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# Trapping radioactive $^{82}$Rb in an optical dipole trap and evidence of spontaneous spin polarization

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Optical trapping of selected species of radioactive atoms has great potential in precision measurements for testing fundamental physics such as the electric dipole moment, atomic parity nonconservation, and parity-violating $\beta$-decay correlation coefficients. We report on the trapping of $10^4$ radioactive $^{82}$Rb atoms ($t_{1/2}$ =75 s) with a trap lifetime of ~55 s in an optical dipole trap. Transfer efficiency from the magneto-optical trap is ~14%. We further report evidence of spontaneous spin polarization of the atoms in optical dipole trap loading. These advancements are an important step toward a new generation of precision nuclear-spin–$\beta$-emission direction correlation measurements with polarized $^{82}$Rb atoms.

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Recent advancements in atom trapping have resulted in exciting breakthroughs in atomic, molecular, and optical physics, with the realization of diverse phenomena such as Bose-Einstein condensation [1,2], Fermi-degenerate gases [3], fermion superfluidity [4], ultracold plasmas [5,6], and atomic clocks.

The technique of trapping ultracold atoms also has great potential for precision measurements because it can provide an ideal sample in a well-controlled environment. There are several attempts and ongoing efforts in $\beta$-recoil measurements on metastable $^{38m}$K($t_{1/2}$=0.9 s) [7,8] and $^{21}$Na($t_{1/2}$ =21 s) [9,20] in a magneto-optical trap (MOT), $\beta$ spin correlation of $^{82}$Rb in a time-averaged orbiting potential (TOP) trap [10], Fr parity nonconservation (PNC) [11,12], and Ra electric dipole moment (EDM) [13,14]. Yet no group has demonstrated the trapping of short-lived radioisotopes in an optical dipole trap, largely due to the small number of atoms in the primary MOT and poor transfer efficiency from the MOT to an optical dipole trap.

Radioactive atoms confined in a far-off-resonance dipole trap (FORT) have many intrinsic advantages for fundamental symmetry experiments, providing a highly polarized, point-like sample with minimal perturbation from the environment which can be well characterized. It is an ideal system for studying parity-violating $\beta$ decay of spin-polarized nuclei. Parity violation was first suggested by Lee and Yang [15] and subsequently discovered in 1957 by Wu *et al.* [16] in the $\beta$ decay of polarized $^{60}$Co. Today, parity violation is encompassed by the standard model (vector-axial vector) interaction between leptons and quarks. Nonetheless, the nature of these helicity couplings is derived from empirical measurements, and the standard model offers no fundamental understanding of the origin of these symmetries and how they become broken at the energy scales probed by modern experiments. 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 [17]. With the advantages mentioned above, the use of a pure optical trap combined with optical pumping will enable a state-of-the-art $\beta$-asymmetry measurement.

The challenges yet to be overcome are to trap a sufficient number of atoms with long trap lifetime and to precisely measure the sample polarization. In this paper, we report the optical trapping of radioactive $^{82}$Rb atoms and demonstrate good trapping efficiency, long trap lifetime, and optical manipulation of the spin states in a dipole trap. The requirements to reduce the background counts from atoms on the walls of the chamber and to obtain a trap lifetime comparable with the nuclear decay lifetime necessitate the use of a separate science chamber. However, a large percentage of the atoms is lost in the process of the transfer to the science chamber. In the future we plan to transfer the $^{82}$Rb atoms directly from the primary MOT into an optical tweezer and transport the atoms to a science chamber for a $\beta$-asymmetry measurement. We expect an order-of-magnitude improvement in the number of trapped atoms.

The radioactive atom trapping system consists of a double MOT coupled to a mass separator (Fig. 1). The trapping of $^{82}$Rb in the primary MOT has been described in detail previously [10,18,19]. Briefly, 10–50 mCi of $^{82}$Sr ($t_{1/2}$=26 d) is loaded in the ion source of the mass separator. As $^{82}$Sr decays into $^{82}$Rb, the Rb is surface ionized, accelerated to 20 keV, mass separated, and collected for about three $^{82}$Rb half-lifes (~200 s) on a 5-mm-diameter Zr foil located inside the primary trapping cell. When induction heated to ~800 °C, the $^{82}$Rb is released from the foil as neutral atoms with ~50% release efficiency as measured by a collimated $\gamma$-ray counter looking at the foil. The atoms released are then laser cooled and trapped in a MOT. The trapping cell is coated on the inside with a silane-based nonstick SC-77 dry film coating (Silar Laboratories) which increases the trapping efficiency by two or more orders of magnitude. The coating can last up to a year in good vacuum (~$10^{-9}$ Torr), but degrades when exposed to the high levels of Rb vapor or to high temperatures associated with extended heating of the foil. Our coating degraded by a factor of ~20 over 6 months of experiment.

