Atomic PNC in Fr as a probe of new physics
FrPNC Collaboration*

**Motivation:** Atomic parity nonconservation (APNC) experiments have been discussed since the early 1990s in the context of searches for ‘new’ physics beyond the Standard Model (SM) [1]. APNC arises from the parity-violating exchange of $Z^0$-bosons between electrons and the quarks in the nucleus, leading to a mixing of atomic levels of opposite parity [2]. As a result, otherwise forbidden electric dipole transitions can be excited between states of the same parity. APNC was first observed in the late 1970s [3]. The measurement by the group of Wieman in Boulder in $^{133}$Cs [4] represents the most precise measurement to date. APNC scales with the nuclear charge roughly as $Z^3$, favoring experiments in heavy atoms (see the recent results in Yb in Ref. [5]), but a successful extraction of the weak interaction physics from the measured atomic quantity also requires a detailed understanding of the atomic wavefunctions. The experiment measures a product of the weak charge and a matrix element (proportional to $\gamma^5$) has to come from precise atomic calculations (e.g. Ref. [7]).

Atomic physics experiments benefit from the long interaction time between the electron and the nucleus compared to high energy collisions. The interaction between an electron and a nucleon can be mediated by a photon if it is electromagnetic, by a $Z^0$ boson if it is weak according to the minimal standard model. APNC has played an important role in uncovering the neutral current weak interaction. Shortly after the landmark e-D inelastic scattering experiment at SLAC [8] measured the parity violating part of the neutral current weak interaction, APNC confirmed these findings at a very different momentum scale. In terms of the electron-quark coupling constants $C_{1u}$ and $C_{1d}$, APNC provides constraints nearly perpendicular to those of the SLAC experiment. A sequence of increasingly refined APNC experiments throughout the 1980s tightened these constraints to well below those of scattering experiments such as e-D at SLAC and e-carbon at BATES. Until the LEP collaborations published their results, APNC provided a competitive value for $\sin^2 \theta_W$. This feat is no longer possible in the post-LEP era, but nevertheless low energy experiments have a key role to play. For example, when new states are discovered at the LHC, it will be important to know their couplings to the first generation of particles.

APNC measures the strength of the weak neutral current at very low momentum transfer. There are three types of such “low-energy” weak neutral current measurements with complementary sensitivity. The atomic weak charge is predominantly sensitive to the weak charge of the neutron, as the proton weak charge is proportional to $1 - 4\sin^2 \theta_W$ which accidentally is near zero. The Qweak electron scattering experiment on hydrogen will be sensitive to the weak charge of the proton (see Ref. [6] for a recent result on weak charge calculations). The SLAC E158 Moeller scattering is sensitive to the electron’s weak charge. Different Standard Model extensions then contribute differently [9]. The atomic weak charge is relatively insensitive to one-loop order corrections from all SUSY particles, so its measurement provides a benchmark for possible departures by the other low-energy observables. Moeller scattering is purely leptonic and has no sensitivity to leptoquarks, so APNC can then provide the sensitivity to those.

In addition to the leading-order *nuclear spin independent* APNC effect, parity-violating nuclear spin dependent effects such as the nuclear anapole moment can be observed [12]. This information can be used to extract isoscalar and isovector coupling constants for the weak interaction in the nucleus. A recent lattice gauge calculation [11] is consistent with the smallness of the isovector nucleon-nucleon parity violating constant $f_\pi$ indicated by $^{18}$F experiments.
**Goals:** One goal is to measure the weak electron-neutron charge in $^{207-213}$Fr and $^{220-225}$Fr with equal or better accuracy to $^{133}$Cs. The charge radii of these heavy nuclei are quite regular, and with the information from PRex on the neutron radius of Pb should minimize the uncertainty from the neutron radius [13], particularly when coupled with our planned hyperfine anomaly measurements concerning the valence nucleon magnetism distribution.

Another goal of the FrPNC collaboration is to measure the anapole moment in $^{207-213}$Fr with few percent accuracy. These nuclei show regular behavior driven by the valence nucleons in their spins, magnetic moments, and even the next moment of nuclear magnetism from the atomic hyperfine anomaly [14]. We plan to measure the extent to which the anapole moment is driven by valence nucleons— itself an open question in the anapole physics and use that information to extract isovector and isoscalar dependence of the weak nucleon-nucleon interaction in the nuclear medium.

**Intensity frontier:** The successful APNC experiments require as many atoms as possible ($N$). Current efforts with rare isotopes incorporate laser trapping and cooling to ensure large samples for interrogation [12], ensuring the large $N$ regime. The planned energy and current for Nuclear studies in Project X at Fermi Lab would allow to produce many orders of magnitude more Fr than currently available at TRIUMF. To achieve this flux of more than $10^{12}$ Fr/s will require development of appropriate targets and handling facilities. The flux has the potential to enable APNC and other fundamental symmetry tests in Fr.

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