

Magneto-Optic Trapping of ^{210}Fr

J. E. Simsarian, A. Ghosh, G. Gwinner, L. A. Orozco, G. D. Sprouse, and P. A. Voytas

Department of Physics, State University of New York, Stony Brook, New York 11794-3800

(Received 13 December 1995)

The alkali element francium has no stable isotopes and has eluded extensive study because sufficient quantities have not been available for detailed investigations. More than 1000 ^{210}Fr atoms have now been contained in a magneto-optic trap. This number is sufficient to allow extensive studies of Fr atomic properties that are necessary input for future tests of fundamental interactions. [S0031-9007(96)00180-9]

PACS numbers: 32.80.Pj, 23.40.Bw, 29.25.Rm

The alkali element francium has no stable isotopes, and has eluded extensive investigation of its atomic structure. Francium was discovered in the decay products of radium [1], but a concentrated sample has been difficult to accumulate since the longest half-life of any isotope is only 22 min. Production with accelerators usually leaves the francium embedded in a solid where it is possible to analyze its nuclear decay properties, but impossible to study its atomic structure.

Francium has a single electron in a $7S$ orbital outside a radon core, and, as with the lighter alkalis, the calculation of the Fr atomic structure can be performed with impressive accuracy [2]. Because of its large atomic number, Fr offers a sensitive test of relativistic effects on atomic structure. It is also an excellent system for the study of weak interactions in atoms [3]. Calculations of parity nonconservation in francium [2] show an effect 18 times larger than in cesium, the element for which the smallest combined theoretical and experimental uncertainty has been achieved [4]. Impressive progress in measurement of parity nonconservation has been achieved in thallium, but the result is limited by theoretical uncertainties [5].

In the last two decades, starting with the observation of the D_2 line of francium [6], the energies of states accessible by laser excitation were measured in pioneering work at ISOLDE [7]. Studies of the hyperfine splittings revealed information about the nuclear structure of the francium isotopes from 207 to 213 and 220 to 228 [8]. Andreev, Mishin, and Letokhov [9] studied several Rydberg levels and the ionization potential using ^{221}Fr , a daughter product of the decay of ^{229}Th , by laser-resonance ionization. Progress has been substantial but no measurements exist of any of the atomic radiative lifetimes, polarizabilities, or even the energies of the $8S$ and $9S$ states.

The recent development of experimental methods [10,11] to take nuclear reaction products and inject them into a magneto-optic trap (MOT) has provided the possibility to study in detail properties of radioactive atoms such as francium. A cold, dense cloud of neutral atoms in a MOT is an ideal sample on which to perform detailed spectroscopic measurements of the structure [12] and lifetimes [13] of energy levels of an atom. However, a

new difficulty arises in loading into a laser trap francium and other elements for which there are no stable isotopes. Stable isotopes of the element cannot be used to provide a frequency reference for the trapping laser. Absolute calibration must come from other sources, such as the tabulated Doppler broadened lines of I_2 [14].

Heavy-ion fusion reactions can, by proper choice of projectile, target, and beam energy, provide selective production of the neutron deficient francium isotopes. Gold is an ideal target because it is chemically inert, has clean surfaces, and has a low vapor pressure. The $^{197}\text{Au}(^{18}\text{O}, xn)$ reaction at 100 MeV produces predominantly ^{210}Fr , which has a 3.2 min half-life. ^{210}Fr has an estimated α decay branching of $(60 \pm 30)\%$ with the remaining decays by β^+ or electron capture [15].

The apparatus used in the present work is based on the same principles of our earlier work [10]. Beams of 100 MeV ^{18}O from the Stony Brook Superconducting LINAC are incident on a Au target mounted on a W rod. The target is heated to ≈ 1200 K by the beam power and by an auxiliary resistance heater. The elevated temperature is necessary for the alkali elements to rapidly diffuse to the surface and be surface ionized. A beam energy of 100 MeV is optimal for production of ^{210}Fr since this isotope is created very close to the surface facilitating its escape from the target. Nonalkali atoms may exit the target, but their ionization potential is too high for them to be surface ionized. This effect helps select the relevant atoms in our system [16].

