Weak interaction studies in Fr

Luis A. Orozco on behalf of the FrPNC collaboration *[1], †

[1] *Joint Quantum Institute, Dept. Physics, University of Maryland, College Park, MD 20742, USA*

A program to study weak interactions at the Francium Trapping Facility in TRIUMF is a unique opportunity to explore weak physics in the presence of strong interactions through the systematic measurement of anapole moments in a chain of Fr isotopes and physics beyond the Standard Model by measuring the weak charge through atomic parity non-conservation.

I. EXECUTIVE SUMMARY

Weak interaction studies in atoms provide through ultra-precise spectroscopy of highly-forbidden transition a unique path to probing the neutral weak current. The approach is complementary to other investigations in nuclear and particle physics. Parity non-conservation (PNC) is a unique signature of the weak interaction. The weak interaction produces two types of PNC effects in atoms: nuclear spin independent and nuclear spin dependent. The nuclear spin independent PNC (V_nA_e) has all the nucleons acting coherently. Nuclear spin dependent PNC occurs in three ways: an electron interacts weakly with a single valence nucleon (nucleon axial-vector current A_nV_e), an electron experiences an electromagnetic interaction with a nuclear chiral current created by weak interactions between nucleons (anapole moment), and the combined action of the hyperfine interaction and the spin-independent Z^0 exchange interaction from nucleon vector currents (V_nA_e).

The weak interaction in hadrons is richer than in leptons since it occurs in the presence of the strong interaction which renormalizes the axial current. Advances both in theory and experiment are increasing our knowledge of this subject. These developments have brought with them the need to better understand Quantum Chromo-Dynamics (QCD) at low energy. There is an impressive theoretical development based on QCD that has produced an effective field theory (EFT) for the hadronic weak interaction.

The attractiveness of heavy atoms, for example Fr, for atomic parity nonconservation (APNC) experiments has been discussed since the early 1990s in the context of searches for new physics beyond the SM. The atomic theory of Fr, can be understood at a level similar to that of Cs where the most precise measurement has been performed to date, yet the APNC effect is almost 20 times larger. The running of $\sin^2\theta_w$ and different sensitivities to physics beyond the Standard Model (SM) require additional electroweak tests in addition to the accurate collider results at the Z-pole. Among the existing and upcoming experiments, APNC is competitive concerning searches for leptoquarks, compositeness, and some classes of extra gauge bosons.

The recently commissioned Francium Trapping Facility (FTF) at the Isotope Separator and Accelerator (ISAC) of TRIUMF in Vancouver, Canada is enabling a program of studies of weak interaction physics in neutral atoms at low energy by the international FrPNC collaboration. The methodology combines nuclear and particle physics techniques with precision measurements based on cold neutral atom trapping and precise spectroscopy. The ultimate goal is to further our understanding of the weak interaction through its study in a system whose atomic properties are well known. The experimental programs under way are: First, the measurement and systematic study of the anapole moments in a series of isotopes that can provide critical and crucial information for enhancing our understanding of the delicate interplay of QCD with the weak interaction in the nucleus.The isotopes from ^{207}Fr through closed neutron shell ^{213}Fr have regular nuclear magnetic moments as well as (through our own precise atomic spectroscopy) the next order magnetism distribution, making them useful candidates for a systematic study of the anapole moment. This opens the possibility to measure the anapole moment of nuclei with an odd number of neutrons to contribute to the understanding of the less-known isoscalar weak N-N interaction. Second, the measurement and systematic study of atomic parity non-conservation that can give the weak charge constraining extensions of the SM.

* Corresponding Author

†Electronic address: lorozco@umd.edu

II. PHYSICS

A. Anapole

The anapole moment in heavy nuclei arises from the weak interaction between the valence nucleons and the core. By including weak interactions between nucleons in their calculation of the nuclear current density, Flambaum *et al.* [1] estimate the anapole moment of a single valence nucleon. Based on this, Flambaum and Murray [2] took the parametrization of Desplanques, Donoghue, and Holstein (DDH) [3] and found the corresponding coupling constants associated with the anapole moment of Cs under these assumptions.

The nuclear anapole comes from a number of effects, though detailed calculations suggest it is dominated by core polarization by the valence nucleons [4]. Anapole moments measurements of odd-neutron and even-neutron Fr isotopes would constrain isovector and isoscalar weak N-N couplings in the nuclear medium, if systematic measurements of the odd-even dependence in several francium isotopes (A around 210) successfully show that polarization of the core by the valence neutron is the main effect. Testing the striking predictions of this simple model near closed neutron shells, such as in francium 213, and its even-odd staggering behavior, could clarify such a phenomenological treatment to allow the extraction of the weak hadronic physics. If the prediction fails, then it would provide necessary information as input to more sophisticated shell model treatments to extract the weak interaction physics. This single valence nucleon approach gives results consistent with the more detailed calculations of Ref. [4] and confirms their assessment that new anapole measurements in odd-neutron nuclei would have great impact, defining a band of the weak meson-nucleon coupling plane. Ref. [5] presents our sensitivity analysis of the isovector and isoscalar weak N-N couplings plane to the anapole measurement.

