Hyperfine Interactions 120/121 (1999) 657–660

Hyperfine anomaly measurements in francium isotopes and the radial distribution of neutrons *

J.S. Grossman, L.A. Orozco, J.E. Simsarian, G.D. Sprouse and W.Z. Zhao
Department of Physics and Astronomy, SUNY, Stony Brook, NY 11794-3800, USA

We have performed precision measurements in a magneto-optical trap of the $7P_{1/2}$ hyperfine structure of the isotopes $^{209–210}$Fr. The ratio of these hyperfine constants to the previously measured $7S_{1/2}$ ground state values reveals a significant hyperfine anomaly. This anomaly results from the different radial dependence of the electron density in the two atomic levels. The measurements are sensitive to changes in the radial distribution of the neutron magnetism.

1. Introduction

Francium is an extremely interesting and important atom for several reasons. It is the heaviest alkali atom, and like other alkalis, its simple structure allows *ab initio* calculation of its properties to high precision. It is the simplest relativistic atom, and can be used to test the most recent techniques for these precision atomic calculations [1]. Because the electron density at the nucleus scales approximately as Z^3, hyperfine interactions and other electron–nucleus effects are largest of all alkali atoms. Francium is therefore an excellent candidate for precision measurements of parity violation which probe the weak interaction between the outer electron and the quarks in the nucleus. In Fr, the effects are predicted to be 18 times larger [2] than those recently measured [3] in Cs. One of the uncertainties associated with the interpretation of these weak interaction effects results from the uncertainty in the radial distribution of neutrons in the nucleus. Any experiment that can get information about neutron distributions is therefore very important. The lighter isotopes near the $N = 126$ nucleus ^{213}Fr are amenable to shell model calculations [4], so they provide an excellent testing ground for understanding the nuclear properties.

The magnetic hyperfine interaction arises from an effective magnetic field of the electrons interacting with the magnetization of the nucleus. Different atomic states have different radial electron distributions, and will sample the radial distribution of the nuclear magnetization with different weights, giving rise to a hyperfine anomaly, or Bohr–Weisskopf [5] effect. Although precision hyperfine structure measurements [6] have been made in the ground state, the precision of the magnetic moments is not sufficient to see any hyperfine anomalies. We chose to perform precision measurements

---

* This work is supported in part by NIST and NSF.

of the $7P_{1/2}$ hyperfine structure in order to search for hyperfine anomalies. Our choice was motivated by the observation that for the francium $7S_{1/2}$ state, there is about 4% lower electron density at the surface of the nucleus than at the center, while for the $7P_{1/2}$ state there is only about a 1% difference. The $7P_{3/2}$ level has an even more uniform effective field, but the inclusion of the quadrupole interaction decreases the precision with which the magnetic hyperfine interaction could be measured.

2. Experimental details

Since none of the isotopes of Fr are stable, the experiments were carried out at the Stony Brook superconducting LINAC, where Fr isotopes can be created with $^{16,18}O(^{197}Au, xn)\ ^{208–211}Fr$, and $^{19}F(^{198}Pt,5n)^{212}Fr$ reactions. Typically 10^6 Fr/s were created and transported into a Magneto-Optical Trap (MOT) as described previously [7]. Figure 1 shows the counting rate/pixel of a CCD camera that views the trap region. Three Ti:Sapphire lasers were used to excite different atomic transitions as shown in figure 2. The long term frequency Fabry Perot cavity [8]. The first two lasers were used to form the MOT in the usual way, with a “trap” stabilization of all of the lasers was monitored and controlled by a computer controlled scanning laser driving the cycling transition and a “repump” laser to return ground state atoms to the trapping cycle. A third “probe” laser was turned on for 40 ns every 10 μs to excite atoms from the lower cycling state to the $7P_{1/2}$ levels. The fluorescence decay of the $7P_{1/2}$ levels was detected with an f/1 optical system and a Hamamatsu R636 photomultiplier. Since the repump laser was at the same wavelength as the fluorescence, it was turned off for 0.5 μs during each detection cycle. In order to obtain high precision for the $7P_{1/2}$ hyperfine splitting, the probe laser was frequency modulated at ∼3 GHz

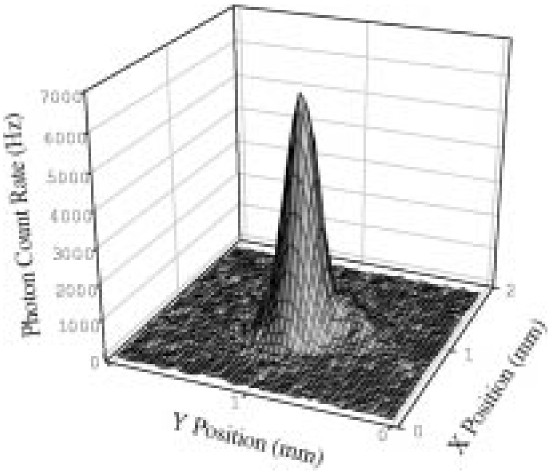

Figure 1. Photon counting rate in CCD camera from trapped francium atoms.

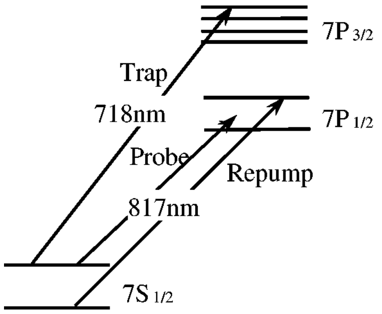

Figure 2. Atomic levels of francium involved in $7P_{1/2}$ hyperfine structure measurement.

