

E. Mariotti¹, L. Moi¹, G. Batignani¹, A. Khanbekyan¹, C. Marinelli¹, L. Marmugi¹, L. Corradi², A. Dainelli², R. Calabrese³, G. Mazzocca³, L. Tomassetti³, and P. Minguzzi⁴

¹ CNISM–Physics Dept. Siena University,

² INFN – Laboratori Nazionali di Legnaro,

³ INFN- Physics Dept. Ferrara University,

⁴ CNISM–Physics Dept. Pisa University

Abstract. We report on the state of art, the main experimental achievements and the perspectives of the TrapRad/Francium collaboration. The ad hoc apparatus allows for production and trapping of radioactive Francium isotopes. This research has a final goal related to Atomic Parity Non Conservation measurements and test of fundamental and Nuclear Physics by the high precision methods typical of laser spectroscopy.

Keywords: Laser spectroscopy, Atom cooling methods, Parity nonconserving transition amplitudes

INTRODUCTION

This paper presents the recent results of the TrapRad/Francium collaboration whose final aim is the measurement of the Atomic Parity Non Conservation effect (APNC) in Francium atoms stored in a Magneto – Optical Trap (MOT).

Parity is an atomic property related to the invariance of the atom as a whole under inversion of the spatial coordinates (mirror invariance). In particular, the energy states of an atom have a specific Parity, according the Electromagnetism, describing the interaction between the charged nucleus and the external electron responsible for the optical properties. This characteristic is broken by the weak interaction that also predicts an exchange of a Z_0 boson between a nucleon and an electron: as a consequence, selection rules in the atomic energy jumps are modified, even if the effect is dramatically small and thus very difficult to detect.

In order to have the possibility of a comparison of the theoretical prediction and the actual experimental data, it is fundamental to choose an “easily calculable” atom; this means to consider an alkali species, because the first group elements have the electron configuration which is formally treatable with relatively low complexity due to its similarity to that of Hydrogen, the simplest atom. At the same time, it is important to choose an atom with high atomic numbers (Z , A), because the probability of a boson exchange increases significantly, both due to the high number of nucleons and the importance of electron trajectories close to nucleus, where the screen given by all other electrons is canceled.

The heaviest alkali and therefore the best candidate for

APNC studies is Francium ($Z=87$), which unfortunately does not exist in stable forms: all the isotopes are radioactive with the longest half time limited to 22 minutes. Due to this fact, Francium has to be produced in a nuclear reaction, given by the continuous bombardment of a high energy charged beam on a solid target. After production, the only possibility to study Francium is collecting atoms efficiently and maintain them fixed in a small volume of space for all their short lifetime. The only way to accomplish this goal is by exploiting the simultaneous action of resonant laser light and a controlled magnetic field gradient: laser beams decelerate (“cool”, as low matter velocity is associated to low temperatures) and pushes atoms in a small volume corresponding to an energy minimum (potential well) created by the magnetic gradient, where they are “trapped”. This is the basic description of a Magneto-Optical Trap (MOT). Our project is the only operating at the moment in the world, and it comes after a pioneer work of Orozco at Stony Brook [1] while in Canada [2] and Japan [3] other collaborations are building new facilities.

METHODS

The TrapRad/Francium experiments are located at the Legnaro National Laboratories of Istituto Nazionale di Fisica Nucleare (INFN), close to Padova, where a dedicated line has been constructed [4], as schematically shown in Fig.1. The energy down scale is impressive, spanning 17 orders of magnitude: at the beginning, an oxygen ion beam accelerated by a Tandem Linear Accelerator at around 100 MeV contains the projectiles hitting a Gold target at rest kept at high temperature.

Correspondence to:

Emilio Mariotti

Physics Dept., University of Siena.

