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Efficient inter-trap transfer of cold francium atoms

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Abstract We report on the status of the FrPNC experiments and summarize our plans for measurements of parity non-conservation (PNC) in a sample of cold francium. The FrPNC collaboration has commissioned a laser cooling apparatus at the TRIUMF accelerator that collects and cools francium atoms for PNC experiments. We have recently demonstrated the robust, high efficiency transfer (50 %) of laser cooled francium atoms to a second laser cooling apparatus, located 0.7 m below the first, where the PNC experiments will be conducted.

Keywords Laser cooling · Atom trap · Instrumentation for radioactive beams

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1 Introduction

Parity non-conservation (PNC) effects are unique signatures of the weak interaction. While these effects are generally very small at low energies, they scale roughly as Z^3 in atoms, thus favoring heavy elements such as francium. The FrPNC collaboration has constructed and commissioned a facility at the TRIUMF accelerator for the on-line laser-cooling and trapping of francium isotopes for PNC experiments [1]. The facility has already been used to study the valence nucleons of francium nuclei via the hyperfine anomaly [2] and test valence electron wavefunctions through isotope shift measurements [3]. In this paper, we present the details of the facility's final engineering physics step of transferring laser cooled francium atoms to the vacuum chamber where the PNC experiments will be conducted. We begin by first reviewing the basic methods for measuring PNC and briefly outlining the operation of the trapping facility.

2 Atomic PNC

Atomic PNC effects can be classified as nuclear spin-independent (NSI) or spin-dependent (NSD). NSI-PNC is produced by Z^0 exchange between an orbiting electron and a nucleon (see Fig. 1a). NSI-PNC effects probe the nucleus's weak charge and can be used to obtain the weak mixing angle and electron-quark weak couplings [4]. In heavy atoms, NSD-PNC effects are dominated by the nuclear anapole moment, an electromagnetic interaction generated by a PNC current of nucleons interacting via the weak force (see Fig. 1b). An anapole moment measurement can be used to determine the weak meson-nucleon couplings [4, 5].

Nuclear spin-indepdendent PNC: NSI-PNC is most readily observed by measuring the very small transition amplitude A_{pnc} of a parity-forbidden electronic transition, such as the $7s$ to $8s$ optical transition at 506 nm in francium (see Fig. 1c). Since the transition rate $|A_{pnc}|^2$ is very small, it can be amplified by interfering it with an induced transition amplitude A_{Stark}, associated with the Stark effect, from an applied electric field $\mathbf{E}_{Stark}$. The total transition rate is $|A_{Stark} \pm A_{pnc}|^2$ where the $\pm$ sign represents the handedness of the apparatus: The cross-term $A_{pnc}A_{Stark}$ is the PNC *observable* and is proportional to the vector product $\mathbf{B}_{DC} \cdot (\eta\hat{k} \times \mathbf{E}_{Stark})$ of orthogonal experimental fields (see Fig. 1d); $\eta\hat{k}$ is a circular polarization vector for the 506 nm laser aligned with its wavevector axis, while $\mathbf{B}_{DC}$ is a static magnetic field that defines the quantization axis for the atoms.

Nuclear spin-dependent PNC: We plan to measure the nuclear anapole moment of francium by driving the parity-forbidden E1 transition at 43–50 GHz ($^{208-212}$Fr) between the $7s$ hyperfine ground levels F and F' (see Fig. 1c) [6]. In this case, the PNC observable for the anapole-induced transition amplitude A_{pnc} is proportional to $\mathbf{B}_{DC} \cdot (\mathbf{B}_{\pi/2} \times \mathbf{E}_{RF})$ (see Fig. 1e), where $\mathbf{E}_{RF}$ is the microwave electric field. The microwave magnetic field $\mathbf{B}_{\pi/2}$ vector is used to put the atoms in an equal superposition of F and F' hyperfine states. Alternatively, the anapole moment can be determined from the dependence of optical NSI-PNC on the initial and final hyperfine levels (F, F') of the $7s$-$8s$ transition [7].

Both PNC measurements require precise control of the electromagnetic environment. A_{pnc} is extracted from the part of the signal (scattering rate or hyperfine populations) that varies with reversals of the fields in the PNC observable [6, 7].

