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WEAK INTERACTION MEASUREMENTS WITH OPTICALLY TRAPPED RADIOACTIVE ATOMS

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Abstract

This is the final report of a three-year, Laboratory-Directed Research and Development (LDRD) project at the Los Alamos National Laboratory (LANL). The goal of this project is to apply the latest in magneto-optical and pure magnetic trapping technology to concentrate, cool, confine, and polarize radioactive atoms for precise electroweak interaction measurements. In particular, we have concentrated our efforts on the trapping of ^{82}Rb for a parity-violating, beta-asymmetry measurement. Progress has been made in successfully trapping of up to 6 million ^{82}Rb ($t_{1/2}$=75 s) atoms in a magneto-optical trap coupled to a mass separator. This represents a two order of magnitude improvement in the number trapped radioactive atoms over all previous work. We have also measured the atomic hyperfine structure of ^{82}Rb and demonstrated the MOT-to-MOT transfer and accumulation of atoms in a second trap. Finally, we have constructed and tested a time-orbiting-potential magnetic trap that will serve as a rotating beacon of spin-polarized nuclei and a beta-telescope detection system. Prototype experiments are now underway with the initial goal of making a 1% measurements of the beta-asymmetry parameter **A** which would match the world's best measurements.

Background and Research Objectives

Four decades have past since the first suggestion by Lee and Yang [1] that parity (or mirror reflection symmetry) could be violated in weak interactions, and the subsequent discovery by Wu *et al* [2] of parity violation in the beta decay of polarized ^{60}Co. Today, parity violation as well as charge conjugation symmetry are described by a universal (V-A) interaction between leptons and quarks. Nonetheless, the standard model offers no fundamental understanding into the origin of these symmetries and how they become broken at the energy scales probed by modern experiments. Within the framework of

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modern gauge theories, an underlying theme speaks of spontaneously broken symmetries wherein discrete symmetries, such as parity, are restored at higher energy scales. 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 the weak interaction [3].

Parity violation is manifest in nuclear beta decay as an asymmetry in the angular correlation of the emitted beta particles relative to the spin orientation of the parent nucleus. Pure Gamow-Teller (GT) transitions offer a direct route to study this asymmetry since such transitions proceed solely through axial-vector couplings which are solely responsible for parity violation. Historically, however, studies of pure GT transitions have been limited for lack of good candidates, namely reasonably long-lived species appropriate for off-line sources and by the fact that many of the pure GT candidates are hindered (as opposed to allowed) transitions. In the few cases where good candidates have been realized, modern experiments are limited in precision due to the fact that solid samples are employed with limited nuclear polarization. It is now possible, however, to envision a new generation of pure GT experiments that exploit the latest developments in optical and magnetic trapping.

At Los Alamos, we are working to exploit magnetically trapped ^{82}Rb in a new generation of fundamental symmetry experiments. ^{82}Rb, a pure and allowed GT beta decaying nucleus, has the appropriate atomic structure and lifetime (75 seconds) to be trapped in a magneto-optical trap (MOT). A prototype experiment has been mounted to measure the positron-spin correlation coefficient (**A**) from polarized ^{82}Rb in a magnetic time-orbiting-potential (TOP) trap. In this case, an essentially massless source of highly-polarized atoms are confined to a localized cloud of ~1 mm in diameter and the direction of an applied continuously rotating bias field serves to align and rotate the nuclear spin in the equatorial plane. Consequently, this rotating beacon of spin-polarized ^{82}Rb nuclei can be exploited to measure the parity-violating correlation as a continuous function of the positron energy and emission angle relative to the nuclear spin orientation. Our initial goal is to undertake a 1% measurement of the beta-asymmetry **A** coefficient which would match the world's best measurements. Beyond this we intend to push the precision down to the 0.1% level and add a recoil detector to enable additional neutrino correlation measurements to further test and refine our understanding of electroweak interactions in nuclei.

