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Traps for neutral radioactive atoms

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Abstract

We describe several methods for efficiently injecting a small number of radioactive atoms into a laser trap. The characteristics of laser traps that make them desirable for physics experiments are discussed and several different experimental directions are described. We describe recent experiments with the alkali element Fr and point to future directions of the neutral atom trapping program.

Keywords: Magneto-optical traps; Radioactive nuclear beams; Cooling; Electron–nucleus interactions; Weak interaction studies

1. Introduction

The development of methods for laser cooling and trapping of atoms [1] opened the possibility for many new areas of investigation, including Bose–Einstein condensation, cold atom–atom collision studies, and more precise atomic clocks. Similarly, the development of methods for producing and manipulating radioactive atoms [2] has allowed many new types of investigations of atomic nuclei and their properties with collinear laser spectroscopy, mass measurements in ion traps, and general decay studies of exotic species. It was only natural to try to merge these two areas of study, and attempt to produce radioactive atoms and confine them by laser trapping. The subject is reviewed in [3]. The experimental challenge is to efficiently capture into the laser trap the small intensities of radioactive atoms (of the order of 10^3–10^8 s^{-1}). The radioactive species are produced with energies of > 10 MeV, and to be captured in the laser trap they must have energies of $< 10^{-4}$ eV. The other constraint is that the atoms have a finite lifetime, and must be successfully removed from the target and injected into the trap in a time short compared to the lifetime.

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2. Trapping methods

Two basic methods have been developed to overcome these experimental challenges, and both have successfully trapped radioactive species for subsequent experiments. The first method [4] relies heavily on the ion source techniques used at ISOLDE and other radioactive beam facilities [2]. The basic method is to create an ion beam at the target, transport it near to the laser trap, and deposit it on a low work function material, that we call the neutralizer. Figure 1 shows a schematic of the apparatus. An atomic beam from the neutralizer is then closely coupled to a vapor cell Magneto-Optical Trap (MOT) [5], that is modified by the addition of a special coating [6] that reduces the fraction of injected atoms that would stick to the walls and not interact with the laser beams. The main advantage of this method is that it allows separation of the ion source from the trap by long distances, with efficient transport between them as ions. This method and its variations are used by most groups doing laser trapping of radioactive atoms [7–9]. A major disadvantage of the method is that the requirement to have the nonstick coating on all surfaces is a severe constraint for some measurements. Transfer of the trapped and cooled atoms to a second trap is then required [7,9].

The second method [10] forms an atomic beam directly at the target (see Fig. 2). Laser beams cool transverse motion and collimate the beam, and a longitudinal laser beam decelerates the atoms for injection into a standard MOT about 2 m away from the target. This method has been successfully used for several measurements with radioactive sodium isotopes. The advantage of this method is that the experiment of interest can be carried out directly in the capture MOT, because there is not a requirement of a nonstick coating on all surfaces. Since there is a direct path from the target to the MOT, it is important to minimize any other atomic species emanating from the target.

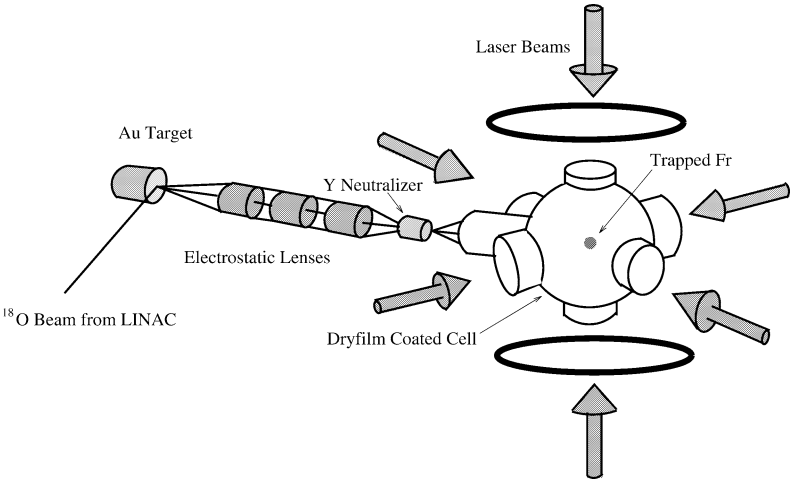

Fig. 1. Schematic of the apparatus to capture radioactive atoms in a magneto-optical trap.

