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# Fundamental symmetries studies with cold trapped francium atoms at ISAC

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**Abstract** Francium combines a heavy nucleus ($Z = 87$) with the simple atomic structure of alkalis and is a very promising candidate for precision tests of fundamental symmetries such as atomic parity non-conservation measurements. Fr has no stable isotopes, and the ISAC radioactive beam facility at TRIUMF, equipped with an actinide target, promises to provide record quantities of Fr atoms, up to $10^{10}$/s for some isotopes. We discuss our plans for a Fr on-line laser trapping facility at ISAC and experiments with samples of cold Fr atoms. We outline our plans for a measurement of the nuclear anapole moment – a parity non-conserving, time-reversal conserving moment that arises from weak interactions between nucleons – in a chain of Fr isotopes. Its measurement is a unique probe for neutral weak interactions inside the nucleus.

**Keywords** Weak interaction · Francium · Anapole

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## 1 Introduction

The pioneering work of the Bouchiats [1] recognized that the size of the effect of parity non-conservation (PNC) in atoms scales faster than $Z^3$, with $Z$ the atomic number. This strong scaling has made possible the successful observation of PNC effects in atoms, as well as precision measurements of the weak interaction coupling constants.

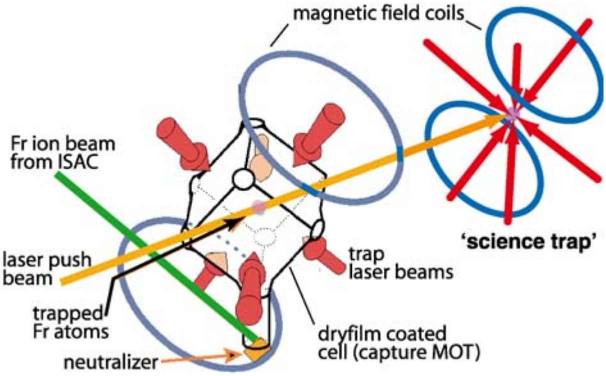
Atomic PNC work has focused on heavy atoms with atomic number greater than 50 [2–5]. Measurements in Cs [2, 6] have reached sensitivity to the nuclear spin dependent part of the interaction (primarily due to the nuclear anapole moment), opening a new avenue for studies of the neutral weak interaction within the nucleus [7, 8], an area very difficult to probe otherwise. The review by M.-A. Bouchiat and C. Bouchiat [9] presents the state of atomic PNC experiments in 1997 and some of the proposed experiments that presently are beginning to take shape.

Francium is the heaviest of the alkali atoms ($Z = 87$) and combines a simple electronic structure with a large nucleus. All its isotopes are radioactive, and the longest-lived one, $^{223}$Fr, has a half life of only 21 min. The atomic structure of Fr is similar to that of the other alkalis, but its heavy nucleus makes relativistic corrections important. A good measure of the size of the relativistic corrections is the fine structure splitting of the first excited $7p$ level into $7p_{1/2}$ and $7p_{3/2}$. They are separated by 15% of their energy difference with the ground state. Other measurements such as the line strength ratio in the $D$ lines show similar behavior [10].

There is less than 30 g of Fr at any given moment on the whole earth, so it is necessary to obtain it either as a decay product from an artificially produced, long-lived isotope (e.g. $^{229}$Th) or by on-line production at an accelerator. The small quantities of Fr that are available call for efficient use of the atoms; this has become possible with the advent of laser trapping and cooling [11]. An important motivation for the original trapping and cooling experiments was the creation of a controlled environment for precision measurements that would probe fundamental discrete symmetries of nature, such as parity and time reversal. Many trapping techniques were developed, but in the case of rare, radioactive neutral atoms, the preferred trapping scheme has been the magneto optical trap (MOT) [12] because of its unsurpassed well depth. Cold neutral radioactive atoms have been used already in weak interaction studies, in particular with precision measurements of beta-decay with cold atomic samples that can place limits on physics beyond the standard model [13–15].