The MOT trapping light is detuned −15 MHz from the $F=3/2 \rightarrow F'=5/2$ trapping transition of $^{82}$Rb by locking a Ti-sapphire laser to the $F=3 \rightarrow F'=3,4$ crossover of $^{85}$Rb and frequency shifting −536 MHz using a double-pass acousto-optic modulator (AOM). The repumping light, which in $^{82}$Rb is shifted by 1.472 GHz with respect to the

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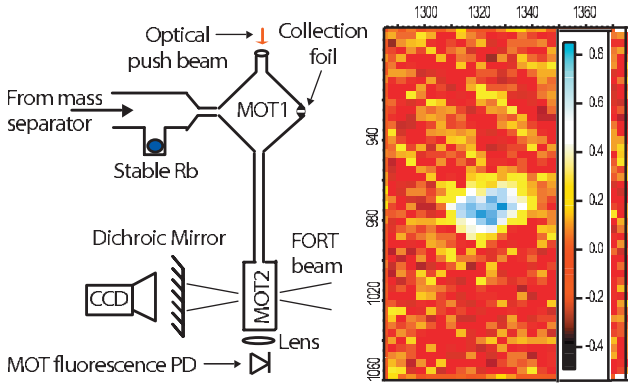


FIG. 1. (Color) The experimental setup and an image of $4\times10^3$ $^{82}$Rb atoms in a dipole trap. The absorption image is taken with the time of flight of 50 $\mu$s. The color scheme denotes the optical density as shown on the scale. One pixel corresponds to 3.7 $\mu$m. The yellow fringes originate from the parallel walls of the trapping cell. The average FORT beam intensity is $2.3\times10^5$ W/cm$^2$, and the calculated trap depth is 340 $\mu$K.

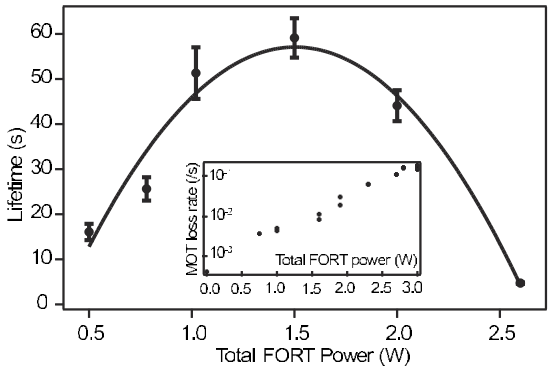


FIG. 3. The dependence of the lifetime of $^{85}$Rb atoms in the FORT on the intensity of the FORT light. The solid line is meant to guide the eye. The inset shows the detrimental effect of the FORT light on the lifetime of the MOT. Total FORT power of 1 W corresponds to a trap depth of ~200 $\mu$K.

trapping frequency, is obtained as a sideband on the trapping beam by an electro-optic modulator (EOM). To detect the MOT fluorescence, we modulate that EOM at 4 kHz and detect the modulated fluorescence with an avalanche photodiode and a lock-in amplifier. In our current system, the trapped $^{82}$Rb atoms are transferred into a science chamber through a 100-cm-long tube with magnetic confinement along the tube axis. The science chamber is a high-quality rectangular 2.5 cm$\times$2.5 cm$\times$10 cm quartz cell. A combination of ion and Ti sublimation pumps is used to achieve a vacuum of better than $10^{-11}$ Torr in the science chamber. This gives a MOT2 lifetime of ~200 s. We are able to trap as many as $10^5$ $^{82}$Rb atoms in MOT2 after a single MOT1-MOT2 transfer. The transfer efficiency is limited to ~10% due to the long transfer distance.

The atoms retrapped in MOT2 are then prepared for loading into a dipole trap. We use a high-power single-frequency solid-state laser (diode-pumped Yb:YAG thin disk laser from ELS Electronic Laser System Corp., maximum single-frequency power 25 W) with $\lambda=1030$ nm for the dipole trap. The laser beam is sent through an AOM operating at 40 MHz. Up to 80% of the light intensity is deflected into the first order, which is coupled into a single-mode fiber. The beam from the fiber is then focused to a ~30 $\mu$m $1/e$ diameter waist after passing through a series of lenses, polarizing cube, and waveplates and is overlaped with the MOT cloud using a single dichroic mirror. For the optical lattice, the beam passes through a second achromat with the same focal length of 150 mm and is reflected back by a dichroic mirror at a normal incidence. The mirrors used to reflect the FORT beam are transparent at 780 nm, which allows us to perform the absorption imaging of the MOT using a probing beam