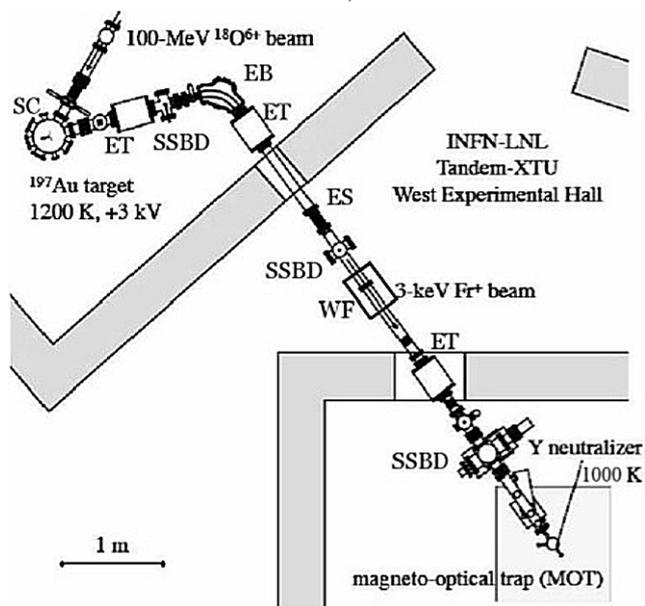
via Roma 56 53100 Siena, Italy.

Tel. +39 0577 234684, +39 0577 234689

email: mariotti@unisi.it

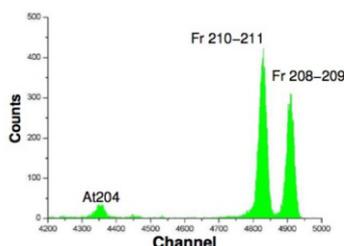
The nuclear reaction is therefore defined as fusion evaporation: $^{197}\text{Au} + (^{18}\text{O}, xn) ^{215-x}\text{Fr} + xn$, where x varies from 3 to 6. Reaction products have still a 10 MeV energy, which is rapidly dissipated in the target. Tuning oxygen energy gives different ratio in the isotopic production, as demonstrated by Fig.2, based on the transmutation decay of Fr where an alpha particle is generated and detected by a Silicon counter (SSBD) associated to the proper electronics and data acquisition system.

Fig 1. Sketch of the LNL beam line for the Fr⁺ production. In the top left corner the scattering chamber (SC) is depicted. After production, Fr⁺ are transported by the secondary line the actual MOT laboratory for neutralization and laser cooling (Lower right corner).



The selected Oxygen energy gives a maximum rate for Francium with $A=210$ a.m.u.. Gold has a work function higher than the ionization energy of Francium in such a way that exciting Fr is ionized. The target is kept at a temperature close to melting point to favor diffusion out of it. The ions are taken away by the “scattering chamber” via a combination of elements generating static electric fields and both focusing and steering the beam: this 8 meter long transport line moves the ions at 3 keV towards the laser laboratory.

Fig 2. particles spectrum generated by the Fr isotopes measured by a Silicon detector (SSBD).
²⁰⁴At is a by-product of the decay chain of ²⁰⁸Fr.

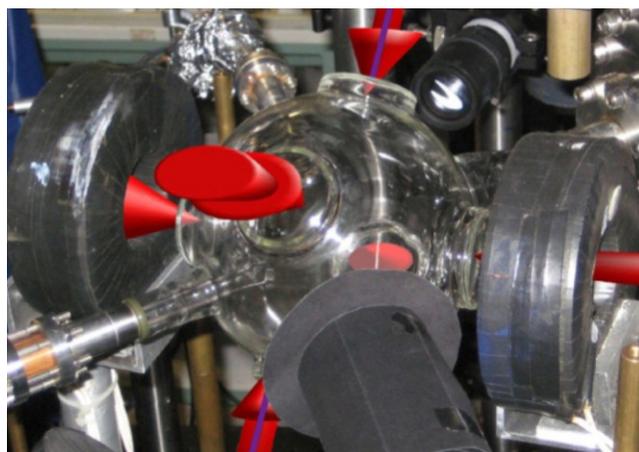


Ions are implanted in a rectangular Yttrium foil of area

less than 1 cm^2 , where ions are neutralized. As a consequence, neutral Francium atoms diffuse out of the foil with the help of a temperature close to 1000 K, therefore at energies of the order of a fraction of eV. The neutralizer is placed in a spherical pyrex cell, shown in Fig.3, that has been optically worked by soldering 6 optical high quality windows along three mutually perpendicular axis through which laser beams can propagate without distortion. All the line is maintained in high vacuum regime by many and different type pump systems: in the cell the vacuum limit is about 5×10^{-9} mbar and this condition is very stringent as background gas easily destroys the trap by collision with the trapped atoms.