The weak interaction in hadrons is richer than in leptons since it occurs in the presence of the strong interaction which renormalizes the axial current. Theoretically the task to relate the underlying electroweak currents to low energy observables is complicated by the fact that in this regime QCD is non-perturbative [7]. In addition to its intrinsic interest, the understanding of how hadronic weak interactions are changed in nuclei has practical phenomenological implications [6]. Recent advances by Wasem [8] on calculating nuclear parity violation on the lattice show promise towards the study of weak interactions in the presence of hadronic interactions.

The 2014 preliminary result of $n+p \to d+\gamma$ supports the ^{18}F and lattice gauge calculations of a very small isovector weak NN coupling. The origin of this small coupling remains a mystery. The isoscalar coupling is defined reasonably well by two other experiments, which the Cs anapole is in tension with, making it an interesting puzzle. That could be a problem with the nuclear structure, which we are in a good position to address in a well-defined regular chain of nuclei and to extract isoscalar and isovector pieces in a heavy nucleus. If the discrepancy remains, that could indicate some renormalization of the interaction in heavy complex nuclei, which would be important to understand for its own sake and for other problems like double beta decay.

B. APNC

APNC has played an important role in uncovering the neutral current weak interaction. Shortly after the landmark e-D inelastic scattering experiment at SLAC [9] measured the parity violating part of the neutral current weak interaction, APNC confirmed these findings at a 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. Electrons and muons can be distinguished in the detectors, but up/down quark jets cannot be distinguished from jets of other generations. APNC and other low-energy experiments are in a unique position to assist with this question.

APNC measures the strength of the weak neutral current at 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 neutron weak charge, 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 proton weak charge. The SLAC E158 Moeller scattering is sensitive to the electron weak charge. Different Standard Model extensions then contribute differently [10]. 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. The low-energy experiments are sensitive in different ways to the parameters of the SM; Qweak and APNC probe different quark combinations and E158 probes leptons, the sensitivities to physics beyond the SM is different.

III. METHODOLOGY

The weak interaction in atoms induces a mixing of states of different parity, observable through PNC measurements. Transitions that were forbidden due to selection rules become allowed through the presence of the weak interaction. The transition amplitudes are generally small and an interference method is commonly used to measure them. A typical observable has the form

$$|A_{PC} + A_{PNC}|^2 = |A_{PC}|^2 + 2Re(A_{PC}A^*_{PNC}) + |A_{PNC}|^2, \tag{1}$$

where A_{PC} and A_{PNC} represent the parity conserving and parity non-conserving amplitudes. The second term on the right hand side of the equation side corresponds to the interference term and can be isolated because it changes sign under a parity transformation. The last term is negligible.

A. Anapole

The measurement strategy of the nuclear anapole moment, detailed in Refs. [5, 11], relies on PNC. Our method looks for the parity forbidden microwave electric dipole (E1) transition between the ground state hyperfine levels in a chain of isotopes of Fr. Measurements in a series of isotopes offer the advantage that they can focus on the differences appearing as the number of neutrons changes.

The E1 transition between hyperfine levels is parity forbidden, but becomes allowed by the anapole-induced mixing of levels of opposite parity. The general approach has been suggested in the past [12–19]. Briefly, francium atoms captured and cooled in a capture chamber are transferred to a science chamber where they are placed inside a microwave Fabry-Perot cavity and held in a blue-detuned dipole trap. The trapped atoms interact with the standing wave microwave field and with an auxiliary traveling microwave in the presence of a static magnetic field to prepare the superposition of the states. Confinement of the atoms to the anti-node (node) of the electric (magnetic) microwave field drive only an E1 transition between hyperfine levels. The second microwave interaction (M1 allowed transition) serves as an amplifier through interference of a parity conserving amplitude with a PNC transition. The excitation rate difference depending on the handedness of the apparatus, measured as a shift of the phase of the Rabi oscillation, is a signal linear in the E1 transition, which is proportional to the anapole moment of the nucleus.