Since the discovery of Fr in the residues of actinium by M. Perey [16] in France in 1938, many research groups have contributed to the development of our current understanding of the atomic and nuclear structure of francium. Among the most important achievements was the spectroscopy of the $7S_{1/2} \rightarrow 7P_{3/2}$ transition, the $D_2$ line of francium, at CERN by the group of S. Liberman [17]. Accurate knowledge of these transition frequencies was crucial for the magneto-optical trapping on-line with the superconducting linear accelerator at Stony Brook in 1995 [18]. The accelerator production combined with the magneto-optical trap provided the first cold sample of about $10^3$ atoms confined in an interaction-free region, ready to be studied. The Stony Brook group has devoted several years to understanding the electronic structure through spectroscopy. The Wieman group at Boulder succeeded in trapping francium produced as a daughter in the radioactive decay of $^{229}$Th [19]. Recent work

**Fig. 1** Proposed schematic for trapping and cooling Fr isotopes in a MOT on-line with the ISAC facility at TRIUMF. The design follows closely that of [24]



at the accelerator in Legnaro, Italy by L. Moi and co-workers has opened a new source for the continuation of research with francium [20]. A review of the present status of the advances in measurements of the atomic structure of Fr is given in [21].

Parallel to the experimental advances, new theoretical methods were developed to perform ab initio calculations of the atomic structure of Fr. The two leading theoretical groups in the field have reviews of their work with details on the current state of the calculations, not only of the structure, but also of the PNC effects in heavy atoms [22, 23].

## 2 Production and trapping of Fr at ISAC

The future actinide target for the ISAC facility at TRIUMF will be able to produce up to $10^{10}$/sec of some particular isotopes. The source uses a combination of fission and spallation to produce large numbers of atoms. This is more than three orders of magnitude above what has been possible using nuclear fusion reactions at Legnaro and Stony Brook. Both of these accelerators use light projectiles ($^{16}$O, $^{18}$O, and $^{19}$F) to induce a fusion reaction with a gold or platinum target.

ISAC will deliver a beam of Fr ions with an energy of a few tens of kilovolts. We expect to use an apparatus very similar to our high-efficiency trap that worked on-line at Stony Brook [24]. It operates in a pulsed mode, during which a yttrium neutralizer collects the Fr ions for about 95% of the time. The trap is in a glass-cell MOT with a silane-based dry-film coating to avoid sticking to the glass walls. The cell has plenty of optical access to maximize the trapping efficiency. During the remaining 5% of the time the neutralizer pivots to completely close the trapping cell and is heated to release the neutral Fr atoms into it. The high efficiency of the trap ensures that about 1–2% of the Fr atoms are trapped. By keeping the trap open most of the time (typical cycle times would be 30 s), we ensure good vacuum resulting in a long lifetime of the trap; closing the trap with the neutralizer delivers the neutral atoms into the trapping region and prevents them from escaping. The operation can be repeated many times and with the option of transferring the trapped atoms to a second chamber for further experiments. Figure 1 shows a schematic of the on-line MOT apparatus.

The second chamber will consist of a second MOT for re-capturing the transferred atoms and an optical dipole trap, preferably blue-detuned to minimize the perturbation on the atoms [25]. The vacuum in this 'science chamber' will have to be very good to ensure a long lifetime of the atoms in the optical dipole trap. The electromagnetic environment will be controlled at the level necessary for precision atomic PNC measurements.

