Magneto-Optic Trapping of Radioactive ^{79}Rb

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Radioactive ^{79}Rb atoms have been produced in a nuclear reaction and were captured into a magneto-optic trap in a cell. A fluorescence signal was obtained from 80 ^{79}Rb atoms in the trap. The efficiency of the process is estimated as 1×10^{-5} atom in the trap for every atom/sec produced. This efficiency is sufficient to develop further experiments to measure atomic properties of Fr with the eventual goal of observing parity nonconservation effects in neutral atoms of different radioactive isotopes of Fr.

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Since the demonstration [1] of magneto-optic forces to slow and trap atoms, there have been extensive new developments in the trapping and cooling of atoms. Injection of atoms into the trap is usually from an atomic beam or from a vapor [2], and macroscopic quantities of atoms of the species of interest are required. There is much interest in magneto-optic traps because the strong confinement of atoms in six-dimensional phase space is important for a broad class of experiments. A possible application of traps is to measure atomic parity nonconservation in radioactive isotopes of heavy alkali atoms to extract lepton-quark weak couplings [3–5]. The heaviest alkali francium, for which there are no stable isotopes, is also interesting in order to carefully study the atomic structure, with the possibility of future parity violation tests, since the atomic parity nonconservation effect is estimated to be 15 times greater in Fr than in Cs. The ease of manipulation of the atomic polarization in a trap would also allow detailed studies of other fundamental processes such as β and α decay. Unlike in a solid, the recoil energy from neutrino emission is large compared to the binding energy of the trap, and this offers new opportunities for measurements of neutrino-electron correlations.

Radioactive atoms have been injected into ion traps [6]. However, for many applications in atomic physics, ion traps do not provide the strong confinement in phase space available in atom traps, as well as requiring the ionized species. On the other hand, atom traps are not as general as ion traps, since the availability of suitable atomic transitions that can be rapidly cycled is limited, and the depths of atom traps are small compared to that of ion traps.

Radioactive atoms are produced in nuclear reactions with energetic projectiles, and the recoil energy is typically 10^7 eV. The energy in the trap is of the order of 10^{-7} eV, so that the energy must be decreased by a factor of 10^{-14}. In addition, the process must utilize the rare atoms efficiently and the transport into the trap must be in a time short compared to the radioactive half-life. The method we have developed is useful for half-lives longer than 10 sec. Variations on this method are currently under development by other groups [7,8].

Demonstration of efficient transport and trapping is a necessary prerequisite before embarking on further experiments, and we sought a suitable probe system. Since our future experiments will focus on Fr, we chose the element Rb because of the similarity of ionization potential and chemistry, while preserving the availability of natural Rb for development and reference.

A beam of 90 MeV ^{31}P from the Stony Brook Tandem Van de Graaff accelerator created radioactive ^{79}Rb ($t_{1/2}$ = 22.8 min) with the reaction ^{51}V(^{31}P,2np)^{79}Rb. A schematic diagram of the apparatus is shown in Fig. 1. The target was positioned 2 cm from a 500 mg/cm^2 Au catcher, which was heated to 820 °C. The Rb atoms stopped in the Au and diffused to the surface, where they were released as ions because of the high work function of the Au surface. This scheme was optimized with Fr in mind, where the Au becomes the target as well as the ionizer. The shortest lifetime isotopes that can be efficiently trapped are limited by the diffusion time of 10 sec out of the Au. The ions were extracted and injected into an electrostatic transport system shown in Fig. 1. The ion transport system served to efficiently move the atoms from the target region to the vicinity of the atom trap, which are physically separated by 1 m to achieve isolation of the accelerator vacuum from the trap vacuum. The trap lifetime is limited by collisions with background gas; the $1/e$ fill time is 25 sec with the trap isolated and a vacuum of $< 1 \times 10^{-9}$ Torr, and 5 sec when open to the accelerator vacuum system.

