Production, transport and laser trapping of radioactive francium beams for the study of fundamental interactions

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Accelerator Physics and Technology Seminar
Fermi National Accelerator Laboratory, Batavia IL (USA)
January 15, 2008
Fundamental interactions and symmetries can be tested efficiently on trapped atoms.

These searches of new physics beyond the Standard Model are complementary to those at high energy.

Two main lines of research:

**Atomic parity violation (APV)** tests weak force at low momentum transfers:
- electron-nucleon interaction parameterized by weak charge;
- nucleon-nucleon through the anapole moment (difficult to access otherwise).

**Search of permanent electric dipole moments (EDMs)** of electrons, nucleons and atoms.

Atomic parity violation is complementary to parity-violating electron scattering (PVES) in determining the effective weak couplings of the quarks

Electric dipole moments (EDMs) are related to violations of time-reversal (T) symmetry. Assuming CPT is conserved, EDMs can shed light on the nature of CP violation. Detection of EDMs near the current experimental limits would unambiguously imply new physics.

[N. Fortson, P. Sandars, and S. Barr, Phys. Today, June 2003]
Francium is one of the best candidates for APV and EDM measurements

Heaviest alkali metal: large nucleus and simple atomic structure

Enhancement of APV ($\sim Z^3$) and EDM (electron x $10^3$) effects

Several isotopes with relatively long lifetimes ($\sim$minutes) to reduce systematics

No stable isotopes, but scarcity partly compensated by accumulation in traps
Several groups are pursuing physics with trapped francium atoms

SUNY Stony Brook, USA
pioneered Fr traps
extensive spectroscopy
moving to TRIUMF

JILA Boulder, USA
vapor cell
spectroscopy of $^{221}$Fr

LNL Legnaro, Italy
status in this talk

CYRIC / Tohoku University, Japan
feasibility tests for EDMs
first beam next spring
[Sakemi, private communication]
Research in this field requires advancements in
francium sources and traps (increase signal)
precision spectroscopy (reduce theoretical uncertainties)

A facility at INFN’s Laboratori Nazionali di Legnaro (LNL)
has been built and commissioned for this purpose
The **TRAP-RAD Collaboration** at LNL is an interdisciplinary team born to combine expertise in several fields: atomic physics and laser spectroscopy, nuclear physics, particle and accelerator physics.

- S. N. Atutov, R. Calabrese, G. Stancari, L. Tomassetti
  University and INFN Ferrara, Italy

- L. Corradi, A. Dainelli
  INFN Laboratori Nazionali di Legnaro, Italy

- P. Minguzzi, S. Sanguinetti
  University and INFN Pisa, Italy

- C. de Mauro, A. Khanbekyan, E. Mariotti, L. Moi, S. Veronesi
  University of Siena, Italy
100-MeV $^{18}\text{O}^{6+}$ beam

$^{197}\text{Au}$ target
1200 K
+3 kV

3-keV Fr$^+$ beam

INFN/LNL
Tandem-XTU
West Experimental Hall

Magneto-Optical Trap (MOT)
The primary $^{18}\text{O}^{6+}$ beam is provided by the Tandem-XTU accelerator at 95–115 MeV.

Maximum intensity is $2 \times 10^{12}$ particles/s (2 µA).

About 2 days/month of beam time dedicated to francium production.
For production of $^{208-211}$Fr, the best combination of projectile/target is $^{18}$O on $^{197}$Au:

- Large fusion-evaporation cross section ($\sim 0.1$ b)
- Large work function of gold (5.1 eV) for surface ionization
- Purity, malleability, and high melting point (1337 K) of gold

Top view of target assembly

- Tungsten rod
- Extraction electrode
- Gold disk

- $+3$ kV
- Insulator, with good thermal conductivity
- Heating wire
- $\sim 300$ W to reach operating temperature (1100 K)

100-MeV $^{18}$O$^{6+}$ ($30$ W)

3-keV Fr$^+$
Experiment concentrates on isotopes that are most abundantly produced:

<table>
<thead>
<tr>
<th>isotope</th>
<th>half life (s)</th>
<th>α fraction (%)</th>
<th>α energy (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{208}$Fr</td>
<td>59.1(3)</td>
<td>90(4)</td>
<td>6641(3)</td>
</tr>
<tr>
<td>$^{209}$Fr</td>
<td>50.0(3)</td>
<td>89(3)</td>
<td>6646(5)</td>
</tr>
<tr>
<td>$^{210}$Fr</td>
<td>191(4)</td>
<td>60(30)</td>
<td>6543(5)</td>
</tr>
<tr>
<td>$^{211}$Fr</td>
<td>186(1)</td>
<td>&gt; 80</td>
<td>6534(5)</td>
</tr>
</tbody>
</table>
Fusion-evaporation cross sections are measured at LNL with PISOLQ apparatus (oxygen on thin gold target)

Primary beam energy chosen experimentally as trade-off between integrated cross section and diffusion time.
Predicted yields are calculated from integrated cross sections

\[ \frac{P}{j} = \int_0^{E_0} \frac{\sigma(E')}{\langle dE/dx \rangle M} N_A \, dE' \]
Measured yields from $\alpha$ decays of francium collected on catcher foil and observed on silicon detector
**Measured yields vs primary beam energy**

![Graph showing measured and predicted yields vs beam energy]

**210Fr yields @ 1.5 x 10^{12}^{18}O/s:**
- 1 x 10^6 ions/s (average)
- 3 x 10^6 (maximum, near melting)

**Efficiency** (extracted/produced) is ~15% (40% max)

**Sufficient for spectroscopy**
- Might need ~10^9 for APV
Yield ratios \( \frac{208 + 209}{\text{total}} \) measured vs beam energy and temperature

Atomic and ionic properties (surface desorption, ionization, transport) cancel out

Diffusion process is efficient above 1100 K:
\[ t_{\text{diffusion}} \gg t_{\text{Fr}} \]
\[ D \gg 2 \times 10^{-9} \text{ cm}^2/\text{s} \]

Yields are limited by surface desorption
Transport beam line decouples radiation and vacuum of production area from laser trapping laboratory.

3 quadrupole triplets (T)
1 cylindrical bend (EB)
3 steerers (S)
1 Wien filter (WF)

Beam line is mass independent to allow tuning with stable Rb$^+$ from target dispenser.

Beam intensity and position with Faraday cups (current) and silicon detectors ($\alpha$ decays).
Ion optics of individual elements designed with Simion 3D

Electrode geometry defined on a discrete grid

Potentials calculated with relaxation method are used to integrate trajectories
Quadrupole triplet built at LNL
Prism built at LNL
Beam line optics designed with pencil, paper, and Trace-3D / PBO-Lab, using transfer matrices of individual elements from Simion 3D.

Constraints include layout of experimental hall and acceptance of MOT.

Optimized electrode voltages are within a few % of design values.
Mass selection is performed with a Wien filter (E x B velocity selector), mainly to suppress thermionic current from hot target.

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Wien-filter resolution set to $\Delta m/m \sim 20/210$ to accept all Fr isotopes.
3-keV Fr\(^+\) beam from beam line

Yttrium neutralizer heated to 1000 K

Trap cell
Neutralizer temperature trade-off:

- increase Fr diffusion and desorption
- possible damage of cell coating

Low work function of yttrium (3.1 eV) enhances release of neutral francium, whose ionization potential is 4.1 eV

(range of 3-keV Fr⁺ in Y is 5.1 nm)
Fr release time measured from:
(a) residual activity of neutralizer
(b) intensity of trap vs time
The magneto-optical trap (MOT) combines production of optical molasses by Doppler cooling (deceleration) and position-dependent Zeeman shifts (confinement) to produce a cold (~mK) cloud of atoms from a vapor.


Its main components are 6 orthogonal red-detuned circularly-polarized laser beams and a constant-gradient magnetic field.
Doppler cooling: an atom in a red-detuned field feels a viscous force ⇒ “optical molasses”
Zeeman-shift confinement: in an inhomogeneous magnetic field, the red-detuned laser beams create a position-dependent confining force if circularly polarized
Magneto-optical trap for Rb and Fr at LNL
Trapping transition is D\textsubscript{2} line at 718 nm, excited with Ti:sapphire laser.

Repumping transition at 817 nm, with diode laser.

Laser beam diameter is 4 cm.

Pyrex cell walls coated with Dryfilm to reduce adsorption (1 \(\rightarrow\) \(10^4\) bounces).