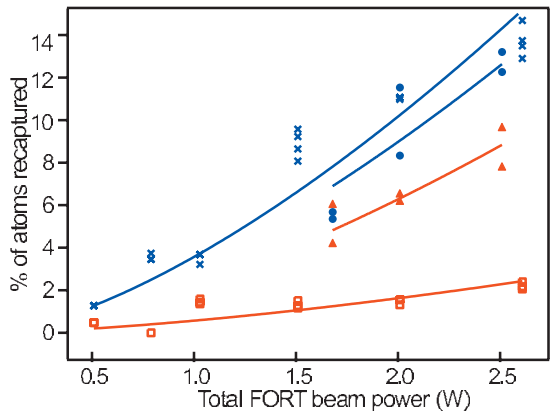


FIG. 2. (Color) The efficiency of MOT-to-FORT transfer of Rb atoms as a function of the FORT beam power, as measured by the MOT retrap technique. The FORT beam remains on throughout the experiment. Red squares, $^{85}$Rb transferred from "bright" MOT. Red triangles, $^{82}$Rb transferred from "bright" MOT. Blue crosses, $^{85}$Rb transferred from the dark MOT. Blue circles, $^{82}$Rb transferred from dark MOT. The fits are derived from the $P^{3/2}$ relation [21]. Total FORT power of 1 W corresponds to ~200 $\mu$K trap depth.

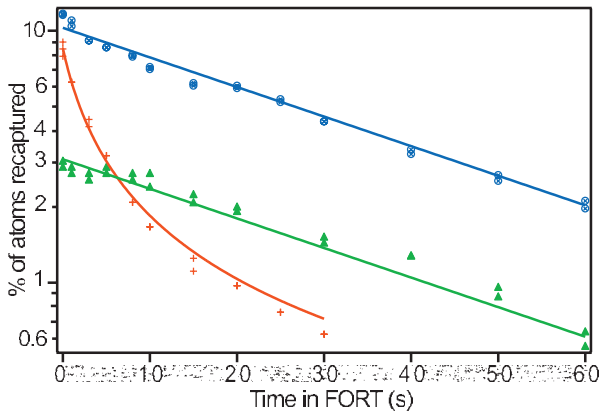


FIG. 4. (Color) The lifetimes of $^{85}$Rb atoms transferred from MOT into the FORT. Both atoms loaded from the dark MOT (blue circles) and from the bright MOT (green triangles) without an intermediate repumping step exhibit the same one-body decay lifetime of ~37 s (blue and green line fits); however, the decay is two-body if the atoms are illuminated, after they are loaded into the FORT from a dark MOT, by repumping light for 100 $\mu$s (red crosses and red line fit).

along the FORT beam on the camera. The fluorescence of the MOT is also collected onto a second charge-coupled-device (CCD) camera located at 90° from the absorption camera.

The FORT loading process consists of compressed and detuned dark MOT stages to achieve a higher density of cold atoms. By increasing the MOT magnetic field gradient by a factor of 4 and detuning the laser frequency by an additional −18 MHz we obtain an improved dipole loading efficiency of up to ~14%. After an adjustable "FORT holding time" delay we switch off the FORT light and absorption image the atoms on the CCD camera using a 50-$\mu$s probe beam resonant with the cycling transition ($F=3/2 \rightarrow F'=5/2$ for $^{82}$Rb) to determine the absolute number and temperature of the trapped atoms. To image atoms in the lower hyperfine state, a 100-$\mu$s repump pulse (resonant on $F=1/2 \rightarrow F'=3/2$ for $^{82}$Rb) was used before the probe. For relative measurements, we use the fluorescence of the atoms recaptured in a MOT without imaging.

We optimize the double-MOT system and the FORT loading using $^{85}$Rb from a Rb getter. Once optimized, $^{82}$Rb can be trapped without any change in the trap alignment and timing. A necessary step in obtaining the FORT is the precise overlap of the FORT beam with the location of the compressed MOT. This is accomplished using a CCD camera focused on the MOT. Our probe absorption beam is collinear with the axis of the trap; therefore, in the case of the optical lattice we image the total number of atoms in all occupied sites at once. We observe the separation of the lattice into two individual dipole traps if the retroreflecting mirror of the lattice is misaligned.

We use the CCD camera to directly image the trapping FORT beam inside the chamber at the location of the trap. By fitting the beam profile to a Gaussian we establish a $1/e$ diameter of $30\pm5$ $\mu$m. Based on this we estimate the trapping frequencies of the FORT to be $2.7\pm0.9$ kHz in the transverse and $30\pm15$ Hz in the longitudinal directions at the laser power of 1.6 W. We have further verified our calculations by measuring the parametric resonances to be 3.5 kHz and 7 kHz for the atoms trapped with a 1.6-W beam, corresponding to the fundamental and first harmonics of the transverse trapping frequency.

