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The FrPNC Experiment, weak interaction studies in Francium at TRIUMF

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Abstract. Francium is an excellent system to study the nuclear weak force due to its large nucleus and relatively simple atomic structure. The FrPNC experiment has a facility to produce cold trapped atomic francium samples for parity non-conservation studies. We are preparing to measure both the nuclear spin independent and dependent parts of the weak interaction in francium. The first one gives information about weak neutral currents at low energies, while the second one is sensitive to weak interactions between nucleons. We present the current status of the experiment.

1. Atomic Parity Non Conservation

Nuclear forces have been studied traditionally by bombarding the nucleus with a high energy projectile and analyzing the kinematics of the dispersed particles. A different possibility for the study of the weak force is by Parity Non Conservation (PNC) measurements in atoms. This technique is actually not that different from the previous one, since there is still a collision with the nucleus, though weak and continuous, but now the projectile is one of the electrons in the atom. The momentum of the electron in the atom is much smaller to what can be obtained in particle accelerators giving smaller weak interaction strength, but that is compensated in the case of atomic PNC by repeated collisions by the same electron that provides long integration times such that the signal can be extracted with high precision measurements. Atomic PNC measurements are useful for studying the nuclear weak force at low energies (around 1 MeV).

Atomic PNC measurements look for subtle deviations in the behavior of the electrons in the atom due to interactions with the nucleus. The interactions coming from the nuclear weak force can be separated from other interactions due to the fact that they violate parity. Since time reversal symmetry is preserved at the measured level, the experiments look for the existence of a parity forbidden transition that becomes allowed due to the weak force. The signal grows with a bigger nucleus since the electron has more nucleons to interact with. Moreover, a nucleus with higher Z has a higher electronic density at the nucleus and the electrons have higher velocity. The three effects combine to give a scaling of the (nuclear spin independent) signal faster than Z^3 [1] making heavy atoms the preferred ones. The extraction of weak interaction constants from the measurements rely on atomic structure calculations [2]. Francium is ideal for atomic PNC studies, since it has a large nucleus and a relatively simple atomic structure [3,4]. Furthermore, it features in enhanced signals for testing other fundamental symmetries, such as time reversal symmetry in electric dipole moment (EDM) measurements of the atom [5].

2. The FrPNC experiment

The FrPNC experiment is devoted to the study of weak interactions using francium atoms. We plan to send Fr ions produced in the ISAC facility at TRIUMF to a Y neutralizer foil. After sufficient accumulation of ions we rotate the foil and heat it to release neutral Fr atoms to a high efficiency laser cooling trap [6]. After cooling the atoms, a laser pulse pushes the sample down to a science vacuum chamber where we recapture the atoms in a second trap [7]. We expect to trap an isotopically pure sample of more than 10^6 atoms confined to a small volume (less than 0.1 mm^3) and at a very low temperature (around 100 μK). The ISAC facility can produce a selection of isotopes in the range of A=203-229. The availability of different isotopes is a particularly interesting feature of the experiment compared to other atomic PNC experiments giving us access to both the neutron deficient and neutron rich francium nuclei. PNC measurements in different isotopes are sensitive to new physics and will help determine neutron skins that will reduce PNC errors induced by them in traditional measurements [4,8]. The long interaction times available with laser cooled atoms allow for coherent measurements that give higher precision, while the absence of atomic motion and the small confinement volume suppress velocity and bias field uniformity related systematic errors.

A 500 MeV proton beam from TRIUMF collides with a uranium carbide target to produce Francium. The ions are extracted with 60 kV and the selected isotope is separated at ISAC. The demonstrated yields for the different isotopes produced reaches values up to 10^8 s^{-1} [9]. The 1% trapping efficiency [6] combined with the production yield gives 10^6 atoms, more than enough for PNC measurements [10]. We have constructed a radio frequency and electromagnetic interference shielded modular room to house the experiment (Fig. 1). The room has an attenuation of 100 dB at electromagnetic frequencies from 14 kHz to 10 GHz that are present in an accelerator environment and also strongly reduces acoustic noise. The temperature and humidity control is currently being installed and should be stable to 0.5˚C and 5% relative humidity (at 45%) year round to maintain the lasers in a stable operating environment.

The weak interaction in atoms has a nuclear spin dependent and an independent part [11]. The nuclear spin independent part is the dominant one since it adds coherently over all nucleons. The magnitude of this interaction has been exquisitely measured in Cesium by quantifying the transition amplitude between the $6S_{1/2}$ to $7S_{1/2}$ levels [12]. The measurement together with atomic structure calculations give the value of the weak charge (Q_W). The weak charge is related to the Weinberg's angle and atomic PNC gives a value of $\sin^2\theta_W=0.2382(11)$ [2] at low energy (below 1 MeV). Francium is heavier than Cesium and the PNC effect is expected to be 18 times larger. The Cesium experiment uses an atomic beam that has the advantage of having a large atomic flux. The number of francium atoms will be smaller, but since they remain trapped, the number of atoms in the interaction region at any given time is similar to the experiments with Cs [13].