The francium ions enter the ion transport system shown in Fig. 1. The target and electrodes are cylindrically symmetric to reduce aberrations, and the ions are extracted at 135° from the ^{18}O beam direction. We measure the number of Fr ions in the beam by stopping them on a retractable plate viewed by a silicon surface-barrier detector. We determine the number of francium atoms from the alpha-particle activity and the known solid angle of the detector. The different alpha energies and lifetimes allow for isotope identification. A beam from the Stony Brook Superconducting LINAC of 6.3×10^{11} ^{18}O ions/s on the Au produced $\approx 1 \times 10^6/\text{s}$ ^{210}Fr in the target, with less than 10% of other isotopes. Approximately 40% of the Fr atoms in the target are extracted into the ion beam.

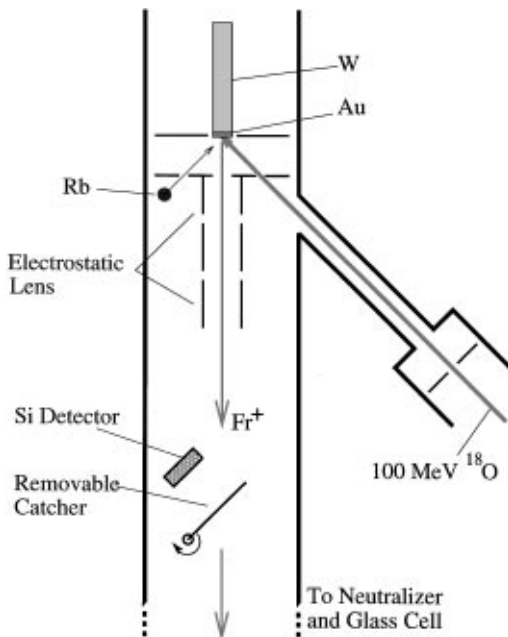


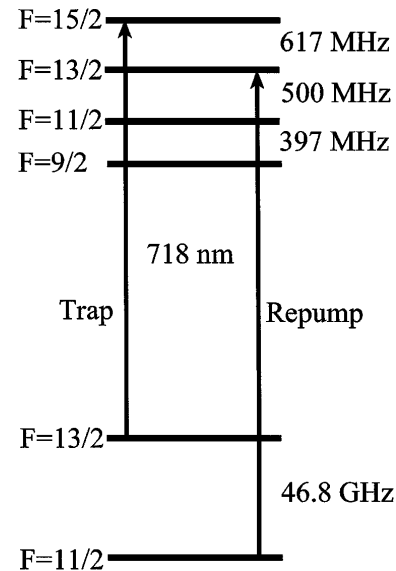
FIG. 1. Schematic view of target and ion transport system.

Separation of the production and the trapping regions is critical in order to operate the trap in a UHV environment. Extracted at 500 V, the francium ions travel about 1 m where they are deposited on the inner surface of a cylinder coated with yttrium and heated to 970 K. Neutral Fr atoms evaporate from the Y surface and form an atomic beam directed towards an aperture into the vapor cell MOT. The arrangement is similar to the one described in Ref. [10], except that the Y tube was moved to within 0.3 cm of the entrance of the cell.

The physical trap consists of a 10 cm diameter Pyrex bulb with six 5 cm diameter windows and two viewing windows 3 cm in diameter. The MOT is formed by six intersecting laser beams each with $1/e^2$ (power) diameter of 4 cm and power of 50 mW, with a magnetic field gradient of 9 G/cm. The glass cell is coated with a nonstick Dry-film coating [17,18] to allow the atoms multiple passes through the trapping region after thermalization with the walls [19].

The atomic energy levels of the ^{210}Fr atom relevant for trapping are shown in Fig. 2. A Coherent 899-21 titanium-sapphire laser with an rms linewidth of less than 500 kHz excites the cycling transition $7S_{1/2}$, $F = 13/2 \rightarrow 7P_{3/2}$, $F = 15/2$ at 718 nm. The ground-state hyperfine splitting for ^{210}Fr of 46.8 GHz requires an extra laser for repumping the atoms that fall into the $F = 11/2$ ground state. A free-running Mitsubishi 4405-01 diode laser cooled to approximately 77 K with liquid nitrogen repumps the atoms into the cycling transition via $7S_{1/2}$, $F = 11/2 \rightarrow 7P_{3/2}$, $F = 13/2$.