The ions are focused toward the far end of a 1.5 cm long, 0.5 cm diam yttrium-lined tube heated to 800 °C, where they impact with an energy of 30 eV and are released as neutral atoms from the low work function surface. The neutralizer tube is 0.6 cm from the trap cell entrance, a 1.2 cm aperture. We determined that a flux of 7×10^4 ^{79}Rb/sec is delivered to the neutralizer tube by measuring the intensity of the 688 keV γ radiation in the daughter ^{79}Kr with a Ge detector near the tube. The ^{79}Rb was uniquely identified by eight strong γ-ray transitions and by its half-life; ^{78}Rb^m and ^{80}Rb were also made in quantities 5%–10% of the ^{79}Rb. With the ^{31}P beam

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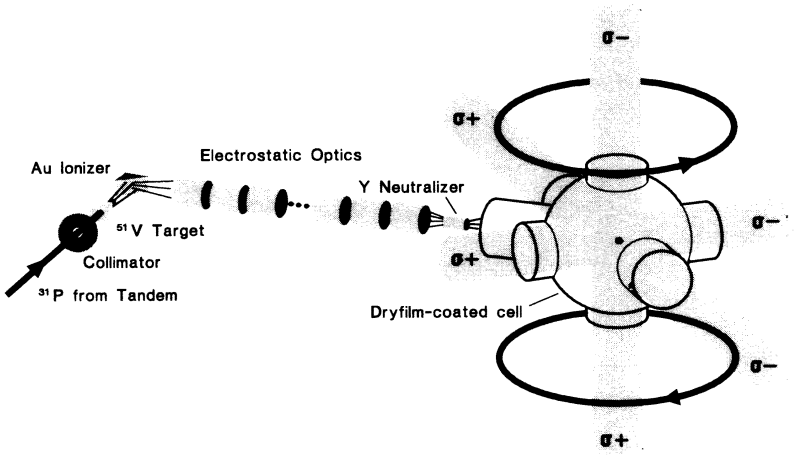

FIG. 1. Schematic view of target, ion transport system, and magneto-optic trap.

current of 50 particle nA, target thickness of 1.4 mg/cm^2, and average production cross section of 80±40 mb estimated by the statistical model calculation CASCADE [9], (20±10)% of the reaction products were transported to the tube. We established that the system works for other alkalis by carrying out an auxiliary experiment to test the production and transport of ^{209,210,211}Fr and we obtained a flux of 1×10^5 ^{210}Fr/sec.

The physical trap consists of a Pyrex bulb with a nonstick dry-film coating [10] which surrounds the magneto-optic trap (MOT). The MOT is formed by six intersecting laser beams each with $1/e^2$ (power) diameter of 4 cm and power of 20 mW, and a field gradient of 9 G/cm. As slow atoms are captured from the low velocity tail of the thermal distribution in the bulb, wall collisions rethermalize the depleted distribution. The process of loading the trap from the atoms condensed on the inside of the neutralizer tube was studied by spraying stable Rb atoms from a small Rb dispenser [11] onto the ionizer.

The main trap laser was a Ti:sapphire laser tuned to the 780 nm resonance line of Rb. A portion of the laser power was split off and passed through a series of acousto-optic modulators to produce a beam which could be offset from 710 to 730 MHz to the blue of the main beam. With RF techniques [12] this beam was locked to the $F = 2 \rightarrow 1 \rightarrow 3$ saturation spectroscopy crossover transition in ^{87}Rb, and this shifted the main trap laser to 5–25 MHz to the red of the $F = 3 \rightarrow 4$ cycling transition in ^{79}Rb. A free running diode laser provided 9 mW of power to repump any atoms that "leak" out of the trapping transition [13]. This "repumper" laser was modulated with an amplitude of 480 MHz around the ^{79}Rb $F = 2 \rightarrow 3$ transition at 2 kHz frequency. An $f/1.6$ optical system collected the trap fluorescence onto a Hamamatsu R636-10 photomultiplier tube. The trap fluorescence was partially modulated at the repumper modulation frequency, and lock-in detection provided a powerful way to reject background from laser light scattered from the cell. Background fluorescence from the Doppler-broadened distribution of stable Rb isotopes was reduced to negligible levels by adjusting the phase of the lock-in detector.