Fig. 1. Shielded room housing the FrPNC experiment in the ISAC hall. The metallic room is located below the blue platform.

The planned measurement of the weak charge follows the technique pioneered by Wieman and coworkers in Cesium [12]. A laser induces a transition between the $7S_{1/2}$ to $8S_{1/2}$ levels in Fr. The excited atoms decay back to either hyperfine level of the ground state. By initially pumping all the atoms into the lower ground hyperfine state, we can make use of a shelving technique to put the atoms that were excited into the upper hyperfine ground state for high efficiency optical detection using a cycling transition [14]. The interpretation of the results requires a good understanding of the atomic structure of Fr, and in that direction extensive spectroscopic studies have been performed over the years [11]. Three important quantities remain to be measured precisely for the eventual extraction of the weak charge: the M1 transition amplitude between the levels of interest [15] and the scalar and tensor polarizabilities (α and β). The measurement of the polarizabilities involves Stark induced transitions between different Zeeman levels. The M1 transition can be measured via an $E1_{\text{Stark}}$-M1 interference. These measurements serve as preparation steps for the more challenging PNC experiment since the method is very similar but with stronger transition amplitudes.

The spin dependent nuclear weak interaction is also of interest since it produces the nuclear anapole moment, which can be related to the weak nucleon coupling constants. The anapole moment has been measured in Cesium [12] and a number of other atomic and molecular PNC experiments are searching for anapole moments as well [16]. The expected signal in Fr is not only 11 times larger than in Cs, but the availability of different isotopes opens the possibility of separating the contributions to the anapole moment coming from valence protons or neutrons. The constraints produced by each one are no longer parallel, giving a crossing region for the weak nucleon coupling constants from a single experiment [13]. A complementary measurement in rubidium is an intriguing option since there are two stable isotopes available that have a valence proton in a different orbital that should produce an anapole signal of opposite sign [7]. The anapole moment can be measured by inducing E1 transitions between hyperfine levels in the presence of a static magnetic field [10]. A coherent interference with an M1 transition gives a signal to noise ratio larger than 1 (in 1s), a very large ratio for a PNC measurement. The extraction of the anapole moment from the measurement requires a good understanding of the nuclear structure involved [4,17].

3. Recent progress

There has been some preliminary work towards an anapole moment measurement using Rb at the University of Maryland. Out of the requirements we demonstrated: long coherence time M1 transitions, the sensitivity of the interference method, a blue detuned trap and a requirement for a pure transverse mode of the microwave cavity. The blue detuned trap uses two perpendicular acousto-optic modulators fed by two phase locked function generators (SRS DG345) to dynamically change the shape of the trap [18]. The measurements using the M1 clock transition give a 180 ms coherence time, which is much larger than the one we obtain using optical Raman transitions [19]. Furthermore, the microwave M1 transitions are simpler to use than the Raman transitions and give less stringent constraints in the mechanical stability of optical elements. To test the interference method we use two M1 fields, one represents the interfering M1 transition and the other one has a Rabi frequency 100 times smaller and simulates the E1 anapole allowed transition. We can resolve the second field with a signal to noise ratio of 20 [19]. We quantified the differential AC Stark shift of the transition in the dipole trap and found a scaling inversely proportional to the detuning. We are designing and constructing a second generation microwave Fabry-Perot cavity, following a quasi-optics solution. The mirrors feature imprinted patterns to control the reflectivity and polarization of the circulating microwaves and the mode will be controlled using the appropriate microwave horns. The mirror design benefitted from calculations using the HFSS electromagnetic field simulation software [20]. Further progress will occur at TRIUMF where we have now a working Rb trap (Fig. 2).