Importance to LANL's Science and Technology Base and National R&D Needs

Since the demonstration of laser cooling [4] and magneto-optical trapping [5] of neutral atoms, there has been a growing interest in exploiting this new technology for a variety of fundamental and applied applications in atomic and nuclear physics. On the fundamental science side, we are pursuing a variety of electroweak interaction measurements: atomic parity nonconservation in Cs and Fr radioisotopes, beta-asymmetry measurements in ^{82}Rb (the focus of this work), and a possible electric dipole moment measurements in ^{225}Ra. In the atomic physics arena, we have just begun an experiment to produce and study cold Fermionic (half-integer total spin) ^{84}Rb atoms at near absolute zero temperatures where the system becomes Fermi degenerate. As an application we are developing the magneto-optical trap as a new ultra-sensitive analysis method for the detection of selected radioactive isotopes of interest to nuclear nonproliferation and environmental pollution concerns. All of these projects have been developed in a synergistic fashion so that more rapid progress could be made collectively compared to what would be possible one project at a time.

There are several reasons why this research is important to the Laboratory. This research program builds on our existing multi-disciplinary expertise in atomic and nuclear science, laser technology, ultra-sensitive detection, mass separation, and our ability to produce and handle radioactive materials. Taken together we have built up a unique capability to trap, detect, and carry out forefront R&D with radioactive atoms. This work is well aligned with the Science and Technical Base (STB) and National and International Security (NIS) program office missions, the core competency area of Nuclear Science, Plasma & Beams, as well as the overall mission of the Laboratory to reduce the nuclear danger to the nation. This work involves innovative science with real-world applications that expand our capabilities and strengthen our science and technology base.

Scientific Approach and Accomplishments

An overview of the ^{82}Rb β-asymmetry experiment is shown in Figure 1. It involves a mass separator to selectively implant ^{82}Rb into a catcher foil which is located within the trapping cell of a MOT. The ^{82}Rb is fed from a ~9 mCi sample of ^{82}Sr that is placed inside the ion source of the mass separator. Upon heating, the ^{82}Rb diffuses out of the sample and is selectively ionized using an electron-bombardment-heated, thermal ion source. Singly charged ions are extracted from the source, accelerated to 20 keV, mass separated, and focussed through a 5-mm diameter opening of the trapping cell and implanted into a thin catcher foil of yttrium-coated tungsten located within the trapping cell. The foil is subsequently (or continuously) heated to temperatures of 700-800 °C using an inductive-heating coil located outside the trapping cell.

Upon heating the implanted ^{82}Rb atoms diffuse out of the catcher foil and are trapped in a standard MOT composed of three orthogonal, circularly-polarized laser beams that are retro-reflected back through the cell. Anti-Helmholtz coils are used to provide a quadrupole field gradient of ~7 G/cm. A Ti:sapphire laser tuned to the D_2 line of Rb at 780 nm provides the trapping laser beams. Acoustic-optical modulators are used to shift the trapping frequency from the D_2 transition in stable ^{85}Rb using a FM sideband locking technique. An electro-optic modulator (EOM) is used to provide repumping light. To improve the trapping efficiency, the inside surface of the trapping cell is coated with a nonstick coating of octadecyltrichlorosilane dryfilm. Once trapped the fluorescing cloud of atoms can be seen with a simple CCD camera. By chopping the EOM, the fluorescence from the trapped cloud can be modulated. Improved detection sensitivity is obtained by using a photomultiplier tube with a lock-in amplifier to demodulate the trapping signal.

In our initial work (1), we were able to trap 6 million ^{82}Rb atoms in pulsed heating of the catcher foil and 3 million atoms in the continuous heating mode with trap lifetimes of 90 s and 30 s, respectively. This represents a two orders of magnitude improvement in the number of trapped atoms over all previous radioactive atom trapping work. Using gamma-ray counting we were able to determine that 35% of the original activity in the source was ionized and implanted into the catcher foil and of that 30% was released from the foil upon heating to 750 °C. Based on a comparison of the number of trapped atoms determined from the fluorescene trapping signal and the number of atoms in the source, we determined an overall efficiency of ~3×10^{-4}. This gives a trapping efficiency of ~0.3% which is a factor of 20 below our expectations based on our previous dryfilm-coated cells work (2). Through gamma counting we learned that the quality of the dryfilm coating was poor and future coatings should help to improve this situation. In large part we attribute the success of this work to the development of a more efficient method of introducing the sample into the MOT with minimal gas loading using the ion implantation and release method with a catcher foil located inside the trapping cell.