We accumulated radioactive ^{79}Rb into the cold neutralizer tube for two half-lives. The tube was then heated while the fluorescence signal was monitored with a 10 sec integration time. As the ^{79}Rb atoms were released into the trapping region, the shaded signal shown in Fig. 2 was obtained. The process was repeated, except that during the central part of the scan, the trap signal was destroyed completely by reversing the magnetic field gradient, confirming that trapped atoms were the source of the signal. We repeated the accumulation and heating cycles with different conditions of laser power and laser detuning. The trapping process is known to be very sensitive to the detuning of the laser from the atomic resonance [14]. The average signal in the peak of the release

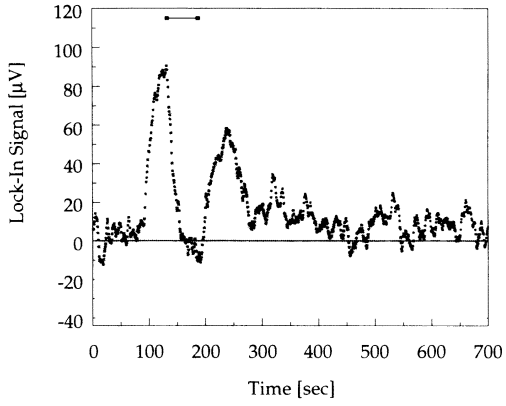

FIG. 2. Fluorescence signal vs time. The shaded area shows the trap signal as the ^{79}Rb atoms are released by heating the neutralizer. The dots show the trap signal going to background levels when the magnetic field is reversed, confirming that the signal is coming from trapped ^{79}Rb atoms. The horizontal bar spans the time during which the field is reversed.

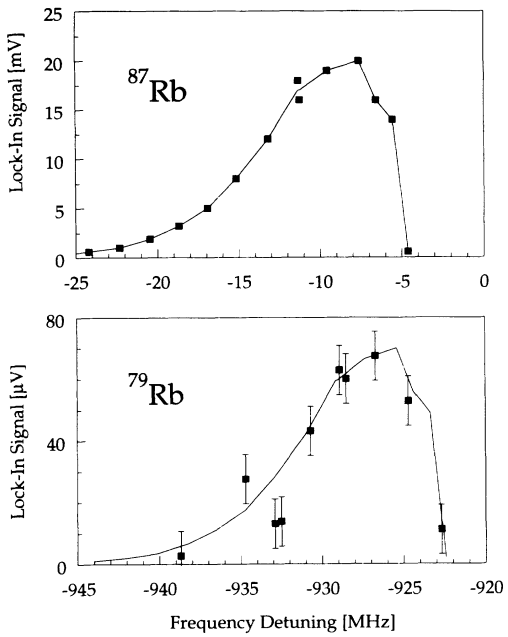

FIG. 3. Trap signal vs frequency shift with respect to the $F = 2 \rightarrow 3$ transition in ^{87}Rb. The line connecting the ^{87}Rb data points was normalized and shifted to guide the eye through the ^{79}Rb data. The laser lock error, determined from the rms fluctuations on an independent measure of the linewidth, is ±0.5 MHz.

period is shown in Fig. 3 plotted as a function of laser detuning. Corrections have been applied to individual data points to account for slightly different initial ^{79}Rb activity (10%) and laser power (30%, calibrated by the natural ^{87}Rb trap). Accumulation cycles with the accelerator beam turned off were also taken and did not show any signal above background. The maximum of the detuning curve shown in Fig. 3 is shifted by 918±3 MHz from the separately measured detuning curve for stable ^{87}Rb, in good agreement with the frequency shift of 920±3 MHz deduced from the isotope shifts and hyperfine structure measurements of Ref. [15].

