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Magneto-optical trapping of radioactive ^{82}Rb atoms

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We report the successful trapping of 6×10^6 ^{82}Rb ($t_{1/2}=75$ s) atoms with a trap lifetime of ~30 s in a magneto-optical trap that is coupled to an off-line mass separator. Efficient sample introduction is achieved by implanting ^{82}Rb ions into a small yttrium catcher foil located inside the trapping cell. Upon heating, the radioactive atoms are released from the foil and trapped without significant gas loading. This advancement makes a variety of high-precision electroweak interaction experiments possible, including the measurement of β-decay correlations associated with spin-polarized ^{82}Rb nuclei. [S1050-2947(98)50309-5]

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Since the demonstration of laser cooling [1] and magneto-optical trapping [2] of neutral atoms, there has been a growing interest in exploiting this technology in atomic, nuclear, and particle physics. Trapped radioactive atoms will enable a new generation of fundamental symmetry experiments, including nuclear β decay, atomic parity nonconservation, and the search for parity and time-reversal violating electric dipole moments. In particular, trapped β-decaying species will enable a new set of high-precision measurements that will elucidate our understanding of the helicity structure of the electroweak interaction and aid in the search of physics beyond the standard model. In many ways, trapped radioactive atoms make an ideal source for β-decay correlation measurements, since relatively intense sources can be harnessed that are effectively massless, pointlike, and nearly 100% spin polarized. Consequently, systematic effects associated with electron scattering effects and polarization uncertainties can be greatly reduced if not eliminated altogether.

It is well known that pure Gamow-Teller transitions, such as those available in ^{82}Rb, are useful candidates to study parity violation, since these transitions are driven solely by the axial vector coupling between leptons and quarks. Given that trap lifetimes can be achieved that are comparable to the 75-s half-life of ^{82}Rb, this species is an excellent choice for a magneto-optical trap (MOT) based experiment. Moreover, since ^{82}Rb is fed by the long-lived ^{82}Sr ($t_{1/2}=25$ d) parent, this experiment can be performed off-line (i.e., not associated with an accelerator).

Although several radioactive species have been trapped [3–7], the current challenge is to trap sufficient numbers of radioactive atoms to undertake a meaningful measurement. For example, one would need to detect approximately 150 000 β-decay events in order to determine the β-particle–nuclear spin correlation function of polarized ^{82}Rb to a precision of 1%. Given a realistic detection geometry, these counting statistics could be achieved in one hour with 10^6 trapped atoms. In a multiple-day experiment, a 0.1% measurement could be obtained. Until this work, as many as 40 000 radioactive atoms have been trapped [8]. Herein we report on the development of a sample introduction method involving the ion implantation and heated release of mass-separated atoms using a catcher foil located inside the trapping cell of a MOT. This has resulted in the trapping of over 10^6 radioactive atoms.

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 precipitated as $SrCO_3$ and loaded into a tantalum crucible. The crucible is then installed into a thermal ion source of the hot-cavity type [9] 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 γ 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 γ-decay rate while the ^{85}Sr γ-decay 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 [10]. $^{82}Rb^+$ 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. 1). The ions then enter the quartz trapping cell through a 5-mm ϕ 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 measured on the foil while minimizing the current measured on the collimator. Typical ion beam intensities of 1×10^8 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 foil. By comparing the 776-keV count rates at the source and foil positions, we find that $\sim35\%$ of the ^{82}Rb produced in the source is ionized, separated, and implanted into the foil. A small rf coil located outside the cell is used to inductively heat the foil to temperatures of 750–850 °C to release the implanted ^{82}Rb as a vapor within the cell. The cell is coated with a nonstick coating of octadecyltrichlorosilane (OTS) dry film to enhance the trapping probability [11].

The magneto-optical trap is formed by six circularly

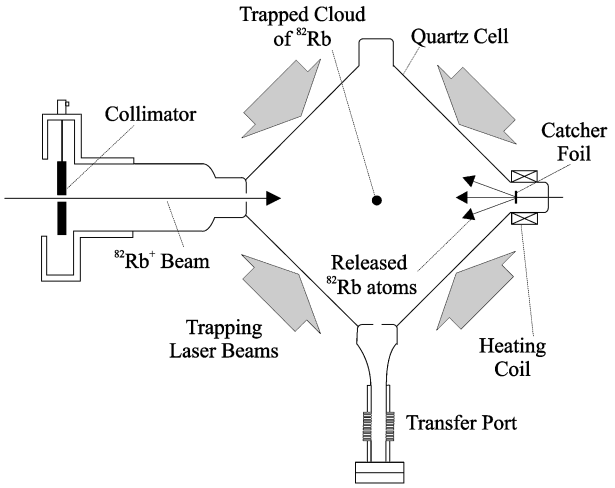

FIG. 1. A schematic of the ^{82}Rb trapping cell. The mass-separated ^{82}Rb ion beam passes through a collimator (5 mm inside diameter) and the opening (5 mm ϕ) of the OTS dry-film-coated quartz cell (a 75-mm cube) is implanted into an yttrium catcher foil (6 mm ϕ). The coil inductively heats the foil to temperatures of 750–850 °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.