Fig 3. Close-up of the Pyrex glass MOT cell.

The two coils for generating the magnetic field gradient are clearly visible in the left and right portion of the image. In the lower left portion, it is possible to see the Y neutralizer inside its dedicated casing. Red arrows pointing to each of the six cell windows indicate the presence of infra-red laser beams.



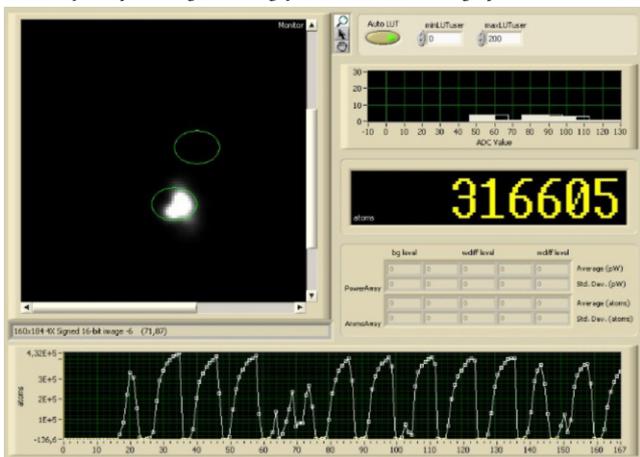
The laser system necessary to get the cooling and the trapping processes is formed by a Titanium – Sapphire solid state laser operating at 718 nm and pumped by an Argon ion laser, plus a free running diode laser at 817 nm. The combination of the two light sources excites (and maintains excited) Francium on the transition from the ground state $7S_{1/2}$ (sublevel $F=3$) to the first excited state $7P_{3/2}$ (sublevel $F'=4$). The laser beams are moved to the cell by an optics line, divided in 6 beams, properly polarized and expanded by six telescope until a size of about 4 cm in diameter, in order to fill by light as much cell volume as possible (Fig. 3). This excitation, provided a proper frequency red-detuning, produces a deceleration of Fr: atoms are slowed down from some hundreds meter per second to a velocity of the order of some mm/s. In this way, lasers transform the free space of flight in a sort of dense viscous medium and are therefore called optical molasses. The final trapping condition is guaranteed by the presence of a magnetic field gradient (see the black-covered coils in Fig. 3), which at the same time creates a potential well adding a restoring force for the atoms and defines the point where the trap will be formed. Trapped atoms can be detected because of light spontaneously emitted after continuous laser excitation. In

this sense the trap is seen as a small continuous “lamp” located in the central zone of overlapping of the six laser beams and the minimum of the magnetic field. The resulting trap volume occupies in our case less than 1 cubic millimeter. The fluorescence light is more intense as more atoms are loaded into the MOT: unfortunately the Francium production and trapping rate is very small and then the “lamp” is limited to something as some picoWatts of light power. This makes necessary the use of a sensitive dedicated detection system: a very sensitive cooled CCD camera allows the detection of the light emitted by only 30 atoms (30 fW), provided the implementation and the use of a proper automatic procedure via software which controls, acquires and processes the signal generated by the CCD [5]. Because of the high competition between the many experiments and collaborations which benefits from the LNL Tandem accelerator, only 10 days of beam time per year are available. It is imperative then to develop alignment and test procedure to be performed off-line, in order to have the whole apparatus ready for the beam time and the actual APNC measurements. The solution is to use stable atoms, easy to be handled, in order to perform tests and optimization of the apparatus whenever required. The chosen species is ⁸⁵Rb: a solid Rb source is installed close the Gold target and is capable to generate an ionic Rb⁺ beam which follows the same path and the same processes as Francium, in order to monitor the functionality of the line. By exploiting a different combination of laser source is then possible to trap also Rubidium in the MOT cell in order to try, test and validate techniques and procedures that will be used on-line once the Oxygen beam is available. In fig.4 an example of an image of a Rb trap taken and processed by the CCD camera and the data acquisition system is shown.