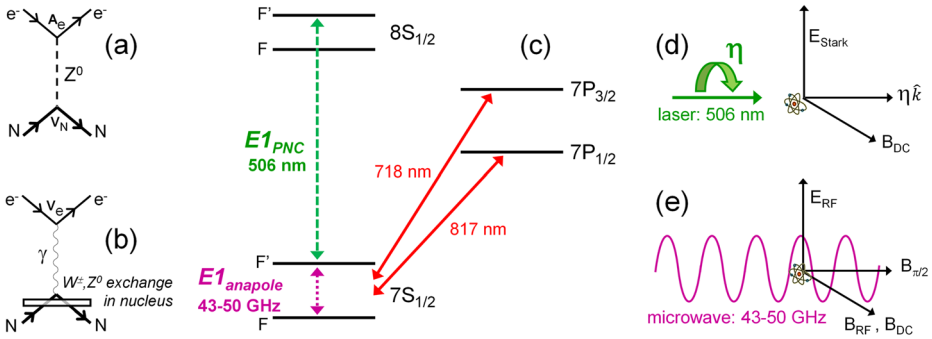

Fig. 1 Atomic parity non-conservation. **a** Nuclear spin-independent PNC (NSI-PNC): An axial-vector electron current A_e exchanges a Z^0 boson with a vector nucleon current V_N. **b** Nuclear spin-dependent PNC (NSD-PNC): A vector electron interacts electromagnetically (γ-photon exchange) with the anapole moment of the nucleus. **c** atomic Fr transitions for PNC experiments: NSI-PNC can be measured by driving the $7s$-$8s$ parity-forbidden E1 transition at 506 nm; NSD-PNC can be probed by driving a parity-forbidden E1 transition between the hyperfine levels ($F \leftrightarrow F'$) of the $7s$ ground level (43–50 GHz). **d**, **e** External electromagnetic field vectors define a coordinate system, whose handedness determines the sign of the PNC signal for the **d** optical NSI-PNC and **e** microwave NSD-PNC anapole moment experiments

3 Francium trapping facility

The Francium Trapping Facility (FTF) is a rf-shielded laser spectroscopy lab in the ISAC I hall at TRIUMF. The FTF houses the laser cooling and trapping apparatus for the optical PNC and anapole moment experiments, as well as the lasers, instruments, and control systems to operate it. We describe it briefly here, and refer the reader to reference [1] for details. Figure 2a shows the laser cooling and trapping apparatus, which consists of two magneto-optical traps (MOTs). The ISAC facility at TRIUMF delivers up to 10^9 Fr/s to the FTF. The capture MOT (top MOT in Fig. 2a) cools and traps francium delivered to the FTF, while the science MOT (bottom MOT in Fig. 2a) provides a laser cooled Fr sample within the multi-use, high-access vacuum chamber (science chamber) for the PNC experiments. Both MOTs trap with light on the D2 line at 718 nm with repumping on the D1 (817 nm) or D2 line (see Fig. 1c). Notably, the apparatus is frequently operated off-line with rubidium (D2: 780 nm, D1: 795 nm). The vacuum systems for the two MOTs are located directly above one another and connected by a differential pumping tube through which laser cooled atoms can be transferred.

Transfer tube This tube connects the vacuum systems for the two MOTs and includes a gate valve for venting either end separately, a shutter for quickly isolating the two vacuum chambers, and viewports for optical access to transiting atoms.

Capture MOT This MOT is optimized for maximum trapping efficiency and has successfully trapped nine isotopes ($^{206-213,221}$Fr) [1–3]. This MOT features large trapping beams (for a high capture velocity) that fill most of the Pyrex vacuum cell of the MOT to optimize the trapping volume. The inside of the cell is coated with a dry-film [8] to re-thermalize and then release physisorbed Fr atoms back into the trapping volume. Neutral Fr atoms are