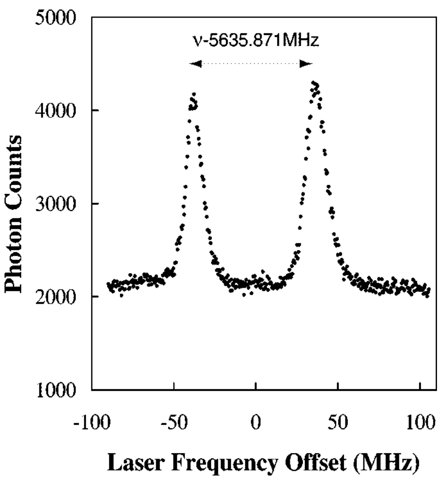

Figure 3. Scan of probe laser with sidebands separated by ∼5.6 GHz.

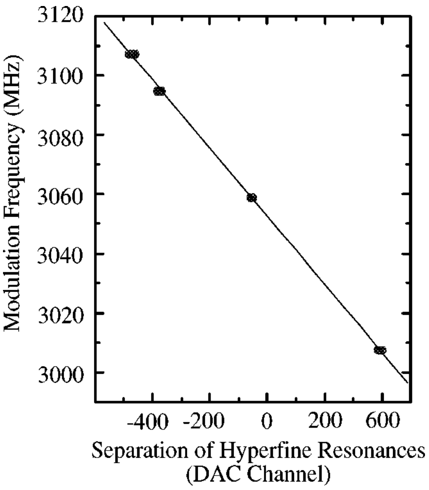

Figure 4. Graph of modulation frequency vs. measured peak separation.

by an electro-optic modulator. The center frequency of the laser was scanned over a small frequency interval near the center of the $7P_{1/2}$ level, so that first one sideband would be resonant with one of the hyperfine states, and then the other sideband would be resonant with the other hyperfine state.

Figure 3 shows the photon counts vs. frequency for one of these scans. For each isotope, the laser scans were performed in both forward and backward directions. The scans were also repeated with different RF frequencies. The frequency differences obtained by fitting the line positions in these spectra were then plotted vs. the modulation frequency as shown in figure 4, and the hyperfine splitting was determined by a least squares fit. The accuracy is set by the stability of the microwave generator, the signal-to-noise ratio of the resonance and linearity of the scan.

3. Results and discussion

In order to see the effect of the hyperfine anomaly, the $7S_{1/2}$ ground state hyperfine intervals determined previously [6] are divided by the $7P_{1/2}$ hyperfine structure values obtained in this work. Preliminary values of these ratios for $^{209\text{–}210}$Fr are shown in figure 5. Work on other isotopes is in progress.

In order to qualitatively understand the observed hyperfine anomaly, let us focus on the additional magnetization added when a neutron is added to ^{209}Fr. If we assume that the proton magnetization distribution is unchanged, then if the odd neutron magnetization is at a larger average radius than the proton magnetization, then the hyperfine interaction will be weaker in the s state than in the p state. The quantitative interpretation of these effects is currently in progress. It will be a significant challenge for nuclear theories to describe correctly both the charge distributions determined by

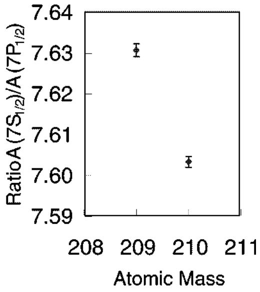

Figure 5. Ratios of hyperfine structure constants in 7S and 7P states for different isotopes.

isotope shift measurements, and the magnetization distributions available from hyperfine anomaly measurements. The eventual goal is to be able to understand in detail where the neutrons are in nuclei so that their weak interactions with the electrons can be evaluated with high precision.

References

[1] V.A. Dzuba, V.V. Flambaum, P.G. Silvestrov and O.P. Sushkov, J. Phys. B 20 (1987) 3297;
W.R. Johnson, Z.W. Liu and J. Sapirstein, At. Data Nucl. Data Tables 64 (1996) 279.

[2] V.A. Dzuba, V.V. Flambaum and O.P. Sushkov, Phys. Rev. A 51 (1995) 3454.

[3] C.S. Wood, S.C. Bennett, D. Cho, B.P. Masterson, J.L. Roberts, C.E. Tanner and C.E. Wieman, Science 275 (1997) 1759.

[4] B.A. Brown, Phys. Rev. C 78 (1998) 220.

[5] A. Bohr and V. Weisskopf, Phys. Rev. 77 (1950) 94.

[6] A. Coc, C. Thibault, F. Touchard, H.T. Duong, P. Juncar, S. Liberman, J. Pinard, J. Lermé, J.L. Vialle, S. Büttgenbach, A.C. Mueller and A. Pesnelle, Phys. Lett. B 163 (1985) 66.

[7] J.E. Simsarian, A. Ghosh, G. Gwinner, L.A. Orozco, G.D. Sprouse and P.A. Voytas, Phys. Rev. Lett. 76 (1996) 3522;
J.E. Simsarian, W. Shi, L.A. Orozco, G.D. Sprouse and W.Z. Zhao, Opt. Lett. 21 (1996) 1939;
W.Z. Zhao, J.E. Simsarian, L.A. Orozco, W. Shi and G.D. Sprouse, Phys. Rev. Lett. 78 (1997) 4169.

[8] W.Z. Zhao, J.E. Simsarian, L.A. Orozco and G.D. Sprouse, to be published in Rev. Sci. Instrum. 69 (1998).