Taking advantage of this large number of trapped atoms, we used an additional probe laser to measure the hyperfine structure of the $5P_{1/2}$ and $5P_{3/2}$ atomic states as well as the isotope shift of the D_1 transition in ^{82}Rb (3). 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. By extrapolating these data to zero trapping light intensity, we determined the $5P_{1/2}$ hyperfine constant to be A = 122.7 (1.3) MHz and the D_1 transition isotope shift of $\delta\nu_{82\text{-}85}$ = -150.8 (2.5) MHz. We also remeasured the $5P_{3/2}$ F=5/2 to F'=1/2 and 3/2 hyperfine splitting to be 90.3 (2.0) MHz in agreement with previous results (6) of 89.3 (9.0) MHz. (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.) The accuracy of this trap and probe method was further verified by performing analogous measurements with trapped ^{85}Rb whose atomic structure is well know from saturated absorption measurements. Not only do these measurements enhance our understanding of the ^{82}Rb atomic structure, but this spectroscopic information is needed for both the optical pumping (polarizing) step and nuclear polarization determination in the β-asymmetry experiment.

After trapping the radioactive atoms in the MOT, the next step in the β-asymmetry experiment is to transfer the atoms to a second MOT using a laser push beam and magnetic guide approach [7]. Typical results from this trap, transfer, and retrap sequence are shown in Figure 2. After optimization we obtained a single-shot transfer efficiency of ~50%. Because the second MOT has a much better vacuum than the first MOT, the lifetime in the second MOT was considerable better (~500 s in MOT II compared to ~30 s in the MOT I). This long lifetime made it possible to accumulate atoms in the second MOT by running in a multi-shot transfer mode. These results are described in our most recent publication (4).

The next steps in undertaking the β-asymmetry experiment are: (a) the optical pumping (polarization) of the atoms into the desired weak-field-seeking, spin-aligned magnetic substate; (b) the loading of the time-orbiting-potential (TOP) magnetic trap [8]; and (c) the detection of the positrons. For the most part, the first two steps will employ techniques that have already been developed, however, in our case a premium will be placed on optimizing the efficiency of the loading process and in maintaining a high degree of nuclear polarization once trapped. Both are critical to the success of our experiment. As of this time, we have done extensive modeling of the TOP trap performance as rotating source of spin–polarized nuclei, constructed our own TOP trap system, and demonstrated that it works with stable rubidium atoms. An initial trapping lifetime of ~70 s was obtained with little optimization and without employing optical pumping we obtained a ~15% TOP trap loading efficiency. We now know how to improve the system further and are prepared to implement the optical pumping step. A first-generation positron telescope has been extensively modeled and tested. Everything is now in place (see Figure 3) and we are looking forward to loading our first samples of polarized ^{82}Rb into the TOP trap and beginning our first beta-asymmetry measurements. As mentioned earlier, our initial goal is to perform a 1% measurement of the beta-asymmetry **A** coefficient which would match the world's best measurements. Beyond this we intend to push the precision down to the 0.1% level and add a recoil detector to enable a variety of beta-neutrino-spin correlations that will further test and refine our understanding of electroweak interactions in nuclei.

Publications

1. Guckert, R., Zhao, X., Crane, S.G., Hime, A., Taylor, W.A., Tupa, D., Vieira, D. J., and Wollnik H., "Magneto-Optical Trapping of Radioactive ^{82}Rb Atoms," Phys. Rev. **A58**, R1637-R1640 (1998).

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4. Vieira, D.J., Brice, S.J., Crane, S.G., Goldschmidt, A., Guckert, R., Hime, A., Tupa, D., and Zhao, X., "Trapping ^{82}Rb for β-Decay Parity Violation Measurements," Trapping Charged Particles and Fundamental Physics, AIP Conf. Proc. **457**, 143-147 (1998).