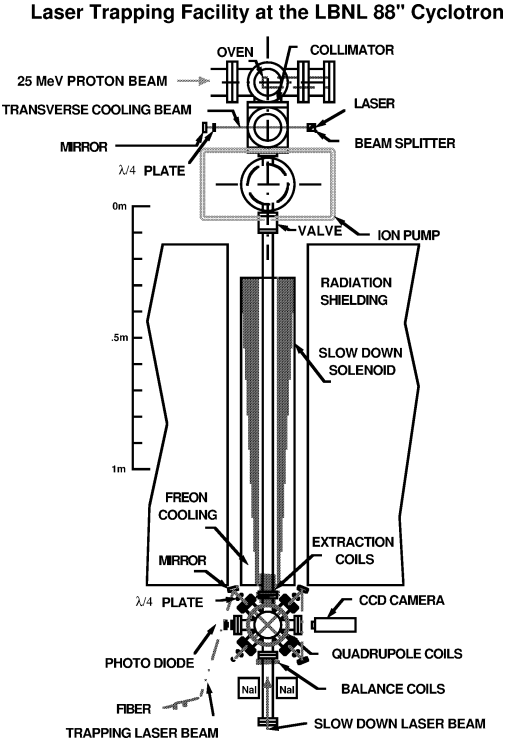

Fig. 2. Apparatus for injection into a MOT directly from an atomic beam from the target.

3. Physics programs

Potential applications arise from several features of the trapped radioactive atoms. Because the atoms are confined not only in physical space, but also in momentum space, there is a six-dimensional compression of the phase space of the atoms. This compression means that very small laser powers are required to excite the atoms to other states, because the available power can be concentrated into the small region containing the trapped atoms, typically of the order of 1–2 mm in diameter. The compression in momentum space also has a great advantage, because the Doppler shift of hot atoms usually spreads the absorption line over a wide range of frequency, so that a narrow laser line does not interact with all of the atoms. This is not the case with the cold atoms in the trap.

The trapping process is a resonant atomic excitation, and is therefore very selective, since atomic resonances for different isotopes and different isomers are usually separated by at least 100 line-widths of the radiation. Laser trapping is even more selective, since the resonance must be excited millions of times each second in order for the atom to remain in the trap, and this constraint has recently been shown to be a very powerful tool for detecting small numbers of rare atoms in the presence of a much larger background of other atoms [11].

The laser trap allows the suspension of the radioactive atoms in free space, without any material to slow or stop any of the decay radiations. This property has allowed the use of a small number of trapped atoms to be used as a beam scanner in a storage ring [12]. The atoms can be moved to different positions with very small fields that do not affect the particles in the ring, and interactions of the stored particles produce ions that can be easily detected with a channel plate. In the future, larger numbers of trapped atoms could be used as a target.

Laser traps are also used to suspend radioactive atoms for beta-decay experiments. The trap potentials are so small that the effects of the recoil of the atom from the emission of a neutrino can be directly measured. This effect has been observed in the beta decay of ^{38m}K by the TRIUMF group [9], and a sensitive search for scalar interactions in beta decay is underway.

Another feature that is of great interest is the ability to easily manipulate the polarization of the trapped atoms and nuclei with laser beams. In this case, the standard trap, the MOT, is not a good choice, since there is a magnetic field gradient on the atoms, and atoms in different locations in the MOT have different field directions. The solution to this problem has been solved for the first time with radioactive atoms by the Los Alamos group [7] that has succeeded in capturing radioactive atoms from a MOT into a rotating magnetic trap [TOP trap].