Fig. 4 – Detail of the custom designed software working interface for CCD control and image elaboration: real time imaging and measurement of a Rb MOT.

In the left part of the image the fluorescence emitted by the cloud of cold atoms trapped in the MOT is clearly visible (white) after the acquisition and elaboration (weighted background subtraction) of the CCD image.

The system is carefully calibrated in order to measure the number of atoms in the MOT (yellow number in the right portion). The lower part of the image shows the temporal evolution of the number of the trapped atoms. In this case, laser where periodically moved from the correct frequency tuning, causing periodical vanishing of the MOT



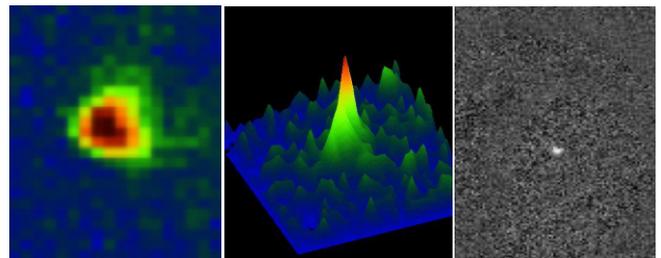
RESULTS

We will present here the main results of these years and some interesting perspectives.

First of all, we have successfully trapped three different isotopes of Francium: those corresponding to Atomic mass 209, 210 and 211 a.m.u., as shown in fig.5, where the CCD images of the three cases are reported. Moreover, we have measured with unprecedented precision the trapping frequencies of these isotopes [6], reaching something of the order of 2 parts over one billion. As a side effect, we were also able to measure the diffusion coefficient of both Fr and Rb in Yttrium, introducing a new, very sensitive method for determining this important experimental parameter [7].

Fig. 5 – Images of the three Francium isotopes MOT.

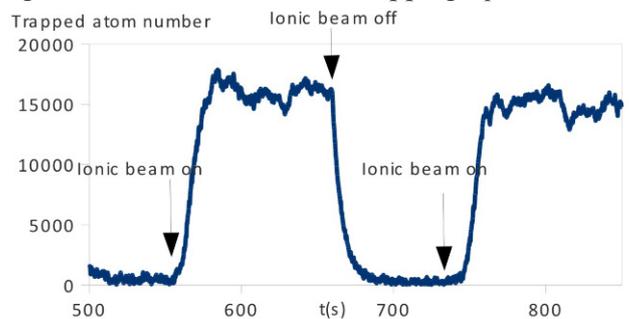
From left to right: false color reconstruction of 8000 trapped atoms of 210 a.m.u. Fr, 3D false color reconstruction of 180 trapped atoms of 209 a.m.u. Fr, direct vision of 200 trapped atoms of 211 a.m.u. Fr.



The population of our traps is at the moment under the threshold of an APNC measurement. More recently, we have spent a lot of efforts to increase the overall efficiency of the apparatus, which implies to separately increase the production, the transport, the neutralization and the trapping efficiency.

For example, we have further studied the complicated dynamics related to the release of atoms by yttrium, and the subsequent cooling and trapping by lasers. In Fig.5 a graph of the Rubidium ionic beam effect is shown. When the beam is switched on, the trapped atom number goes from zero to a value related to the intensity of the beam and to the efficiency of the release plus the trapping process. When the ionic beam is switched off, the trap population and thus its fluorescence goes back to zero.

