Tests of Fundamental Symmetry Violations in Rare Atoms

Since the pioneering work of Khriplovich[1], and Bouchiat[2], it has been realized that the atom can be used as a laboratory to study the properties of the weak interaction. Such studies can complement the beautiful measurements at high energy that have determined the masses of the W and Z to high precision, and can provide a unique window to probe the weak interaction. The properties of some atoms can now be calculated[3,4,5] with 1% accuracy, with good prospects for further improvement. The heavy elements, Rn, Fr, and Ra are of particular interest, because in these nuclei, the electron-nucleus interaction is largest. In these atoms, the availability of a wide range of isotopes from an advanced accelerator facility would allow testing the isotopic dependence of the interactions, which can make the results less dependent on the theory of the atom, and can check whether there is a good understanding of the nuclear properties necessary to extract the weak interaction effects. In the following, we will discuss three possible types of measurements: 1) Testing the Standard Model with atomic parity nonconservation in francium; 2) Measurement of nuclear anapole moments in Fr to test the nucleon-nucleon weak interaction; and 3) Searching for the electric dipole moment in atoms to probe time-reversal violation.

Testing the Standard Model with Atomic PNC in Fr

The weak interaction between the electrons in an atom and the quarks in the nucleus produces an extremely small but measurable parity non-conserving(PNC) effect. Precision measurement[6] of this small effect in Cs, along with precision calculations[3,4,5] of the atom, has yielded results that differ from the Standard Model predictions by several standard deviations. Recently, this deviation has been interpreted[7] as a hint of the existence of a second Z^0. Clearly, this work needs to be extended and tested. The Cs experiment was very highly developed and future improvements will required new ideas and new methods. A promising pathway to improvement is to carry out the experiments with the heaviest alkali, francium, in which the PNC effects are 15-18 times larger than in Cs. Although Fr has no stable isotopes, recent progress in trapping radioactive atoms[8] has allowed detailed studies of the atomic properties of Fr[9,10]. A PNC experiment in Fr would have to be carried out in a neutral atom trap. The magneto-optical trap(MOT) that has been used in most applications is not suitable for a PNC measurement, because the magnetic field is non-uniform. An all-optical trap based on the dipole force can confine a cold sample of atoms in a controlled region. The measurement could then be carried out with a cycle to load, cool and excite the atoms. As in the Cs experiment, an electric field would be applied to the atoms in the trap, to induce a Stark mixing that interferes with the PNC amplitude. Interference between this and the PNC transition enhances the small PNC signal permitting the extraction of weak charge information.

Measurement of nuclear anapole moments in Fr to test the nucleon-nucleon weak interaction

It was realized for some time[1] that the electromagnetic interaction of atomic electrons with the nuclear anapole moment might generate a measurable nuclear-spin dependence in atomic parity violation experiments. The associated effects, which are considerably weaker than those of the coherent Z^0 interaction, involve a vector coupling to the atomic electrons and an axial coupling to the nucleus. The axial coupling to the nucleus is not coherent (only the last unpaired nucleon contributes). The nuclear anapole moment has the remarkable property that it grows as $A^{2/3}$, where

A is the atomic number, thus increasing in proportion to the nuclear surface area. The problem of separating the anapole moment contribution from the much larger coherent Z^0 exchange can be done by studying the dependence of the parity-violation signal on the choice of hyperfine level. The precision of the measurements of Wood et al.[6] produced the first definitive isolation of this nuclear-spin-dependent atomic parity violation. Calculations [11] show that the largest contribution to the nuclear anapole moment arises from parity mixing in the nuclear wave function, and measurements of the anapole moment now provide a new technique for studying the hadronic weak interaction. This interaction has proven more elusive than the weak interactions involving leptons. Whereas the charged-current hadronic weak interactions can be studied in strangeness- or charm-changing decays, the standard model predicts that neutral-current interactions do not change flavor. Thus, the only opportunity for studying the hadronic interactions of Z^0 is provided by nucleon-nucleon interactions, where parity violation must be exploited to separate the weak interaction from the much stronger strong and electromagnetic interactions.