Atomic spectroscopy of radioactive elements is another application of interest. Francium, the heaviest alkali element, was discovered in 1939, but eluded investigation of its atomic properties until work at ISOLDE in the late 70s [2].

It is the heaviest "simple" atom, i.e., its properties can be calculated ab initio to high precision with modern methods. Its lighter neighbor, Cs, has been the focus of an extensive experimental [13] and theoretical [14] effort to search for the effect of the weak interaction in the atom, to compare with that predicted by the Standard Model. This comparison has indicated a slight deviation, that has been interpreted [15], along with other evidence, as a hint of the existence of a second Z boson. This result is not very significant statistically, and it is important to try to make an improved test. Francium is a natural choice for another experiment, since the size of the parity nonconservation effect in Fr is 15–18 times larger than in Cs. Additional experimental challenges must be overcome, because of the small quantity of Fr available. In addition, the preparation of a precision measurement in a trap requires new developments. Theoretical improvements must also be made to include still higher orders of interactions in a systematic way, but this development seems promising [16]. At present, it is necessary to continue to measure properties of Fr, so that comparison with theory can be carried out in detail. We have been carrying out a program [17] to test the Fr atomic theory to a level comparable to Cs, by measuring level energies, lifetimes and hyperfine structures. We present below the results of one of the recent measurements to determine the hyperfine anomaly in the light Fr isotopes, and its comparison with theory.

The weak interaction of the outer electron in an alkali is primarily with the neutrons [18]. Since the electron density is not uniform over the nuclear volume, accurate knowledge of the neutron distribution is necessary in order to extract the weak interaction strength from a measured atomic matrix element. A very similar situation occurs with the hyperfine interaction of the $7S_{1/2}$ and $7P_{1/2}$ states, where the different variation of the electron

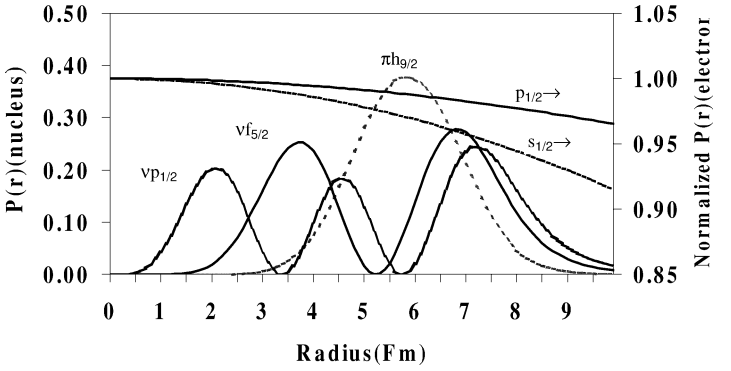

Fig. 3. Radial dependence of the normalized electron probability distribution near the Fr nucleus (right-hand scale) and radial dependence of the probability distributions for the valence proton and neutron states.

densities over the nuclear volume samples the nuclear magnetization with different radial dependence. The ratio of these two hyperfine interaction strengths is sensitive to the differences of radial distribution of the magnetization in different isotopes. Figure 3 shows the calculated radial electron distributions, along with the radial densities of various valence nucleon wave functions calculated with a Hartree–Fock description of the nuclei [19].

The even-N Fr isotopes have magnetic moments primarily attributable to the proton $h_{9/2}$ orbital, while the odd-neutron isotopes have, in addition, the spin moment of either the $p_{1/2}$ or $f_{5/2}$ neutron orbitals. The neutron magnetization is distributed at a larger radius than the proton magnetization.

