The FrPNC Experiment at TRIUMF: Atomic Parity Non-Conservation in Francium

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Abstract. The FrPNC collaboration has begun the construction of an on-line laser cooling and trapping apparatus at TRIUMF to measure atomic parity non-conservation (PNC) and the nuclear anapole moment in a string of artificially produced francium isotopes. Atomic PNC experiments provide unique high precision tests of the electroweak sector of the Standard Model at very low energies. Furthermore, precision measurements of spin-dependent atomic PNC can determine nuclear anapole moments and probe the weak force within the nucleus. Francium is an excellent candidate for precision measurements of atomic PNC due to its simple electronic structure and enhanced parity violation: both the optical PNC and anapole moment signals are expected to be over an order of magnitude larger than in cesium.

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INTRODUCTION

Parity non-conservation (PNC) in atomic systems provides a unique low-energy probe of the electroweak sector of the Standard Model and of inter-nucleon weak interactions. While atomic PNC effects are generally very small, they are enhanced in heavy atoms, and the high precision of atomic spectroscopy is sufficient for resolving PNC signals. The FrPNC collaboration is establishing a facility at the TRIUMF nuclear physics accelerator in Vancouver, Canada, to conduct precision atomic PNC measurements in a series of francium isotopes.

The planned francium PNC measurements are sensitive to extensions of the Standard Model in the electroweak sector and can constrain PNC electron-quark couplings complementary to electron scattering. Measurements of francium anapole moments in a string of isotopes will help separate the isovector and isoscalar parts of the weak nucleon-nucleon interaction: At present, low-energy nuclear parity violation experiments and nuclear anapole moment measurements are at odds and do not produce a consistent set of weak nucleon-nucleon couplings [1, 2].

ATOMIC PNC

Atomic PNC processes can be separated into nuclear spin-independent (NSI) and nuclear spin-dependent (NSD) interactions between orbiting electrons and the nucleus. The dominant PNC effect in heavy atoms is the NSI process in which an axial electron exchanges a Z^0 boson with a vector nucleon, as shown in Figure 1(a). In this case, the effect adds coherently for all nucleons, and in the limit of an infinitely heavy nucleus, the PNC Hamiltonian for a single valence electron without radiative corrections is given by [3]

$$H_{PNC,NSI} \simeq \frac{G_F}{\sqrt{2}} \frac{Q_W}{2} \gamma_5 \rho(\overrightarrow{r}) \tag{1}$$
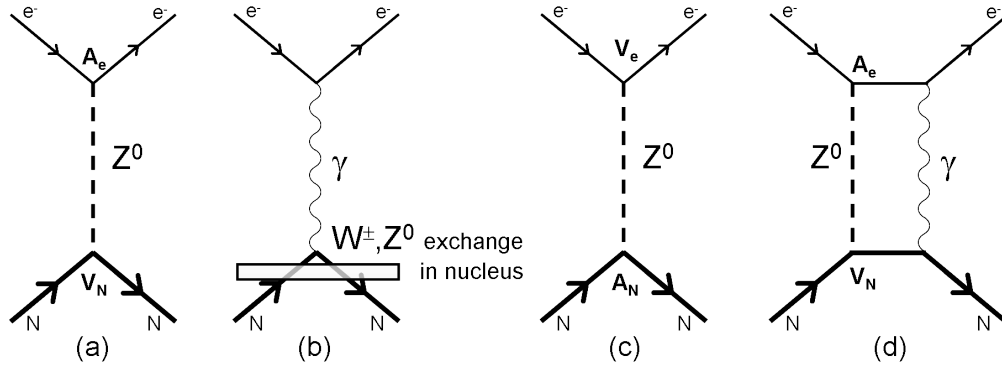
FIGURE 1. Atomic PNC processes. (a) The dominant process in NSI optical PNC involves the exchange of a Z^0 boson between an axial vector electron current and a vector nucleon current. (b) The dominant NSD PNC effect in heavy atoms is due to the anapole moment of the nucleus, which is generated by inter-nucleon weak interactions. The remaining diagrams show the much smaller contributions to NSD PNC involving (c) NSD Z^0 exchange between an axial vector nucleon current and a vector electron current, and (d) NSI Z^0 exchange in combination with the hyperfine interaction.

where $G_F = 10^{-5} m_p^{-2}$ is the Fermi constant, m_p is the proton mass, γ_5 refers to the Dirac matrix, $\rho(\vec{r})$ is the neutron distribution, and $Q_W = 2(\kappa_{1p}Z + \kappa_{1n}N)) \approx -N$ is the weak charge of the nucleus (Z and N are the number of protons and neutrons, respectively). At tree level, the Standard Model gives $\kappa_{1p} = \frac{1}{2}(1 - 4\sin^2\theta_W)$ and $\kappa_{1n} = -\frac{1}{2}$ with the Weinberg angle $\sin^2\theta_W \sim 0.23$. NSI parity violation scales as $Z^3 R$ with a relativistic enhancement factor R, favoring heavy atoms such as francium: the PNC signal in francium is expected to be 18 times larger than in cesium [4, 5].