The frequency of the lasers is referenced to the atlas of the I_2 spectrum [14]. In this region of the spectrum the I_2 cells do not show much absorption unless heated to

FIG. 2. Energy levels of ^{210}Fr relevant for trapping.

temperatures greater than 570 K and the features are about 1 GHz wide. The tabulated line 381 is about 3.5 GHz away from the expected trapping laser frequency. A portion of the Ti:sapphire laser beam is sent through an electro-optic modulator to generate FM sidebands at 3.1 GHz (see Fig. 3). The FM modulated beam shift an additional 400 MHz. It then passes through a heated I_2 absorption cell so that when the lower frequency shifted sideband is on resonance with line 381, the laser frequency is close to the trapping transition. The iodine absorption signal comes from the mixed-down photocurrent of an Antel AR-S1 fast photodiode providing an absolute, but rather broad reference. A thermally stabilized etalon with broadband mirrors and 500 MHz free spectral range serves as a secondary reference. This etalon is further stabilized against drifts by a diode laser locked to a saturation spectroscopy resonance in Rb.

The repumper laser is modulated in frequency with an amplitude of 500 MHz. Between the I_2 lines 387 and 388 of Ref. [14] there is a small absorption feature that matches the position of the repumping transition in ^{210}Fr .

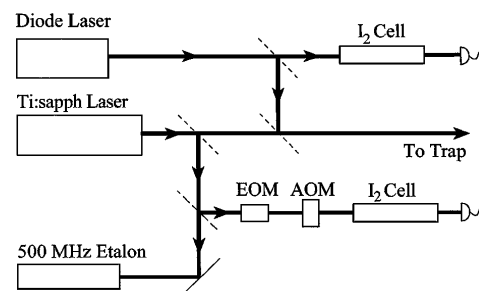


FIG. 3. Block diagram of the laser system.

We use this feature to keep the repumper laser frequency on resonance.

The hyperfine splittings of the ^{210}Fr levels of the excited state are much larger than in the other alkalis (see Fig. 2), so that the expected leakage to other levels should be smaller, requiring less repumper power. The modulation depth of the trap fluorescence due to a change in the repumper frequency is uncertain in francium, so the method of repumper modulation used to detect ^{79}Rb in our previous work [10] was not feasible. Instead the trapping laser is frequency modulated with amplitudes from 1 to 15 MHz at a frequency of 14.5 kHz. Lock-in detection allows the rejection of the laser light scattered from the cell while measuring the fluorescence from the captured atoms. An $f/2$ optical system collects the trap fluorescence onto a Hamamatsu R636-10 photomultiplier tube, and the signal is demodulated by a Stanford Research SRS 852 lock-in detector.

Before trapping Fr, the apparatus is tested extensively using stable ^{87}Rb injected into the cell. The rubidium comes from a dispenser next to the Au target (see Fig. 1) and follows the same path through the apparatus as the francium. We use the trapped Rb to optimize the position of the photomultiplier that detects the trapped atoms. Then we change the laser frequencies to the francium resonances without further adjustment of the detection optics.

Given the uncertainty in the location of the trapping transition with respect to our frequency reference, we scanned the trapping laser in the region of the resonance [20]. We recorded the lock-in signal along with the I_2 absorption spectrum and the stabilized etalon signal. With a trap lifetime of the order of 10 s, we chose a scan rate slow enough to allow atoms to accumulate in the trap. Figure 4 shows the fluorescence signal from the captured francium atoms. Panel (a) is a plot of the fluorescence signal of the trapped atoms as the trapping laser is scanned in frequency over a 60 MHz range at 0.5 MHz/s. The fluorescence signal was integrated with a 1 s time constant. The lower panels show a different, wider scan of the laser. Panel (b) shows the fluorescence from trapped atoms. Panel (c) shows the transmission of the reference etalon. Panel (d) is the I_2 absorption of the shifted sideband. For the wide scan two rates were used. Around the center of the scan we used 1.0 MHz/s, with a faster one elsewhere. The center of gravity of the trap signal is $13923.3866 \pm 0.0026 \text{ cm}^{-1}$, in agreement with the calculated value of $13923.3887 \pm 0.0020 \text{ cm}^{-1}$ for the $^{210}\text{Fr } 7S_{1/2}, F = 13/2 \rightarrow 7P_{3/2}, F = 15/2$ transition from the data by Bauche *et al.* [20]. The uncertainty in our measurement comes by adding in quadrature 0.0019 cm^{-1} from the previous calibration of line 381 [14], 0.0007 cm^{-1} from the fit to the shifted 381 line in our experiment, and 0.0016 cm^{-1} from systematics.