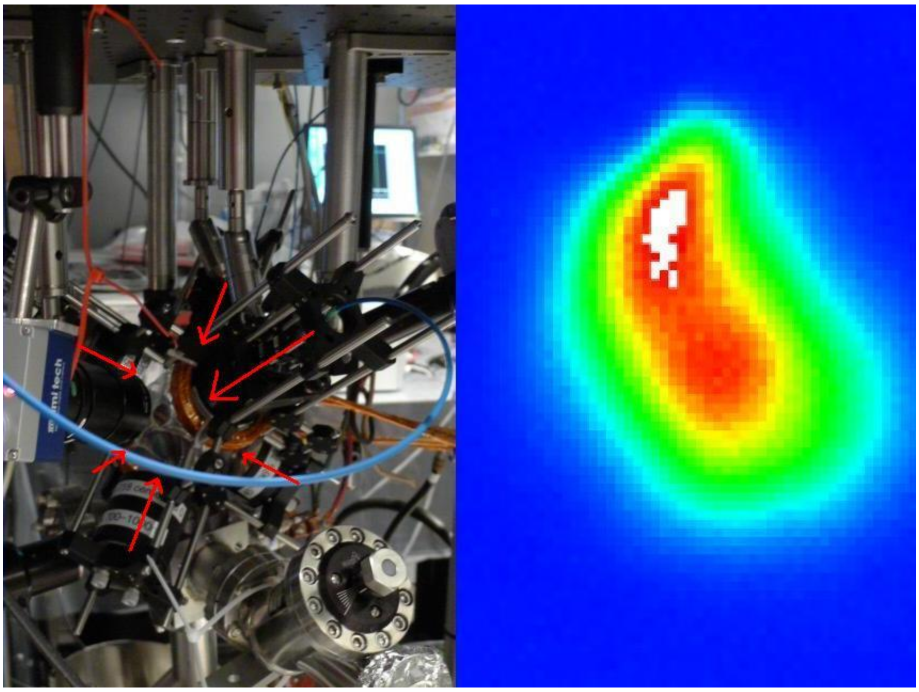

Fig. 2. Optical fiber-based laser cooling trap at TRIUMF (left, with red arrows indicating the trapping laser beams) and fluorescence image of the trapped Rb atoms (right).

In summary, the FrPNC collaboration has now moved to TRIUMF where we are building a facility for obtaining cold and trapped francium atoms. We plan to use the francium for atomic PNC measurements to probe and study the weak nuclear force. A measurement of the nuclear spin-independent part can be used to determine the weak charge and the weak-mixing Weinberg angle at low energies, while a measurement of the nuclear spin-dependent PNC and the anapole moment will help constrain the weak nucleon coupling constants.

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References

[1] Bouchiat M A and Bouchiat C 1997 *Rep. Prog. Phys.* **60** 1351
[2] Porsev S G and Beloy K and Derevianko A 2010 *Phys. Rev.* D **82** 036008
[3] Ramsey-Musolf M J and Page S A 2006 *Annu. Rev. Nucl. Part. Sci.* **56** 1
[4] Sil T and Centelles M and Viñas X and Piekarewicz J 2005 *Phys. Rev.* C **71** 045502
[5] Mukherjee D and Sahoo B K and Nataraj H S and Das B P 2009 *J. Phys. Chem.* A **113** 12549
[6] Aubin S and Gomez E and Orozco L A and Sprouse G D 2003 *Rev. Sci. Instr.* **74** 4342
[7] Sheng D and Orozco L A and Gomez E 2010 *J. Phys.* B **43** 074004
[8] Brown B A and Derevianko A and Flambaum V V 2009 *Phys. Rev.* C **79** 035501
[9] http://www.triumf.info/facility/research_fac/yield.php?element_name=Fr
[10] Gomez E and Aubin S and Sprouse G D and Orozco L A and DeMille D P 2007 *Phys. Rev.* A **75** 033418
[11] Gomez E and Orozco L A and Sprouse G D 2006 *Rep. Prog. Phys.* **69** 79
[12] Wood C S and Bennett S C and Cho D and Masterson B P and Roberts J L and Tanner C E and Wieman C E 1997 *Science* **275** 1759
[13] Behr J A and Gwinner G 2009 *J. Phys.* G: *Nucl. Part. Phys.* **36** 033101
[14] Wood C S and Bennet S C and Roberts J L and Cho D and Wieman C E 1999 *Can. J. Phys.* **77** 7; Rowe M A and Freedman S J and Fujikawa B K and Gwinner G and Shang S Q and Vetter P A 1999 *Phys. Rev.* A **59** 1869
[15] Savukov I M and Derevianko A and Berry H G and Johnson W R 1999 *Phys. Rev. Lett.* **83** 2914
[16] Ferro F and Surzhykov A and Stöhlker T 2011 *Phys. Rev.* A **83** 052518; DeMille D and Cahn S B and Murphree D and Rahmlow D A and Kozlov M G 2010 *Phys. Rev. Lett.* **100** 023003; Mandal P and Mukherjee M 2010 *Phys. Rev.* A **82** 050101(R)
[17] Kanjilal D and Saha S and Bhattacharya S and Goswami A and Kshetri R and Raut R and Muralithar S and Singh R P and Mukherjee G and Mukherjee B 2011 *Phys. Rev.* C **84** 064321
[18] Sheng D and Perez Galvan A and Zhang J and Orozco L A “Atoms in a blue detuned dipole trap: studies of coherence and dynamics for precision measurements in the classical and quantum regimes.” To be submitted
[19] Sheng D and Zhang J and Orozco L A “Sensitivity test of blue-detuned dipole traps designed for parity non-conservation measurements in Fr.” Submitted
[20] Zhang J and Hood J D and Orozco L A “Microwave Fabry-Perot open resonator for francium spectroscopy.” To be submitted