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Possibilities for francium spectroscopy in a light trap

J.A. Behr, S.B. Cahn, S.B. Dutta, A. Görlitz, A. Ghosh, G. Gwinner, L.A. Orozco, G.D. Sprouse and F. Xu

Department of Physics, SUNY, Stony Brook, NY 11794-3800, USA

An experimental program is under way to capture neutral francium atoms in a magneto-optic trap. Production and transport of the radioactive Fr atoms near to the trapping region have been tested, with a steady state of 10^7 atoms. If one hundred atoms are captured from the Maxwell–Boltzmann distribution into a magneto-optic trap, this will be a sufficient number for spectroscopy of the unknown excited states. These measurements would then open the path to investigations of parity-violating transitions in francium.

1. Introduction

Alkali atoms have provided a wealth of information about the electronic as well as the nuclear structure of atoms. The single electron in the outer shell is a superb probe for subtle effects and is a very good handle for quantitative comparisons with theory. The energy levels of the alkalis are well known except for the heaviest of them, francium, with atomic number 87, because it has an unstable nucleus. Its required production in accelerators or as a daughter of radioactive processes has limited the study of its spectroscopy. A series of experiments during the last fifteen years [1,2] located the wavelength of the D_1 and D_2 lines of francium, as well as the hyperfine splitting of some of the different isotopes. Up until now, there are no experimental measurements of the position of the 8S energy level, although some calculations exist [3].

New and important studies of the spectrum of francium are now becoming feasible with the aid of novel techniques. The determination of the 8S energy level would be the first measurement to do in a light trap and would provide a good test of state-of-the-art calculations. It would also initiate the way towards the future detection of parity-non-conserving transitions.

Our efforts at Stony Brook during the last year have brought together two pieces of technology that can facilitate the search for the 8S energy level. We have developed a francium production apparatus consisting of a target, an ion transport system and a neutralizer. This apparatus provides up to 2×10^5 francium atoms per second at thermal energies. The production of francium atoms is optimized for the isotopes 209, 210, and 211, whose lifetimes exceed 30 seconds. Parallel to the

production and transport of the francium, we have built and operated magneto-optic traps for rubidium that permit us to have high densities of atoms trapped from the vapor in a cell. After some tests with rubidium in the accelerator, we will interface the francium production in the accelerator with a magneto-optic trap, in order to have a sample of cold francium atoms for laser spectroscopy. This combination of tools opens the possibility for very precise spectroscopy of radioactive atoms.

The ultimate goal of this project is to use the atom as a laboratory for precision measurements of parity-violating interactions. When the electron's wavefunction overlaps the nucleus, it can feel the weak force that destroys its pure parity state and thus allows a transition between two energy levels with the same orbital angular momentum. In order to be able to perform a measurement of the parity-non-conserving probability, one needs a very good knowledge of the atomic structure of the atom. This enables the separation of the different components that contribute to the signal and the extraction of information about the weak force.

A precision measurement of parity-violating transitions in francium can provide information about the interaction of electrons with quarks and as such probe effects of physics beyond the standard model. Atomic physics experiments with different elements map the parameter space of generalizations of the standard model and give information not available from high energy experiments [4].

As a first but firm step towards the parity-non-conservation measurements, we need the precise location of the 8S energy level. The electric dipole transition between 7S and 8S, forbidden by parity, is the one of interest here because our measurement can provide a testing ground for the most developed theories of electronic structure [5]. The comparison between the predictions and the experimental result has the potential to decrease the theoretical uncertainties that limit the precision of the Weinberg angle from the present cesium parity-non-conservation measurements [6].

2. Production and transport of francium

The first problem to study with francium is its production. At the superconducting linear accelerator of Stony Brook, we have built a low-energy ion transport system for francium and other alkalis. Among the different targets available for production of francium, we chose gold for its inert chemical properties, low vapor pressure and high melting point.

A tungsten rod holds a thick gold target at 45° to the accelerator beam direction. The heavy-ion fusion reaction of 115 MeV $^{18}O + {}^{197}Au$ produces francium recoil products (isotopes 211, 210 and 209) which are stopped in the target. The gold is heated to close to its melting point, allowing the francium to diffuse to the surface. The francium ionizes when it exits because of the high work function of gold. An electrode at 90° to the accelerator beam direction extracts the Fr ion beam. The francium ions are then transported by electrostatic optics to the vicinity of the trap about one meter away. To quantify the efficiency of the system, first we have

estimated the francium yield of the $^{18}O + ^{197}Au$ reaction by a statistical model calculation fitted to literature data [7] on the $^{16}O + ^{197}Au$ reaction. The result is that more than 15% of the francium produced in the target reaches the catcher. We have detected a rate at the catcher of 2×10^5 Fr/s, yielding at equilibrium a sample of 3×10^7 francium atoms. This scheme physically decouples the target diffusion at high temperature from the surface neutralization process, which can occur at a lower temperature more compatible with the neutral-atom trap. We have successfully neutralized francium by using surfaces coated with yttrium. We have determined that greater than 90% of the francium leaving such a surface is neutral by looking for francium α decays after the neutral atomic beam passes through a biased aperture. Our injection efficiency into the neutralizer remains to be determined. Similar geometries have achieved an overall neutralization efficiency of 80% [8].

3. Magneto-optic traps

Magneto-optic traps [9,10] provide an excellent environment for laser spectroscopy. They have been used successfully to measure ionization cross sections of rubidium [11]. The atoms are almost at rest, minimizing Doppler broadening.

The principle of operation for a magneto-optic trap combines three properties of the interaction between atoms and photons. Photons can transfer momentum to the atoms. Excitation of the atoms with photons slightly detuned to the red side of the resonance can lower the kinetic energy of the atom. Selective absorption of photons with appropriate angular momentum can be tuned by a spatially varying magnetic field.