We estimate the number of atoms in the trap by comparing the measured amplitude of the modulated fluorescence signal from the trap with the expected

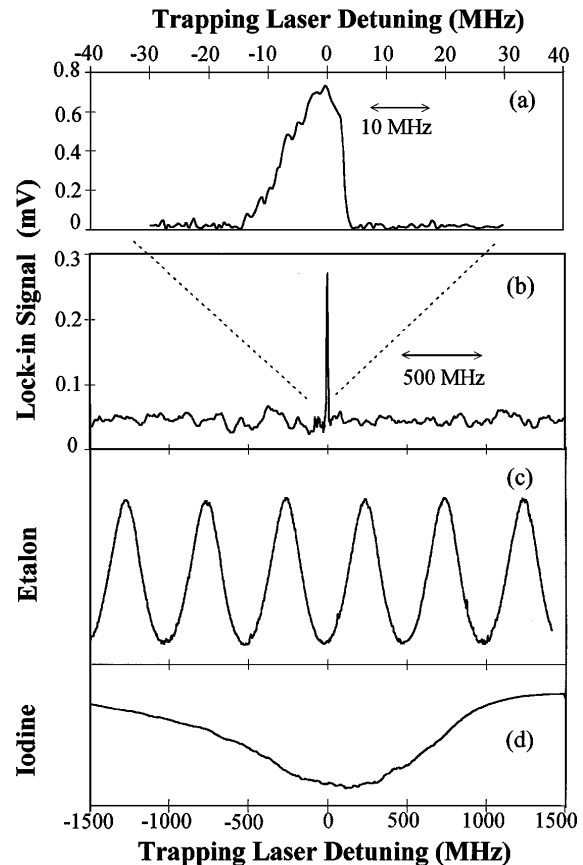


FIG. 4. (a) Trap fluorescence vs frequency detuning (60 MHz scan). (b) Trap fluorescence vs frequency detuning (3.0 GHz scan). (c) Etalon transmission with the 500 MHz marks (3.0 GHz scan). (d) I_2 absorption line (3.0 GHz scan).

fluorescence/atom. We use the calculated value of 20 ns for the atomic lifetime of the $7P_{3/2}$ state [2,21]. To obtain a rather strict lower bound for the number of captured atoms, we assume that the fluorescence from the trap is 100% modulated. The observed signal corresponds then at least to 1000 atoms. The fraction η of atoms trapped from the Fr produced in the target is given by

$$\eta = \frac{N_{\text{trap}}}{\tau_{\text{trap}} I_{\text{Fr}}}, \quad (1)$$

where N_{trap} is the number of atoms in the trap, $\tau_{\text{trap}} = 10 \text{ s}$ is the lifetime of the trap, and I_{Fr} is the number of Fr atoms per second produced on the target. We measure $\eta = 1 \times 10^{-4}$, which is a factor of 50 improvement over the previous ^{79}Rb results. We are investigating methods to further increase the trapping efficiency.

In summary, the radioactive element Fr produced in a nuclear reaction has been successfully injected into a magneto-optic trap. We have increased the efficiency a factor of 50 from the previous work with ^{79}Rb , but we are working on improving it more. It is sufficiently high to be able to study unknown atomic properties of Fr such as the energies and properties of the $8S$ and $9S$ states, that

we are now undertaking. We are not limited to studying ^{210}Fr . By changing the beam energy or by changing to ^{16}O beams, Fr isotopes from ^{207}Fr to ^{211}Fr may be explored. Previously, such experiments were possible only with the very high fluxes of Fr available at a few facilities in the world. The simple structure of the alkali atoms which allows precise calculations has made them useful in the study of fundamental interactions. Francium, as the heaviest alkali and with many isotopes, offers the possibility for a most sensitive test of the standard model.

We thank John Behr for his continuing interest in this project. This work was supported in part by a Precision Measurement Grant from NIST and by the NSF.