Measurement of the anapole moment requires performing a PNC measurement in two different hyperfine levels. The difference of the PNC matrix elements between the two levels results from the anapole moment of the nucleus, while the average value can be related to the exchange of Z^0. Measurement of the anapole moment for a sequence of isotopes would be essential to be able to separate the nuclear structure effects from the basic interactions.

Search for the electric dipole moment in atoms to probe time-reversal violation.

Recent theoretical work by Flambaum and others[12] has shown that for certain heavy nuclei of Rn, Fr, and Ra that there can be considerable enhancement of the T-odd, P-odd electromagnetic moments. The nuclear moment can arise from a time reversal violating component of the hadron-hadron interactions. This moment can be considerably enhanced by the existence of closely spaced parity doublets in the spectrum of a nucleus with octupole deformation. The nuclei of most interest are ^{223}Rn, ^{221,223}Fr, and ^{223,225}Ra. The two Fr isotopes, which are most amenable to laser trapping, have lifetimes of 4 and 22 minutes respectively, while the Ra isotopes, which are ideal for ion trapping have lifetimes of 11 and 14 days respectively.

An electron electric dipole moment can also cause the atom to have an electric dipole moment, and this moment can be considerably enhanced by the nature of the atomic structure. Flambaum[13] has calculated the enhancement of the electron electric dipole moment in Fr as 910 and in Ra as 5400. The most recent measurement was done in Tl[14] with an enhancement factor of 585. An experiment to search for an electric dipole moment would consist of polarizing the atom of interest, and then applying a static magnetic field. Reversal of a strong electric field applied parallel or anti-parallel to the magnetic field will result in a change in the precession frequency if an atomic electric dipole moment is present.

Summary

Tests of fundamental symmetries can be more sensitive if heavy nuclei can be used, because of the enhancement of the effects by several factors. In some cases, the best nuclei for the measurements are unstable, and the measurements can only be made if copious amounts of the species of interest are available. Precision measurements of very small quantities require considerable time to be able to track down and sort out systematic uncertainties, so an important requirement for a facility is that there be the capability to provide some fraction of the beam to these experiments for an extended period of time. During actual data taking, intensities of $>10^{10}$/sec are estimated to be required for a broad range of isotopes.

References

1. See I.B. Khriplovich, Parity Nonconservation in Atomic Phenomena, Gordon and Breach, Philadelphia (1991) and references therein.
2. Bouchiat MA in Atomic Physics 12, Ed. R.R. Lewis and J.C. Zorn, AIP, New York, p. 399 (1991).
3. V. A. Dzuba, V. V. Flambaum, and O. P. Sushkov, Phys. Rev. **A51,** 3454 (1995).
4. W.R. Johnson, Z.W. Liu, and J. Sapirstein, At. Data Nucl. Data Tables **64,** 279 (1996).
5. M.S. Safronova, W.R. Johnson, and A. Derevianko, To be published in Phys. Rev A(2000).
6. C. S. Wood, S. C. Bennett, D. Cho, B. P. Masterson, J. L. Roberts, C. E. Tanner, and C. E. Wieman, Science 275, 1759 (1997), and C. S. Wood, S. C.Bennett, J. L. Roberts, D. Cho, and C. E. Wieman, Can. J. of Phys. 77, 7(1999).
7. Jens Erler and Paul Langacker, Phys. Rev. Lett 84 212 (2000), and J. L. Rosner, Phys. Rev. D 61, 016006 (2000).
8. G. D. Sprouse and L. A. Orozco, Ann. Rev. Nucl. Part. Phys., 47 (1997) 429-461.
9. 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).
10. See for example: J.S. Grossman, L.A. Orozco, M.R. Pearson, J.E. Simsarian, G.D. Sprouse, and W.Z. Zhao, Phys. Rev. Lett.**83,** 935 (1999), and references therein.
11. V. V. Flambaum, I. B. Khriplovich, O. P. Sushkov, Phys. Lett. B 146, 367 (1984).
12. V. Spevak, N. Auerbach, and V.V. Flambaum, Phys. Rev. C 56(1997)1357.
13. V. A. Dzuba, V.V. Flambaum, and J.S.M. Ginges, LANL preprint 9912028.
14. E. D. Commins, S. B. Ross, D. DeMille, and B.C. Regan, Phys. Rev. A50(1994)2960.