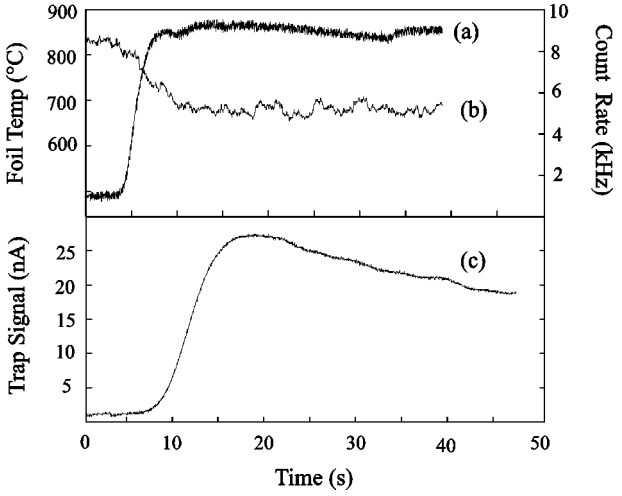

FIG. 2. Pulsed release and trapping of ^{82}Rb. The top figure shows the foil temperature [(a) left axis], and 776 keV γ-count rate [(b) right axis] of ^{82}Rb accumulated and then released from the foil upon heating. The modulated fluorescence trapping signal as measured with a photomultiplier and a lock-in amplifier is shown in (c). The lock-in amplifier has an integration time constant of 3 s.

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 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 $5S_{1/2}$, $F=3\rightarrow 5P_{3/2}$, $F'=3,4$ crossover transition of ^{85}Rb using a FM sideband technique [12]. A double-pass acoustic optical modulator (AOM) driven at 268 MHz provides the 536-MHz frequency shift needed to excite the $5S_{1/2}$, $F=3/2\rightarrow 5P_{3/2}$, $F'=5/2$ trapping transition in ^{82}Rb [13]. In order to repump atoms that fall into the $5S_{1/2}$, $F=1/2$ ground state, sidebands are added to the trapping beam by using an electro-optical modulator (EOM) tuned to 1.470 GHz, which excites the $5S_{1/2}$, $F=1/2\rightarrow 5P_{3/2}$, $F'=3/2$ transition. For trapping ^{85}Rb, however, the EOM is tuned to 1.463 GHz and the second upper sideband generates the repump light. Trapped atoms are detected by chopping the EOM at 4 kHz that modulates the trap fluorescence signal. A 58-mm $f/1.4$ lens images the trap fluorescence onto a photomultiplier tube 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. In addition, a charge-coupled-device (CCD) camera with an $f/1.2$ 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. 2 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. 2, 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.

In the bottom half of Fig. 2, the lock-in trapping signal is plotted as a function of time. A strong trapping signal is evident with a rise time 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. In Fig. 3, we show the trap fluores-

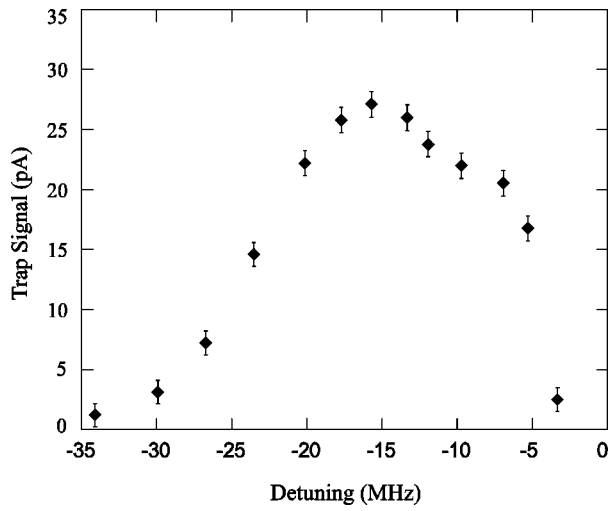

FIG. 3. ^{82}Rb trapping signal measured with a photodiode as a function of trapping laser detuning under continuous heating of the foil. The zero on the detuning scale corresponds to the center of the $5S_{1/2}, F=3/2\rightarrow 5P_{3/2}, F'=5/2$ transition in trapped ^{82}Rb. Relative frequency uncertainties, as limited by the laser locking system, are estimated to be 1 MHz.

cence signal as a function of laser detuning for continuous foil heating. 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 attribute the signal to trapped ^{82}Rb.