4. Measurement of the $7P_{1/2}$ hyperfine structure in Fr

We recently measured the differential hyperfine anomaly in five isotopes $^{208–212}$Fr [17] and showed its sensitivity to the neutron radial distribution in the nucleus. The experiment consisted of preparing a sample of the Fr isotope of interest in a MOT, and then measuring the hyperfine splitting in the excited $P_{1/2}$ state. Since none of the isotopes of Fr are stable, the experiments were carried out at the Stony Brook LINAC, where we created $^{208–211}$Fr isotopes 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 to the MOT. The goal of the measurement technique was to transfer the hyperfine splitting to a frequency measurement in a way that would minimize drifts and other systematic errors. The ground-state hyperfine structure has been measured to very high precision by atomic beam resonance [20]. We use these measurements for the $7S_{1/2}$ ground state hyperfine structure, along with our new measurements for the $7P_{1/2}$ states to form the ratios, $\Delta = A(7S_{1/2})/A(7P_{1/2})$ that are plotted in Fig. 4. The ratios show a marked dependence on neutron number that is far greater than the measurement errors. In order to understand the observed changes in Δ let us first assume that the magnetization radius $\langle r^2\rangle_m$ is the same as the charge radius. The changes in the mean-square charge radii, $\langle r^2\rangle_c$, are known from [21]. The expected

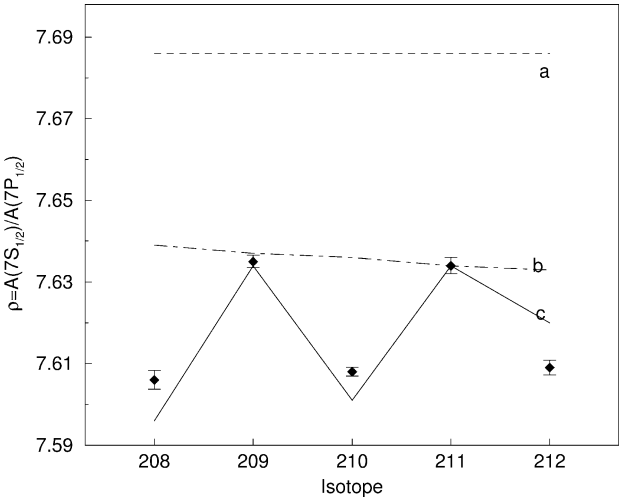

Fig. 4. Ratio of hyperfine structure constants $A(7S_{1/2})/A(7P_{1/2})$ for different isotopes of Fr. Curve a is for point nuclei, curve b assumes that the magnetization radius is the same as the charge radius and curve c is the calculated result with nuclear wave functions from [19].

dependence of the hyperfine constant ratio on the radial distribution of magnetization from Dzuba [11] is used for curve b in Fig. 4 with the assumption that the magnetization radius is proportional to the charge radius. The expected changes are consistent with the observations of the two odd–even nuclei, ^{209}Fr and ^{211}Fr, but do not show the large deviations of the nuclei with an odd number of neutrons. It is clear that the changes in the magnetization radii are much larger than the changes in the charge radii.

We then calculated the Bohr–Weisskopf effect [22], ϵ, with the methods of Ref. [23] for each isotope and then formed the ratio for the $7S_{1/2}$ and $7P_{1/2}$ states. These results are plotted in Fig. 4 as curve c. The calculation fits the data reasonably well. The additional experimental information provided by this hyperfine anomaly and the charge radii, can help to further constrain the model to give correct radial distributions of both neutrons and protons. These measurements provide one of the few handles on the neutron radial distribution in nuclei, and will help to constrain nuclear structure calculations. In addition, as the nuclear charge and magnetization radii are better understood, they will help to further test and refine the ab-initio atomic calculations which are of crucial importance to the understanding of PNC and QED effects in atoms. The light francium isotopes form a unique laboratory in which detailed calculations of both the nucleus and the atom are possible. More refined calculations in both systems should be able to eliminate many of the uncertainties which have clouded our understanding of the electron–nucleus interactions.

5. Conclusions

Atom traps have many unique features that make them a valuable tool for the study of radioactive atoms. Although the field is in its infancy, there are already many exciting applications to a broad range of physical problems.

Acknowledgement

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