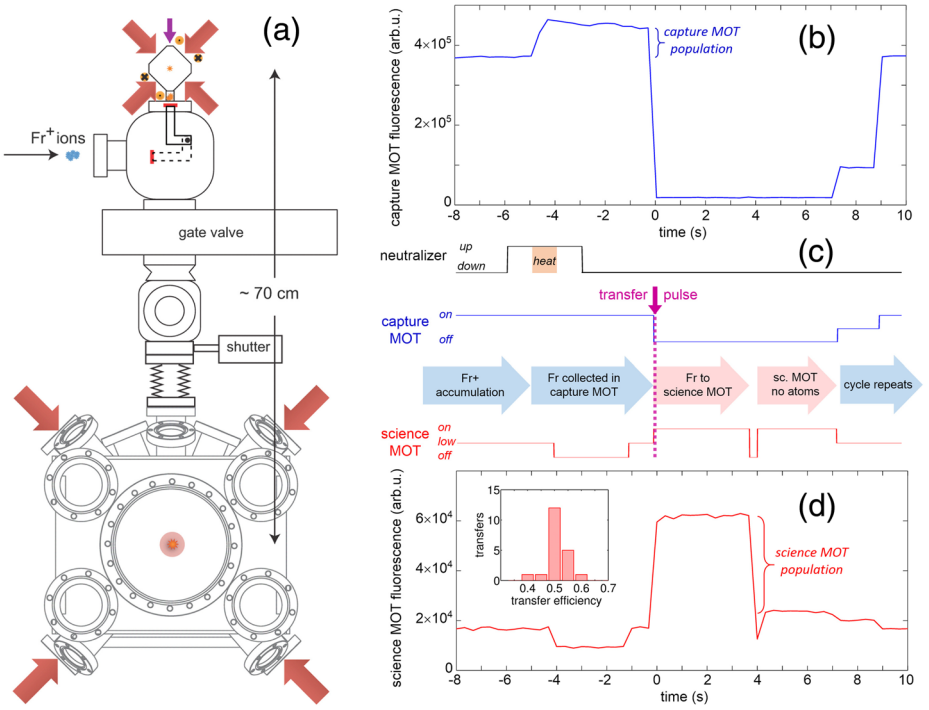

Fig. 2 Laser cooling and trapping apparatus and transfer results. **a** Capture MOT (*up*), science MOT (*down*) and connecting transfer tube. Fr^+ ions are collected on a two-position yttrium neutralizer (*vertical* and *horizontal red segments*), which releases neutral atoms when heated. Both MOTs consist of six laser beams (four are shown as *red arrows*) and an anti-Helmholtz coil (capture MOT: *orange dots* indicate coil currents). Capture MOT atoms are transferred to the science chamber MOT by a laser (*purple arrow*) that pushes them downwards. Parts **b–d** use a common time axis to detail the transfer of capture MOT Fr atoms to the science MOT. **b** The fluorescence of the capture MOT shows the initial trapping of ^{211}Fr atoms released from the neutralizer, and their transfer at $t = 0$ to the science MOT. **c** The timing diagrams show the order of operation for the neutralizer (orientation and heating), the capture MOT beams, science MOT beams, and transfer pulse (*purple*). **d** The fluorescence of the science MOT shows the trapping of ^{211}Fr atoms transferred from the capture MOT at $t = 0$ (only 18 s of the 36 s experimental cycle are shown). The transfer efficiency for the data in (**b**, **d**) is 52 %. *Inset in (d):* A 20 cycle histogram of transfer efficiency

dispensed into the capture cell by a 2-position yttrium neutralizer: in its downward position (for 20 s or more), the neutralizer collects 20 keV Fr^+ ions delivered into the FTF via an ISAC beamline, while in its upward position, the neutralizer releases neutral Fr atoms when heated for 1 s. While the capture MOT features efficient trapping [1, 8], it is not suitable for PNC experiments given its poor optical access, modest vacuum, and imprecise control of electric and magnetic fields.

Science MOT This MOT is located 0.7 m below the capture MOT and is optimized for the PNC experiments. It operates within a large vacuum chamber with excellent optical access (30 vacuum ports of various sizes) and sufficient volume to house electric field plates and an optical cavity, or a microwave cavity. The vacuum chamber is constructed of low magnetic permeability steel (316L for the body and 316LN for the flanges) to minimize residual magnetization.