The center frequencies of the trapping transitions in trapped ^{82}Rb and ^{85}Rb were determined by using a separate probe beam of 80 μW and a 5-mm ϕ which is split off from the main trapping beam and frequency shifted using two AOMs arranged in series, giving a net shift of -25 to 25 MHz. The second AOM is chopped on and off to modulate the probe beam at a rate of 7 kHz. When the circularly polarized, counterpropagating probe beam is overlapped with the trapped cloud, the result is to partially modulate the trapping fluorescence signal. Maximum modulation in the trapping signal occurs when the probe beam is on resonance. In this way, we determine the trap detuning to be -17 ± 1 MHz for both ^{82}Rb and ^{85}Rb. The resulting frequency difference between the $5S_{1/2}$, $F=3/2 \rightarrow 5P_{3/2}$, $F'=5/2$ transition in ^{82}Rb and the $5S_{1/2}$, $F=3 \rightarrow 5P_{3/2}$, $F'=4$ transition in ^{85}Rb is thus measured to be 536 ± 5 MHz, in agreement with the previous measurement of 540 ± 7 MHz [13].

The number of trapped atoms is deduced from the trapping signal using a calibrated photodiode, yielding $(6 \pm 2) \times 10^6$ and $(3 \pm 1) \times 10^6$ trapped ^{82}Rb atoms for the pulsed and continuous operation, respectively. From CCD image measurements of the cloud size [full width at half maximum (FWHM)], we obtain a density of $\sim 10^{10}$ atoms/cm^3, consistent with reradiation limited densities reported in the literature [14]. Calculating the overall trapping efficiency as $\eta_{total} = N_{trap}/(\tau_{trap} A_{Rb})$, where $N_{trap} = 3 \times 10^6$ is the number of trapped atoms, $\tau_{trap} = 30$ s is the lifetime of the trap, and $A_{Rb} = 3 \times 10^8$ disintegrations per second is the ^{82}Rb activity in the ion source, we obtain an overall efficiency of $\sim 3 \times 10^{-4}$. Breaking this down stepwise, we obtain an ionization and separation efficiency of 35%, a catcher foil release efficiency of 30% at 750 °C, and a trapping efficiency of $\sim 3 \times 10^{-3}$.

Using a third collimated NaI counter, we attempted to measure the number of trapped ^{82}Rb atoms through the detection of 776-keV γ rays. We failed in this respect, finding a constant count rate with or without a ^{82}Rb cloud present that indicates 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 coating performance is less than optimal when compared to previous work [11,15]. 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 γ-ray monitoring technique to select the best type of dry-film coating.

Given the success in trapping large numbers of ^{82}Rb, we plan to transfer the atoms to a second, low-background MOT using a laser push and magnetic guide approach [16]. After retrapping, the atoms will be optically pumped into a spin-aligned magnetic substate and loaded into a time-orbiting-potential (TOP) trap [17]. Presently under construction, this pure magnetic trap will be used as a rotating beacon of spin-polarized ^{82}Rb nuclei. Exploiting the pointlike geometry and rotating spin features of the TOP trap, we will measure the β-particle–nuclear spin asymmetry function as a continuous function of β energy and angle between the β particle and nuclear spin alignment vector using a single (or small set of) positron detector(s). Not only is the symmetry of this system attractive from the standpoint of reduced systematic errors, but the complete mapping of the parity-violating correlation may enable the simultaneous extraction of recoil order corrections, such as the weak magnetism term, which are expected to lead to small deviations in the asymmetry ($\cos\theta$) and anisotropy ($\cos^2\theta$) terms. With a proof-of-principal measurement in hand, we will then include the detection of β-recoiling nuclei to reconstruct the neutrino degrees of freedom relevant for the simultaneous measurement of the neutrino-spin asymmetry and the electron-neutrino correlation functions.

In summary, this work reports the trapping of over 10^6 radioactive ^{82}Rb atoms in a MOT coupled to an off-line mass separator. This represents a two orders of magnitude improvement in the number of trapped atoms over previous work. Essential to this success is the development of a more efficient method of introducing the sample into the MOT with minimal gas loading using an ion implantation and internal catcher foil release method. Combined with other recent atom trapping developments, a new generation of high-precision β-decay correlation experiments is foreseen.

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