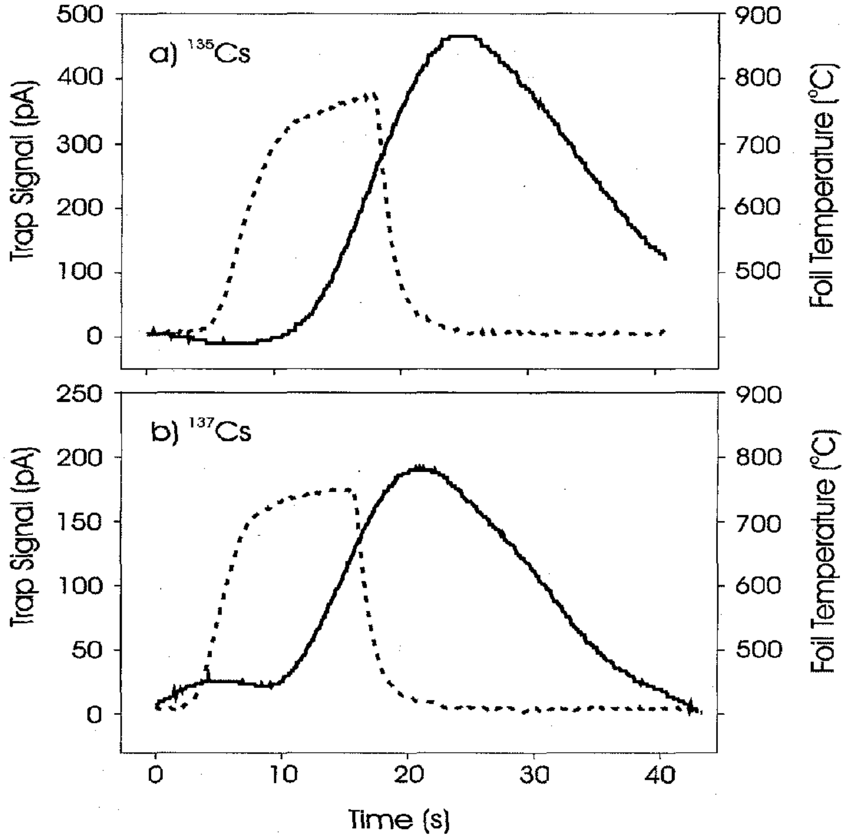

Figure 4. The trapping and detection of (a) ~50,000 ^{135}Cs atoms and (b) ~20,000 ^{137}Cs atoms in a MOT. The trapping signal (solid line) is derived from the trap fluorescence using a trap modulation / lock-in detection technique. The catcher foil temperature (dashed line) is measured with an optical pyrometer.

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