For a successful $\beta$-asymmetry measurement, we have to achieve good transfer efficiency from the MOT to the dipole trap with a lifetime comparable to the nuclear decay lifetime. Further, the trapped atoms have to be polarized in a stretched electric-nuclear $m$ state and the degree of polarization determined to a high precision.

As demonstrated in earlier dipole trapping work [21], we expect improved trapping efficiency with increased laser power. Figure 2 shows the MOT-FORT transfer efficiencies as a function of dipole laser power for both the dark compressed MOT and bright compressed MOT (repump left on during compression). Much larger efficiency was observed for the dark compressed MOT with a maximum efficiency of ~14% at approximately 2 W power (trapping depth =425 $\mu$K). The dependence of the MOT-FORT transfer efficiency on the FORT power $P$ is consistent with the $P^{3/2}$ relation as discussed in [21].

The lifetime of the dipole trap as a function of laser power is shown in Fig. 3. The lifetime increases up to a power of 1.5 W where it then decreases. This decrease we attribute to fiber-coupling limitations with the eventual damage caused to the optical fiber. One early indicator of this damage is an increased noise which was observed on the power spectrum below 5 kHz when the fiber output is more than 2 W where it exceeds the capabilities of a power feedback control system. We also found that FORT laser light has a pronounced effect on the MOT lifetime. The inset in Fig. 3 shows the loss rate of the atoms from the MOT as a function of the FORT light power. The loss is a one-body process and the exponential power dependence is completely different from the dipole trap loss. We attribute these losses to the light shift caused by the dipole trapping laser on the trapped atoms. The combination of the redshift of the ground $5S_{1/2}$ state and of the blueshift of the $5P_{3/2}$ state results in an effective trapping laser detuning of −7.8 MHz per 100 $\mu$K [22], or, approximately, −16.6 MHz per W of our total FORT laser power in our experimental conditions. This increased detuning reduces the maximum MOT trapping velocity along the FORT beam, resulting in increased loss rate of the atoms.

The dipole trap loss also depends on the spin composition of the trapped atoms. Figure 4 shows the decay of $^{85}$Rb atoms in the trap. When the atoms are loaded directly from the MOT in either the upper (bright MOT) or lower (dark MOT) hyperfine state, the decay is a single exponential, a signature of one-body decay. It is known that two-body inelastic spin-exchange collisions are associated with a two-body trap loss from optical traps. The absence of two-body decay indicates a suppression of two-body spin-exchange collisions in our trap. We interpret these results as evidence that the atoms are polarized to a single spin state, $F=3, m_F=3$ or −3 for the upper hyperfine state and $F=2, m_F=2$ or −2 for the lower, resulting in a negligible two-body decay rate. The fact that the atoms are polarized without conventional optical pumping is a pleasant surprise and requires further investigation. We think it might be due to the spontaneous spin polarization during the dipole trap loading. The spontaneous spin polarization has been studied in Cs vapor [23,24]. This effect occurs when optical pumping and electronic spin exchange take place faster than spin relaxation. For certain orientations of small external magnetic fields the state of zero spin orientation is unstable and the slightest bias leads to the spin alignment either parallel or antiparallel to the field. In our case, the detuned trapping beam acts as an effective off-resonant pump. The high atomic density in the dipole trap increases the spin-spin interaction, leading to the observed effect. Figure 4 also shows that when atoms are depolarized with a repump beam, the decay becomes a clearly two-body process. If the atoms are loaded into an optical lattice instead of a single-beam trap, the trap decay also has the two-body signature. A systematic investigation of this effect is underway and will be published in a follow-up paper.

In summary, we have demonstrated trapping of a short-lived radioactive isotope in an optical dipole trap. We have obtained a transfer efficiency of ~14% and trapping lifetime of 55 s. This is an important step towards the undertaking of a $\beta$-asymmetry measurement in an optical dipole trap.

To achieve a 0.1% precision measurement of the $^{82}$Rb $\beta$-asymmetry coefficient it is necessary to trap at least $10^5$ atoms and to measure the degree of polarization to 0.1%

accuracy. Optical imaging methods could be employed to sample the fraction of atoms (1%) that are trapped but not in the fully aligned state with 10% precision. This can be accomplished with $10^5$ $^{82}$Rb atoms in the dipole trap. The off-resonance scattering at 1030 nm is on the order of 1 Hz, depending on the trapping parameters. This may require the 1030-nm dipole laser to be circularly polarized relative to the uniform bias field, so once the atoms are polarized to the stretched state, the off-resonance scattering maintains the polarization. Naturally, one can also reduce this scattering rate to the order of 0.001 Hz with a $CO_2$ laser dipole trap; this would enable the application of a rotating bias field without any appreciable effect on the sample polarization, so that a complete mapping of angular distribution can be measured with a single detector [10].

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