The number of radioactive atoms in the trap was calibrated by injecting a 0.05 nA current of stable ^{87}Rb atoms into the neutralizer. With the laser frequency set to the maximum of the detuning curve for ^{87}Rb, the absolute intensity of the fluorescence of the trap was measured and it was determined that 1×10^5 ^{87}Rb atoms were in the trap. The ratio of the lock-in signals between the stable and radioactive atoms indicated that at the peak of the release curve of Fig. 2, 80 atoms of ^{79}Rb were trapped. (The hyperfine splittings of the relevant excited states are almost the same in ^{87}Rb and ^{79}Rb [15], making this direct comparison possible.) This implies an efficiency of 6×10^{-5} ^{79}Rb atoms in the trap per ion/sec at the neutralizer, and an efficiency of 1×10^{-5} ^{79}Rb atoms in the trap per atom/sec produced in the vanadium target.

Future directions are to improve the efficiency of trapping and to increase the lifetime of the trap. A possible improvement is tighter coupling between the neutralizing surface and the trapping volume; the present design conservatively kept the neutralizer outside the trap cell to insure good vacuum and avoid heat damage to the nonstick coating. References [16,17] suggest that increasing the laser power by an order of magnitude in the present geometry would trap an order of magnitude more atoms. The feasibility of experiments that detect nuclear decay processes generally require that the number of radioactive atoms in the trap be large compared to the number which are sticking to the walls. Transfer of cooled atoms to a second trap may be the way in which to realize this or other experimental requirements.

This work has demonstrated the feasibility of injecting radioactive atoms into a magneto-optic trap without any laser predeceleration. Crucial to the success of the method employed here was the use of a nonstick coating to allow the atoms many passes through the trapping laser beams. The present efficiency is sufficient to develop further experiments to measure atomic properties of Fr.

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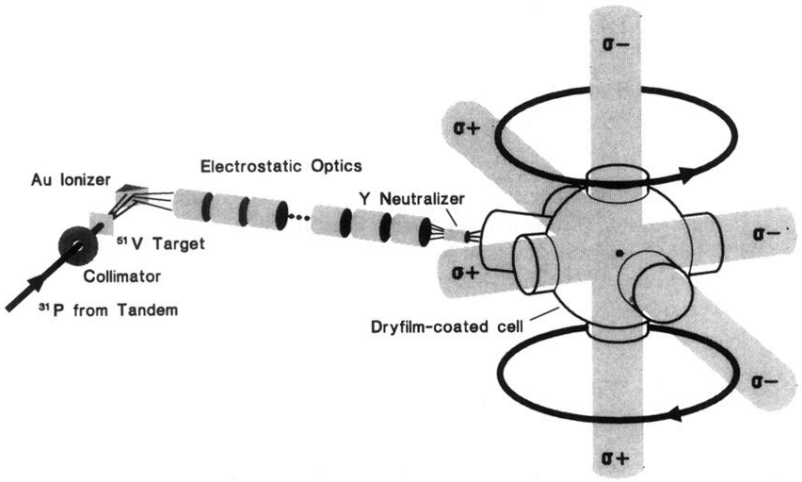

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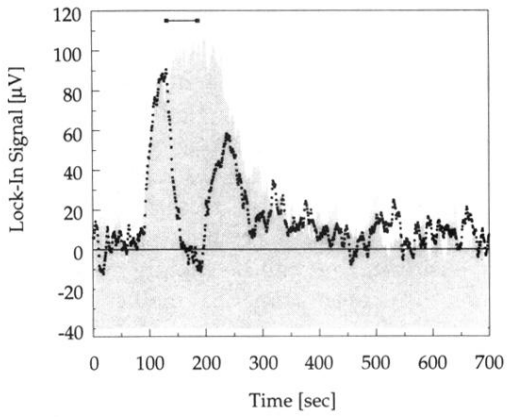

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