209-210-211 Francium MOT Optical Signals

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INTRODUCTION

Francium is the heaviest of the alkali elements and is a promising candidate for the test of fundamental symmetries: parity violation, nuclear anapole moment and electric dipole moment of the electron (EDM). However, francium has no stable isotopes and therefore it must be produced either by radioactive decay or by nuclear reaction: unfortunately these processes can deliver only small amounts of this element. The use of a magneto-optical trap (MOT) allows to efficiently cool and collect the radioactive atoms, so as to partly compensate their scarcity.

Two research groups in the USA have succeeded in trapping Francium atoms in a MOT, while in Japan an experiment is starting with the purpose of using Francium for testing the EDM. In Europe, francium production and trapping is currently performed at the Legnaro laboratories: this year, we trapped the 209Fr, 210Fr and 211Fr atoms and observed them with our low-noise CCD detector. We report here our last measurements, performed on these three isotopes.

SETUP

The apparatus, with the last upgrades, has already been thoroughly described in last years LNL Annual Reports [1]. Francium is produced by nuclear fusion of a 100 MeV 18O beam colliding on a thick gold target, followed by neutron evaporation. The Fr ions extracted from the target are injected in a secondary electrostatic beam line and conveyed inside the MOT cell to a thin yttrium foil, the neutralizer. Francium is released from heated yttrium in its neutral form, and then cooled and confined in a small volume (typically 1 mm3) by the MOT.

The magneto-optical trap has a standard configuration, with six counterpropagating laser trapping and repumping beams in the three directions of space, and a magnetic-field gradient (∼10 G/cm). The trapping light, slightly red-detuned with respect to the 7S − 7P3/2 cycling transition at 718 nm, is provided by a Ti:Sa laser.

The repumping beam comes from a diode laser tuned to the 7S − 7P1/2 transition at 817 nm: it prevents the accumulation of Fr atoms in the wrong ground hyperfine state out of the cycling transition.

The francium cold cloud is imaged onto a low-noise calibrated CCD detector: the intensity of the fluorescence collected by the CCD camera indicates the number of trapped atoms. The sensitivity of the system, better than 50 atoms, is limited essentially by the laser light scattered on the surface of the MOT cell.

The whole setup, from the secondary beam line to the magneto-optical capture and fluorescence detection, is tested with rubidium atoms. To this purpose, a Rb dispenser has been placed near the target: Rb atoms that arrive on the gold surface are ionized and injected in the electrostatic line, following the same path as Fr. The efficiency tests performed with Rb, which proved to be decisive for the obtaining of a stable francium trap, are described in Ref. [2]

LOOKING FOR FRANCIUM TRAPPING FREQUENCIES

Obviously no reference cell is available to find francium lines, so we use our wavemeter to tune the lasers: the trapping and repumping frequencies, measured with a wavemeter by Orozco’s group, are known with an accuracy of 90 MHz [3]. However, the linewidth is smaller, 7.6 MHz: in order to find the francium trap, we should patiently scan the frequency of both lasers until we see a signal from our CCD detector. This would not be a problem if we expected high signals, with a stable francium production: in practice, the accelerator conditions and the target performance can undergo important fluctuations that decrease the MOT signals below our sensitivity. In these conditions, it is important to be able to find the trap as quickly as possible, after optimization of the francium production. In order to be less sensitive to the repumping laser frequency, we enlarge then the diode emission spectrum to 100 MHz by current modulation at a rate of 4 kHz: this technique removes the need to scan the repumping frequency, allowing us to save precious time.

We also mention that we will now be able to tune the lasers to the right frequencies without resorting to scan, with our new high-resolution frequency-meter and a more accurate determination of francium line frequencies [4].
<table>
<thead>
<tr>
<th>Isotope</th>
<th>209</th>
<th>210</th>
<th>211</th>
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<tbody>
<tr>
<td>Trapping freq.</td>
<td>417415.10(5)</td>
<td>417412.45(5)</td>
<td>417412.63(5)</td>
</tr>
<tr>
<td>Repumping freq.</td>
<td>366897.43(5)</td>
<td>366898.70(5)</td>
<td>366895.57(5)</td>
</tr>
</tbody>
</table>

**TABLE I:** Francium trapping and repumping frequencies in GHz, measured with the calibrated wavemeter.

**CONTINUOUS REGIME**

This year, in the first beam-time, we sent the $^{210}$Fr beam to the hot (730 °C) neutralizer and tried to observe the trapped atoms. We managed to trap 50 atoms at the first scan of the Ti:Sa laser frequency. After a careful optimization of the Fr production rate, by increasing the intensity of the primary $^{18}$O beam, we could observe as much as 350 trapped atoms. In a following beam-time, thanks also to better vacuum conditions, we reached a value of 1000 trapped atoms (the actual number of atoms could differ by a factor of two, due to calibration uncertainties).

We also trapped $^{209}$Fr (270 atoms) and $^{211}$Fr (180 atoms), produced in the usual nuclear reaction with lower rates. We measured with our wavemeter the frequencies of the trapping transitions (in correspondence to the maximum signal) for the three isotopes (Table I). The wavemeter was calibrated with an accurate secondary frequency standard [4]: the quoted accuracy, 50 MHz, corresponds to the correction introduced by the calibration.

The trapping efficiency was found to be better than for rubidium [2]: with $1 \times 10^{15}$ Fr$^+$/s arriving to the neutralizer we observed a trap of 200 $^{210}$Fr atoms.

**FREQUENCY SCAN**

For each isotope, we acquired the trap signal as a function of the trapping laser frequency (measured with the interferometer presented in Ref. [4]). The resulting lines are reported in Fig. 1.

**PULSED REGIME**

When the yttrium neutralizer is not heated, francium ions stick into it. It is possible then to operate in a pulsed regime. We let francium accumulate on cold yttrium for three half-lives: when we turn on the neutralizer, francium atoms are released altogether. This technique, already used in Stony Brook [3], results in a gain on the number of trapped atoms: we managed to detect a pulsed $^{210}$Fr trap of 8000 atoms (Fig. 2). When we heat yttrium, the MOT is loaded in a few seconds, then the signal decreases with a relaxation time less than 30 s, corresponding to the release time from yttrium (Fig. 3).

**CONCLUSION**

We trapped $^{209}$Fr, $^{210}$Fr, $^{211}$Fr atoms and detected their fluorescence with our low-noise CCD camera. The trapping and repumping frequencies were measured for the three isotopes, with an improved accuracy of 50 MHz with respect to published data.

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