In heavy atoms such as francium, the dominant contribution to NSD parity violation is due to the electromagnetic interaction of an electron with the nuclear anapole moment of the valence nucleon, depicted schematically in Figure 1(b). The anapole moment is a parity violating nuclear electromagnetic moment due to inter-nucleon weak interactions. The Hamiltonian for an electron interacting with the anapole moment is given by

$$H_{PNC,\,NSD} = \frac{G_F}{\sqrt{2}} \frac{K \vec{I} \cdot \vec{\alpha}}{I(I+1)} \kappa_{a,i} \widetilde{\delta}(\vec{r}) \text{ , with } \kappa_{a,i=n,p} = \frac{9}{10} g_i \frac{\alpha \mu_i}{m_p \widetilde{r}_0} A^{2/3} \tag{2}$$

where $K = (I+1/2)(-1)^{I-l+1/2}$, l is the orbital angular momentum of the valence nucleon, I is the nuclear spin, $\vec{\alpha}$ are Dirac matrices, and $\widetilde{\delta}(\vec{r})$ indicates that the anapole moment produces a contact interaction for the electron dictated by the valence nucleon distribution. $\kappa_{a,i=n,p}$ is the effective interaction constant for the anapole moment produced by a valence neutron or proton, respectively. α is the fine structure constant, μ_i is the magnetic moment of the valence nucleon in nuclear magnetons, $\widetilde{r}_0$=1.2 fm is the nucleon radius, and $A = Z + N$ is the atomic mass. While NSD Z^0 exchange and NSI Z^0 exchange in combination with the hyperfine interactions, shown respectively in Figures 1 (c) and (d), produce NSD parity violation, their contribution is expected to be more than an order of magnitude smaller than that of the anapole moment. The NSD parity violation produced by the anapole moment leads to a $Z^{8/3}R$ scaling for the atomic PNC signal: the NSD PNC effect in francium is expected to be 11 times larger than in cesium [6].

EXPERIMENTAL IMPLEMENTATION

The FrPNC collaboration proposes to measure both optical PNC and the nuclear anapole moment in a chain of laser-cooled francium isotopes produced by spallation of a uranium carbide target with 500 MeV protons at the ISAC facility at TRIUMF. Both experiments measure the degree of PNC-induced mixing of the $|s\rangle$ and $|p\rangle$ opposite parity wavefunctions with parity-forbidden transitions. The weak mixing angle can be determined from an optical PNC measurement of the parity forbidden E1 transition between the $7s$ and $8s$ levels (see Figure 2(a)), originally pioneered by Wieman and co-workers in cesium [7]. Nuclear anapole moments can be measured with microwave parity-forbidden E1 transitions between the hyperfine manifolds of the $7s$ level (see Figure 2(a)) [8] or through the dependence of the optical PNC method on the hyperfine states [7].

The experiments measure a change in the "forbidden" transition rate upon the reversal of the handedness of the atoms' coordinate system. The coordinate system of the atom is defined by reversible perpendicular external fields. In
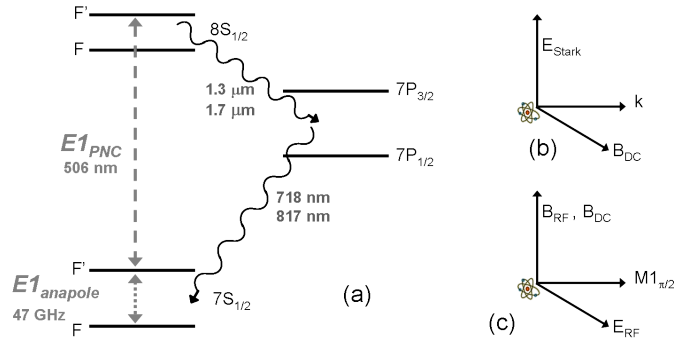
FIGURE 2. Francium energy levels and effective PNC coordinate vectors. (a) The 7*s*, 8*s*, and 7*p* energy levels relevant for the PNC measurements: the optical PNC method relies on the parity forbidden transition between the 7*s* and 8*s* levels, while the anapole moment experiment measures the NSD parity forbidden transition between the hyperfine manifolds of the 7s level. External electromagnetic field vectors are used to form a coordinate system, whose handedness can be changed by flipping any one of the defining fields, for the atoms in (b) the optical PNC and (c) anapole moment measurements.

the optical PNC experiment, the momentum $\overrightarrow{k}$ of the excitation photon, an external Stark shift electric field $\overrightarrow{E}_{Stark}$, and a magnetic field $\overrightarrow{B}_{DC}$ determine the sign of the transition rate change, which is proportional to $\overrightarrow{B}_{DC} \cdot (\overrightarrow{k} \times \overrightarrow{E}_{Stark})$ (see Figure 2(b)). Similarly, in the case of the anapole moment experiment, the population change in the hyperfine levels upon application of an electric microwave field $\overrightarrow{E}_{RF}$ is proportional to $\overrightarrow{B}_{DC} \cdot (\overrightarrow{M1}_{\pi/2} \times \overrightarrow{E}_{RF})$, where a microwave magnetic field employing an M1 transition is used to put the atoms in an equal superposition of two upper and lower hyperfine states (see Figure 2(c)). Accurate extraction of the weak-mixing angle from an optical PNC measurement and of isoscalar and isovector weak nucleon-nucleon interaction parameters from an anapole measurement will benefit significantly from conducting a series of measurements in a string of isotopes in order to account for uncertainty in nuclear structure and the neutron skin thickness [9]. Existing efforts to directly measure the neutron skin thickness in ^{208}Pb are also important for reducing this source of systematic uncertainty [10, 11].

At present, the FrPNC collaboration is in the process of constructing a radio-frequency shielded laser laboratory room in the ISAC hall of TRIUMF. The ISAC facility at TRIUMF has successfully produced a number of francium isotopes at rates in the range of $10^7 - 10^8$Fr/s, including $^{206-213}$Fr and $^{220-222}$Fr. Once the laboratory is completed, the collaboration will proceed with laser cooling and trapping of francium, followed by experiments to measure hyperfine anomalies and the strength of the strongly suppressed 7*s*-8*s* M1 transition, before starting the optical PNC and anapole moment measurements.

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