Fig. 6 – Rubidium ionic beam trapping dynamics study

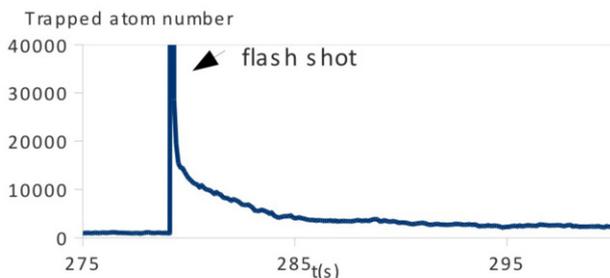


The rising time of the signal is an indirect indication of how fast the neutralization proceeds inside the foil. We are modeling the processes via a mathematical system of rate equations that can be analytically solved in

terms of a set of parameters to be extracted by fit procedures.

Another delicate question is what happens when an atom in vapor phase collides with the cell walls. A very bad consequence can be the adhesion (adsorption) of the atom on the surface: since those atoms are potentially lost, this phenomenon should be possibly excluded or, at least, reduced. A well tested method to contain this phenomenon is to coat the pyrex wall by an organic polymer, able to ensure elastic – type collisions and to maintain the number of atoms in the vapor phase without significant losses. Anyway, an accumulation of atoms inside the surface is inevitable. Nevertheless, the bound energy in the case of a coated surface is one order of magnitude smaller and even a simple photographic flash can detach stored atoms from the walls and make them available again for trapping. In Fig.6 an example of this phenomenon, named Light Induced Atomic Desorption (LIAD) [8], is given for Rubidium atoms. Also in this case, we start from a situation where the trap is absent and the flash generates a huge cloud of alkali atoms that is immediately captured by laser beams; the long fluorescence tail towards zero is a signature of the very good vacuum condition reached in the MOT cell. We want to apply LIAD also in the case of Francium.

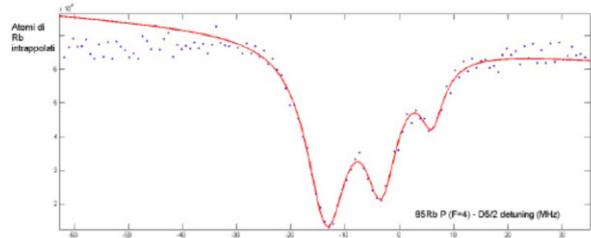
Fig. 7 – Light Induced Atom Desorption trapping of Rubidium



At the same time, apart from optimization skills, we have elaborated a new strategy that, in a simple but effective way, allows for detection of transfer of atoms from a MOT level to a highly excited level. This is important as we want both to look for yet undetected energy states and to test our ability to be more and more sensitive, in the APNC measurement perspective [9]. The method consists in the study of the effect of an excitation laser beam, resonant with a transition connecting the ground/first excited state towards other levels. Scanning the laser frequency gives a change in the number of trapped atoms, depending on the laser intensity and on the transition amplitude. In Fig.8 we show the result for a Rubidium line that has a viable Francium counterpart; it is interesting to underline that the structure width is small in the limit of natural linewidth due to very slow movement of trapped atom. In the picture the signal level on the left and on the right indicates the number of trapped Rubidium atoms in the usual configuration; the x axis shows the frequency position of the excitation laser. The three

downwards peaks, corresponding to a strong decrease in the trapped atom number, are the signatures of hyperfine resonant structures of $5P_{3/2} - 5D_{5/2}$ line. Relative distances are both about 9 MHz, while the frequency value of the excitation laser is 386341.08 GHz.

Fig. 8 – Detection of Rubidium $5D_{5/2}$ line by trapped atom number modification



CONCLUSIONS

We have built a facility for radioactive atom trapping where Francium isotopes have been successfully trapped. We are going towards an optimization of the apparatus in order to get, step by step, the possibility of a detection of APNC signals. The application of very high precision atomic spectroscopy to nuclear physics is an interesting interdisciplinary effort that can give new insights on fundamental physics problems as well as to technical developments.

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