The explanation given by Raab et al. [9] is as follows. An atom with a $J = 0$ ground state and $J = 1$ excited state in the presence of a weak magnetic gradient in the x direction will have its excited energy levels Zeeman split (see fig. 1 based on

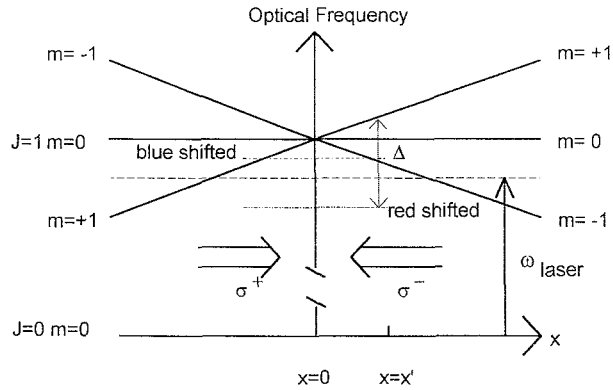

Fig. 1. Arrangement for a MOT from ref. [9]. The horizontal dashed line represents the laser frequency seen by an atom at rest. When moving, it will see the blue or red shifted frequencies. At $x = x'$, an atom moving to the right sees the σ^+ beam detuned by Δ, but the σ^- beam is almost resonant with the transition to $m = -1$.

ref. [9]). The atom is then illuminated with circularly polarized light, σ^+ propagating in the $+x$ direction and σ^- propagating towards $-x$. If the laser is tuned below the zero magnetic field resonance frequency, an atom at $x > 0$ will absorb more σ^- photons than σ^+ photons since the laser frequency is closer to the $\Delta m = -1$ transition. The momentum transferred by the σ^- photons will produce a new force toward the origin. For an atom at $x < 0$, the Zeeman shift is of opposite direction, and the force will again be directed towards the origin. Since the laser is tuned to the red side of the atomic resonance, cooling will occur. The laser detuning sets the order of magnitude of the trap well depth. When the excitation frequency is a linewidth away from resonance, the laser provides a well depth of about 0.5 K.

Due to the small well depth of the trap, collisions with background gas limit its lifetime far more than the deeper ion traps. However, since the lasers provide both cooling and trapping, it is possible to use them to trap from the Maxwell–Boltzmann distribution one finds in a cell [10]. As the slow atoms fall into the trap, the walls thermalize the depleted distribution, and then more can fall into the well.

The scheme we are developing now will trap the francium atoms in a glass cell connected at the end of the transport system and open only through the neutralizer. The separation between target and trap is vital for vacuum reasons.

The magneto-optic trap will operate in the D_2 line of francium at 718 nm. The trapping source is a Spectra Physics 380 ring dye laser. However, for the successful operation of the trap, it is necessary to repump the atoms that fall into the other hyperfine ground state [9,10]. We now have diode lasers Mitsubishi ML4405, cooled to liquid nitrogen temperature, working at 718 nm. They are tunable to the correct hyperfine transition for repumping.

To obtain an estimate for the laser frequencies needed, we take the 7S to 8S energy interval from table 3 of Dzuba et al. [3], and then use the measured values for the D_1 and D_2 lines [1]. Once the atoms are trapped, a scanning laser around 1730 nm will provide excitation from the $7P_{3/2}$ to 8S (see fig. 2). Some of the atoms

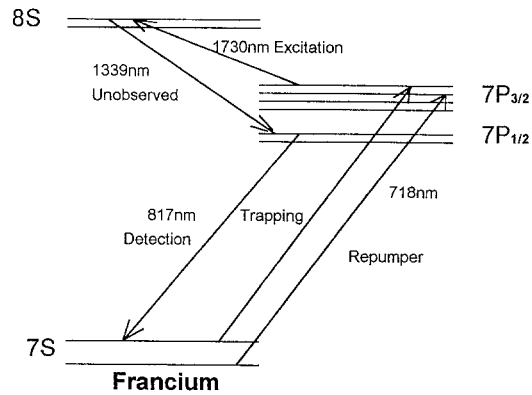

Fig. 2. Energy levels of francium used for the detection of the 8S state.

will decay down to the $7P_{1/2}$ state, emitting 1339 nm photons followed by a return to the 7S ground state with 817 nm photons. The last decay will clearly identify the transition.

From a Maxwell–Boltzmann distribution at room temperature and assuming a trap with a capture velocity of 8 m/s optimized according to the work of Lindquist [12], we calculate the number of passes through the interaction region necessary to capture 100 atoms from our available flux in a trap with lifetime longer than 1 second. The result is that if the atoms can bounce ten times off the walls, one hundred of them will end up trapped and the expected count rate from the $7P_{1/2}$ state at line center will be 15 KHz.

Many technical problems remain. One of the most important is the question of how many bounces will a francium atom make off the cell walls before it is lost either by sticking to them or by exiting the cell. The studies on cell coatings in the spin polarization of optically pumped atoms [13] quantify the stickiness of alkalis to the walls. The work by Stephens et al. presented at this workshop addresses in a systematic way the sticking problem in the context of capture of radioactive atoms [14].

4. Summary

The possibilities of francium spectroscopy are opening up right now. The techniques developed here are not unique to this atom and apply to many other atoms. It is important to note that laser cooling and trapping will allow preparation of a completely polarized sample of radioactive atoms. This will permit careful studies of the beta and alpha decay angular distributions that have relevance to the fundamental interactions in the nucleus.

The application of new atomic physics methods will again offer new insight into understanding fundamental interactions of nature.

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