B. Optical APNC

The optical APNC measures the excitation rate of a highly forbidden transition. The electric dipole transition between the $7s$ and $8s$ levels in francium becomes allowed through the weak interaction. Interference between this transition and the one induced by the Stark effect due to the presence of an static electric field generates a signal proportional to the weak charge. The best APNC measurement to date uses this method to reach a precision of 0.35% [20, 21]. Francium atoms would accumulate in a MOT on a capture chamber. Then, after further cooling to control their velocities, they would be transferred to another region in a science chamber where a trap will keep them ready for the measurement. The measurement would be performed by placing the rap with the atoms in the mode of a high finesse optical Fabry-Perot interferometer tuned to the $7s$ to $8s$ transition in a region with a DC electric field present. If an atom gets excited it will decay via the $7p$ state. Optical pumping techniques allow one to recycle the atom that has performed the parity non-conserving transition many times enhancing the probability to detect the signature photon. Redundancy in the reversal of the system of coordinates would help identify and suppress systematic errors.

IV. FUTURE

The recent commissioning of the Francium Trapping Facility (FTF) at TRIUMF [22] has opened a platform for our weak interaction studies. The copious availability of many isotopes at ISAC on both sides of the nuclear stability line, we have trapped isotopes 206 to 213, and 221, will allow to further our understanding of the weak interaction and help study systematic changes in the behavior of this PNC experiments. This multinational collaboration with significant

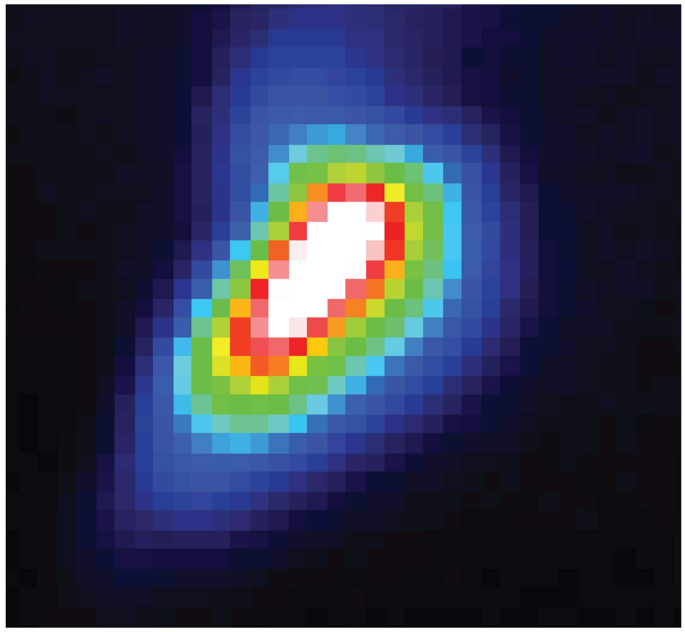

FIG. 1: False CCD color image of the fluorescence of more than 10^5 trapped ^{209}Fr atoms at the Francium Trapping Facility.

contributions from USA/Mexico/Canada is positioned to explore of the weak interaction at the FTF. Looking into the future, FRIB may offer, when fully operational, higher fluxes and more shifts availability with a similar variety of isotopes to TRIUMF. Under those conditions other experiments, beyond PNC, can be thought; for example an EDM experiment in Fr.

We are encouraged by the continuous role played by APNC on studies of physics beyond the standard model. The weak neutral current can have contributions from ultra-weakly coupled bosons with lower mass than the Z^0. At scales of a few MeV, APNC sets extremely good limits on parity-violating couplings [23]. Recent work analyzing its importance is highlighted in Refs. [24–26]. We also expect that the anapole measurements will illuminate our understanding of the hadronic weak interaction in the nucleus.

FrPNC collaboration, September 2014

S. Aubin, Dept. Physics, College of William and Mary, Williamsburg, VA 23197, USA.
J. A. Behr, M. R. Pearson, M. Tandecki, TRIUMF, Vancouver, BC V6T 2A3, Canada.
V. V. Flambaum, School of Physics, University of New South Wales, Sydney 2052, Australia.
E. Gomez, Instituto de Fisica, Universidad Autonoma de San Luis Potosi, San Luis Potosi 78000, Mexico.
G. Gwinner, R. Collister, K. Shiells, Dept. of Physics and Astronomy, University of Manitoba, Winnipeg, MB R3T 2N2, Canada.
D. Melconian, Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA.
L. A. Orozco , M. Kossin, J. Zhang, JQI, Dept. of Physics, and NIST, University of Maryland, College Park, MD 20742, USA.
G. D. Sprouse, Dept. of Physics and Astronomy, Stony Brook University, Stony Brook, NY 11794, USA.
Y. Zhao, State Key Laboratory of Quantum Optics and Quantum Optics Devices, Shanxi University, Taijuan 030006, China.

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