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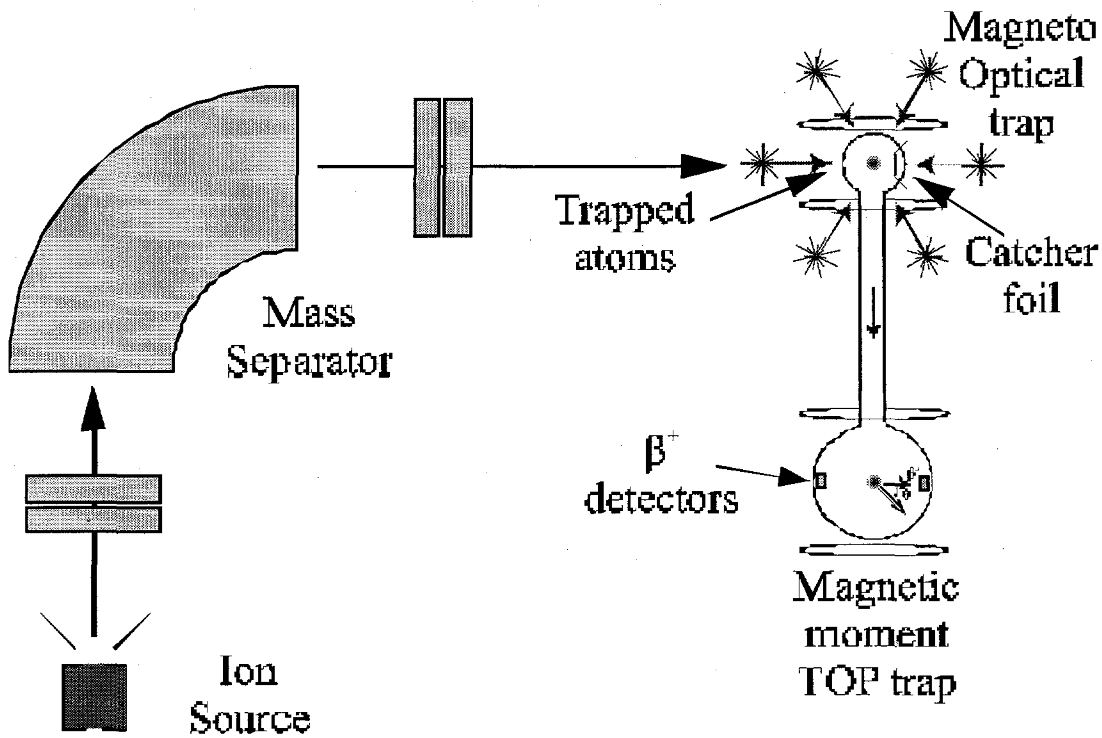

Figure 1: General layout of the ^{82}Rb beta-asymmetry experiment.

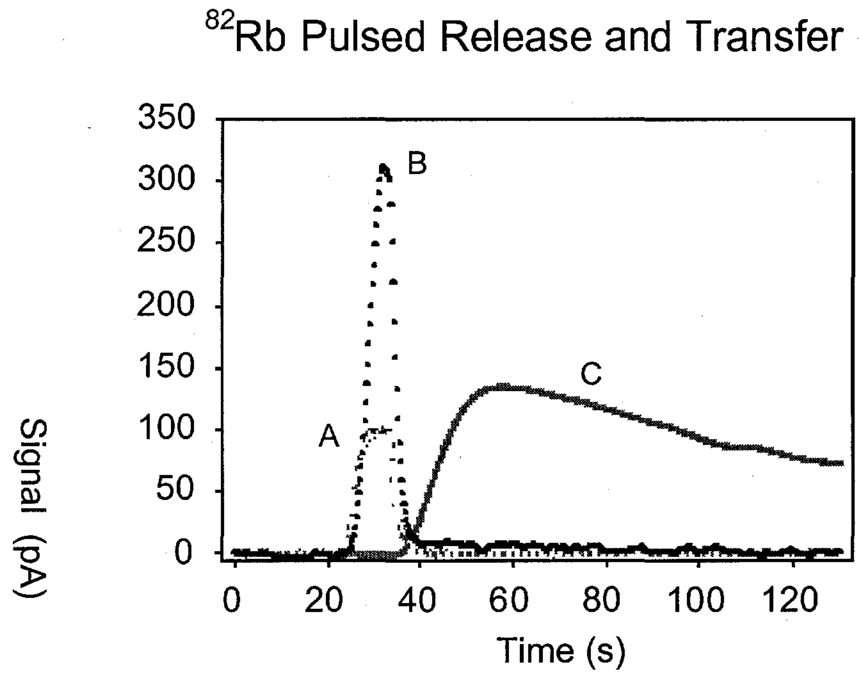

Figure 2: Pulsed release, trapping and transfer of ^{82}Rb in a double MOT system. Trace A gives the optical pyrometer readout of the foil temperature which is rapidly heated to a temperature of 700 °C for ~10 s. Trace B shows the lock-in trapping signal from the first MOT. At the ~35 s mark, the first MOT is switched off and the atoms are rapidly "pushed" using another laser beam over to the second MOT where they are retrapped. Trace C shows the MOT2 lock-in trapping signal.