-
- [1] M. Perry, C. R. Acad. Sci. **208**, 97 (1939).
- [2] V. A. Dzuba, V. V. Flambaum, and O. P. Sushkov, Phys. Rev. A **51**, 3454 (1995).
- [3] W. J. Marciano and J. L. Rosner, Phys. Rev. Lett. **65**, 2963 (1990). Also see P. Langacker, M. Luo, and A. K. Mann, Rev. Mod. Phys. **64**, 87 (1992); *Precision Tests of the Standard Electroweak Model*, edited by P. Langacker (World Scientific, Singapore, 1995).
- [4] M. C. Noecker, B. P. Masterson, and C. E. Wieman, Phys. Rev. Lett. **61**, 310 (1988); S. A. Blundell, W. R. Johnson, and J. Sapirstein, Phys. Rev. Lett. **65**, 1411 (1990).
- [5] P. A. Vetter, D. M. Meekhof, P. K. Majumder, S. K. Lamoreaux, and E. N. Fortson, Phys. Rev. Lett. **74**, 2658 (1995).
- [6] S. Liberman, J. Pinard, H. T. Duong, P. Juncar, J.-L. Vialle, P. Jacquinet, G. Huber, F. Touchard, S. Büttgenbach, A. Pesnelle, C. Thibault, R. Klapisch, and ISOLDE Collaboration, C. R. Acad. Sci. Ser. B **286**, 253 (1978).
- [7] E. Arnold, W. Borchers, H. T. Duong, P. Juncar, J. Lermé, P. Lievens, W. Neu, R. Neugart, M. Pellarin, J. Pinard, J. L. Vialle, K. Wendt, and ISOLDE Collaboration, J. Phys. B **23**, 3511 (1990).
- [8] A. Coc, C. Thibault, F. Touchard, H. T. Duong, P. Juncar, S. Liberman, J. Pinard, J. Lermé, J. K. Vialle, S. Büttgenbach, A. C. Mueller, A. Pesnelle, and ISOLDE Collaboration, Phys. Lett. B **163**, 66 (1985).
- [9] S. V. Andreev, V. I. Mishin, and V. S. Letokhov, J. Opt. Soc. Am. B **5**, 2190 (1988).
- [10] G. Gwinner, J. A. Behr, S. B. Cahn, A. Ghosh, L. A. Orozco, G. D. Sprouse, and F. Xu, Phys. Rev. Lett. **72**, 3795 (1994).
- [11] Z.-T. Lu, C. T. Bowers, S. J. Freedman, B. K. Fujikawa, J. L. Mortara, S.-Q. Shang, K. P. Coulter, and L. Young, Phys. Rev. Lett. **72**, 3791 (1994).
- [12] M. Walhout, H. J. L. Megens, A. Witte, and S. L. Rolston, Phys. Rev. A **48**, R879 (1993); R. W. Fox, S. L. Gilbert, L. Hollberg, J. H. Marquardt, and H. G. Robinson, Opt. Lett. **18**, 1456 (1993).
- [13] C. W. Oates, K. R. Vogel, and J. L. Hall, Phys. Rev. Lett. **76**, 2866 (1996).
- [14] S. Gersternkorn, J. Vergès, and J. Chevillard, *Atlas du Spectre D'Absorption de la Molécule d'Iode, 10,000–14,000 cm⁻¹* (Editions du Centre National de la Recherche Scientifique, Paris, 1978), Pt. I.
- [15] M. R. Schmorak, Nucl. Data Sheets **31**, 283 (1980).
- [16] J. A. Behr, S. B. Cahn, S. B. Dutta, A. Ghosh, G. Gwinner, C. H. Holbrow, L. A. Orozco, G. D. Sprouse, J. Urayama, and F. Xu, Nucl. Instrum. Methods Phys. Res., Sect. A **351**, 256 (1994).
- [17] D. R. Swenson and L. W. Anderson, Nucl. Instrum. Methods Phys. Res., Sect. B **29**, 627 (1988).
- [18] M. Stephens, R. Rhodes, and C. Wieman, J. Appl. Phys. **76**, 3479 (1994).
- [19] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).
- [20] J. Bauche, H. T. Duong, P. Juncar, S. Liberman, J. Pinard, A. Coc, C. Thibault, F. Touchard, J. Lermé, J. L. Vialle, S. Büttgenbach, A. C. Mueller, A. Pesnelle, and ISOLDE Collaboration, J. Phys. B **19**, L593 (1986).
- [21] C. E. Theodosiou, Bull. Am. Phys. Soc. **39**, 1210 (1994).