## 3 Possible PNC experiments

There is interest in measuring the anapole moment in francium to improve our very limited knowledge of weak nucleon-nucleon interactions in nuclei. Gomez et al. [26] have proposed inducing microwave E1 transitions between the hyperfine levels of the francium ground state. Alternatively, it can be extracted from measurements of optical $7s \rightarrow 8s$ transitions between different hyperfine states. Generally, a transition that is parity-forbidden in a purely electromagnetic world acquires a small but finite amplitude due to the mixing of states of opposite parity by the weak interaction. In the case of the nuclear anapole moment, this parity mixing stems from parity-violating nucleon–nucleon interactions. To get a larger observable, and more importantly, to obtain a parity-violating signature in the experiment, the interference between the anapole-induced amplitude and a much larger, parity-conserving amplitude is observed. In principle, a measurement of the anapole moment in a chain of isotopes provides information to separate the anapole moment due to the valence proton from that of the neutron, if the nuclear structure can be understood at a sufficient level. In a 'naive' picture of valence-only anapoles, the moments due to a valence proton or neutron are almost orthogonal in the weak meson–nucleon coupling space [26, 27]. The first successful measurement of an anapole moment [2] shows that atomic PNC is a unique probe for neutral weak interactions inside the nucleus, which otherwise remain hidden by much larger charged currents.

The microwave experiment requires $\approx 10^6$ trapped atoms localized around an anti-node of the standing wave electric field in a Fabry–Perot resonator (microwave frequency $\nu_m \sim 45$ GHz and wavelength $\lambda_m \sim 6.6$ mm for francium). In this location, corresponding to a node of the magnetic field, the allowed M1 transition between the same states as the much weaker PNC-induced E1 ($|A_{E1}/A_{M1}| \approx 10^{-9}$) is greatly suppressed (further reduction is required and discussed in detail in [26]). This placement could be accomplished by confining the atoms with a blue-detuned optical dipole trap which would minimize the perturbation of the atoms by the light field. The PNC amplitude is amplified by interfering it with a parity-allowed optical Raman transition in the presence of a static magnetic field. The fields present define the system of coordinates for the experiment. The combination of electric and magnetic fields gives the observable $i(\mathbf{E_M} \times (\mathbf{E_1} \times \mathbf{E_2})) \cdot \mathbf{B}$, with $\mathbf{E_M}$ the microwave electric field, $\mathbf{E_1}$ and $\mathbf{E_2}$ the Raman fields, $\mathbf{B}$ the static magnetic field and the $i$ is present in accordance with time reversal symmetry.

An optical atomic PNC experiment can address both the spin independent and the spin dependent parts of the atomic weak interaction [28]. Although different approaches to optical measurements have been taken (see [9]), they all interfere the PNC amplitude with a larger, parity-conserving amplitude to enhance the signal.

A possible avenue for francium has been suggested in the contribution by Orozco in [29] following the approach with stable Cs by the Boulder group (see article by Wieman in [30]).

The accumulation and preparation of the atomic sample would be the same as for the microwave technique, with the atoms confined in an optical dipole trap but instead of in a microwave Fabry–Perot, they would be in an optical cavity tuned to the $7s \rightarrow 8s$ transition of Fr. A static electric field **E**, static magnetic field **B**, and the Poynting vector **S** of the excitation field in the Fabry Perot, define a handed system of coordinates such that the observable of the experiment is proportional to $\mathbf{B} \cdot (\mathbf{S} \times \mathbf{E})$. The static electric field induces Stark mixing between levels of opposite parity, leading to a parity-conserving Stark amplitude between the $7s$ and $8s$ levels of Fr. It is then possible to interfere this electromagnetic term with the weak-interaction-induced amplitude giving rise to a left-right asymmetry with respect to the handedness of the coordinate system. The PNC signal is the difference in rate of excitation between measurements in left-handed and right-handed coordinate systems.

## 4 Outlook and conclusions

TRIUMF is expected to deliver copious amounts of Fr atoms in the near future, making possible a series of PNC measurements in a chain of Fr isotopes. The preliminary work done elsewhere [21] shows that our understanding of the atomic physics is very good and the theoretical work for the atomic structure is also at a point where it is not of concern. There is still the question of the nuclear structure; however, the systematic change in the number of neutrons along a chain of isotopes will allow for careful studies of the influence of nuclear structure on the PNC signal. Anapole measurements in francium will make an important contribution to understanding the weak nucleon–nucleon interaction in nuclei, and together with improved nuclear models, has the potential to extract nucleon–nucleon weak couplings in nuclear matter.

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