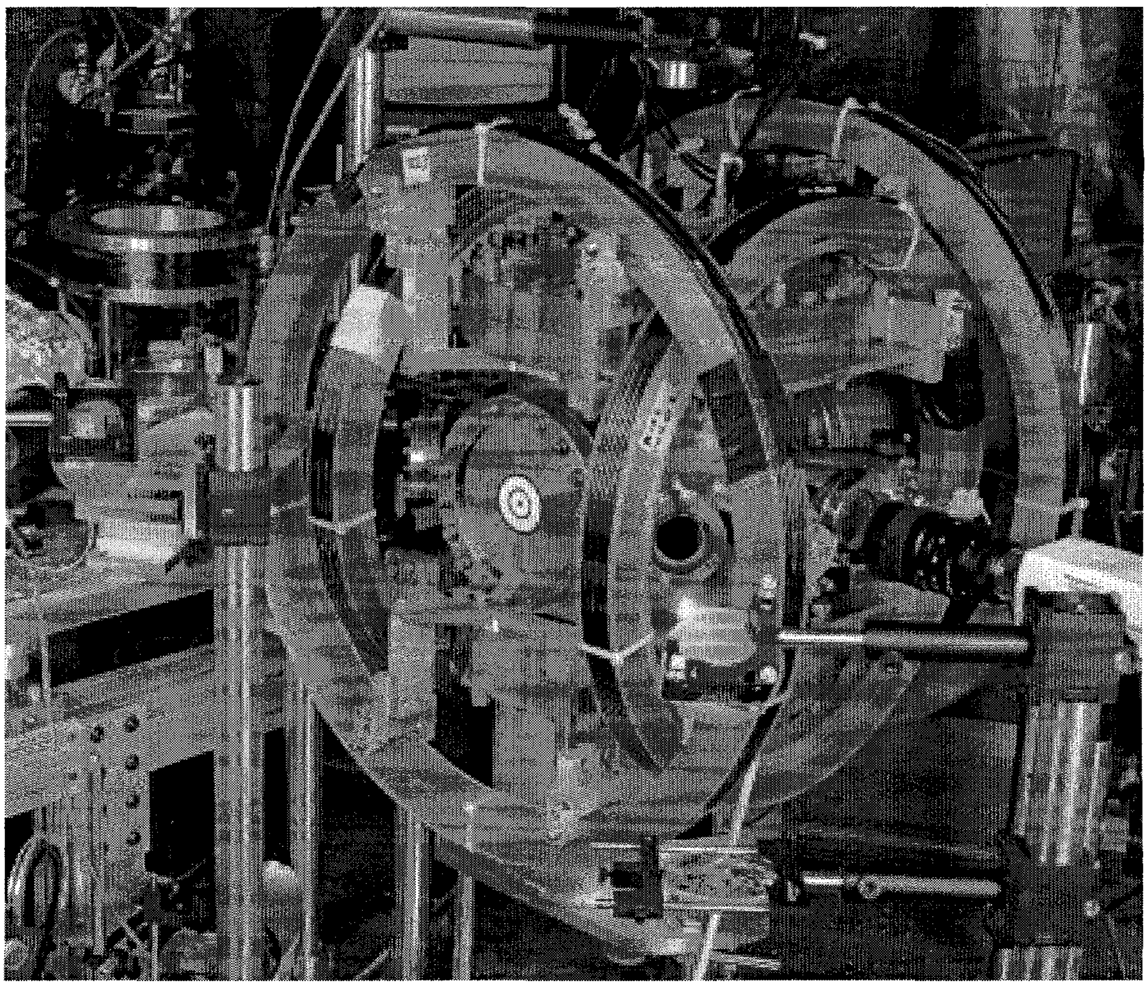

Figure 3: Photograph of the magneto-optical trap (MOT) plus the time-orbiting potential (TOP) trap setup for measuring the parity-violating, beta-decay asymmetry of ^{82}Rb. The second MOT and TOP trap chamber are surrounded by large bias coils. The beta detector will be installed on the flange marked with a bullseye.