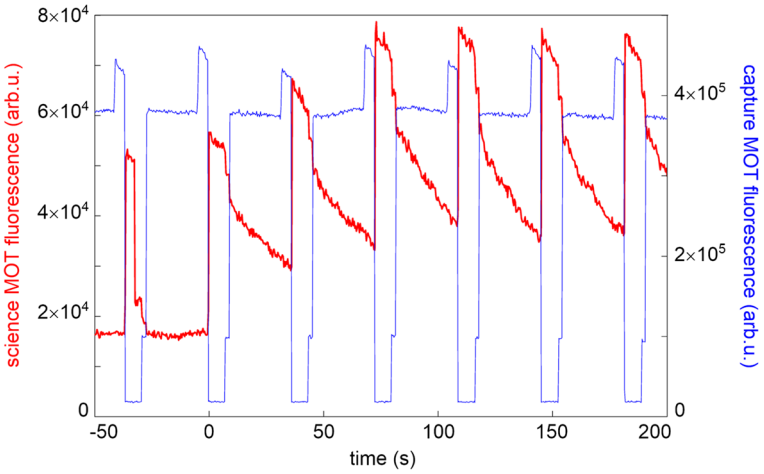

Fig. 3 Accumulation of Fr atoms in the science MOT. The plot shows seven transfers of atoms from the capture MOT. The first transfer is similar to the one in Fig. 2, while the last six transfers are accumulated in the science MOT. Each transfer cycle is 36 s. *blue curve:* Capture MOT fluorescence (*right axis*). *red curve:* Science MOT fluorescence (*left axis*). The experimental cycle and timing is similar to that in Fig. 2b–d, except that the science MOT is never turned off, though its laser power is reduced (i.e. the "low" setting in Fig. 2c, which causes a drop in fluorescence) when the capture MOT is on

4 Efficient transfer demonstration

We use a push beam to transfer ^{211}Fr atoms from the capture MOT to the science MOT with an efficiency of 50 %. Figure 2c shows the basic timing of our method. After sufficient atoms have been collected on the neutralizer, the atoms are released into the cell and trapped by the capture MOT. The neutralizer is then swung to its downward position (unblocking the cell exit), the transfer tube shutter is opened, and the trapping beams for the capture MOT are turned off. We then apply a downward-directed, near-resonant laser beam to the atoms (trapping transition at 718 nm) for 10 ms to push the atoms towards the science chamber.

We operate both MOTs with trapping beams of the same intensity, so that the ratio of the fluorescence of the two MOTs is identical to the ratio of the MOT populations. Two nearly identical imaging systems monitor the MOTs. Figure 2b and d show the capture MOT and science MOT fluorescence recorded by the two cameras. The timing sequence also includes periods when the MOTs contain no atoms, thus generating background signals. We find that our transfer efficiency is about 0.5 with a spread of about ± 0.1. The inset in Fig. 2d shows a histogram of 20 transfers. Our transfer scheme has an efficiency approaching 0.8 for ^{85}Rb. The anti-Helmholtz coils of the MOTs are not adjusted dynamically during the transfer, though we do optimize the magnetic gradient of the science MOT. After geometric alignment of the push beam, we position the capture MOT atoms for optimal transfer by trimming the magnetic bias fields. Briefly boosting the laser power and ramping the laser detuning for up to 100 ms to help "catch" the atoms provides little improvement. Once optimized, the transfer is quite robust and is not particularly sensitive to any of the experimental parameters.

Multiple transfers can be loaded cumulatively into the science MOT. Figure 3 shows the accumulation of atoms in the science MOT over the course of six transfers. We use a similar timing sequence to that in Fig. 2c but leave the science MOT on throughout the

experimental cycle. Importantly, we find that the push beam does not harm the science MOT population. The accumulation of multiple transfers is essential for maximizing the Fr population available for PNC experiments. The science MOT decay constant for the data shown in Fig. 3 is $\tau = 41(4)$ s, which is considerably smaller than the radioactive $1/e$ lifetime of ^{211}Fr ($\tau = 4.5$ min). Improving the vacuum of the science chamber should lengthen the science MOT lifetime and increase the number of accumulated atoms.

5 Outlook

The efficient transfer of Fr atoms to the science MOT sets the stage for future PNC experiments. The science MOT also enables a host of supporting spectroscopy measurements that rely on good optical (and microwave) access and precise control of electric and magnetic fields. For example, planned measurements include the $7s$ hyperfine splitting and the Stark effect for the $7s$-$8s$ transition.

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