Typical vacuum in cell is \(\sim 10^{-9}\) mbar.
Rubidium trap: response to changing magnetic field and laser frequency
Light detection is challenging: small number of atoms, background from stray light.

Detection with cooled CCD camera: Rb trap example (500 atoms)

- Photodiode and lock-in technique
- Cooled CCD camera

Raw image: region of interest (ROI)
Background subtracted: noise < 5 fW (50 atoms)
$^{210}\text{Fr}$ trap observed!
Trapping efficiency depends on several factors, including cell coating and geometry (through $W$), vacuum ($C$), laser power ($L$), and neutralizer temperature ($\varepsilon$)

$$N_t = \frac{L \varepsilon}{CW} I$$

$\sim 2 \times 10^{-3}$ s
First results on precision laser spectroscopy of $^{209}$Fr, $^{210}$Fr and $^{211}$Fr have been obtained.

Precision on trapping transitions improved by factor ~20 with confocal Fabry-Perot interferometer calibrated with two-photon Rb transition.

$^{210}$Fr example:

<table>
<thead>
<tr>
<th>Trap freq. (MHz)</th>
<th>Uncertainty (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNL (preliminary)</td>
<td>417,412,490</td>
</tr>
<tr>
<td>Stony Brook</td>
<td>417,412,460</td>
</tr>
</tbody>
</table>

Atomic spectroscopy necessary to test relativistic many-body calculations. Continue with search of unobserved transitions.
We can easily improve precision on some francium lifetimes.

\[ T_{1/2}^{210\text{Fr}} = 185.5 \pm 4.9 \text{ s} \]

\[ T_{1/2}^{209\text{Fr}} = 50.1 \pm 3.8 \text{ s} \]
Measurements of atomic parity violation in forbidden transitions to 1% precision will probably require intensities $\sim 10^9$ ions/s [Sanguinetti et al., Eur. Phys. J. D 25, 3 (2003)]

Several options are being explored:
- study alternative observables, such as linear Stark shifts [Bouchiat, arXiv:0711.0337v2] with $\sim 10^4$ trapped atoms
- duplicate part of apparatus at CERN/ISOLDE
- study feasibility of a recirculating-beam ion source
Production of secondary beams with standard techniques is usually inefficient (~10^{-6}): most interactions are electromagnetic, not nuclear.

One may wish to re-use the primary beam until the desired reaction is obtained: a recirculating-beam ion source.

The negative effects of the target on the primary beam need to be compensated.

It was recently proposed to produce $^8\text{Li}$ and $^8\text{B}$ beams (for beta beams, hadron therapy) from a primary beam stored in a small ring with an internal thin target. Ionization cooling could provide reasonable lifetimes. [Rubbia et al., NIM A 568, 475 (2006); Neuffer, NIM A, in press (2007)]

\[
Y = \phi_{\text{in}} \sigma \ n_{\text{turns}} \ \Delta x/m_{\text{target}}
\]

**yield:**
- **input flux**
- **useful cross section**
- **lifetime (# of turns)**
- **target thickness**
STORED $^7\text{Li}^{3+}$ BEAM
25 MeV
(B rho) = 0.64 Tm
lifetime 1.5 ms ($10^4$ turns)
$10^{12}$ ions, 3.5 A
circumference 4 m

INPUT $10^{15}$ $^7\text{Li}^+$ ions/s
160 $\mu$A

D$_2$ TARGET
$\Delta x = 0.3$ mg/cm$^2$
$\Delta E = 300$ keV/ion
350 kW to dissipate

RF BEAM POWER
(300 kV)(3.5 A)/3
= 350 kW

Output
$10^{14}$ d($^7\text{Li},p$)$^8\text{Li}$ reactions/s
($10^{15}$ total)

[= Rubbia et al., NIM A 568, 475 (2006)]
Could this scheme work for francium?

**INPUT**
- $2 \times 10^{12} \, ^{18}\text{O}\,^{6+}$ ions/s
- 2 µA

**STORED \(^{18}\text{O}\,^{8+}\) BEAM**
- 100 MeV
- $(B\rho) = 0.77 \, \text{Tm}$
- Lifetime 0.15 ms (500 turns)
- 3.1 x $10^8$ ions, 1.3 mA
- Circumference 10 m

**OUTPUT**
- $3 \times 10^8 \, ^{197}\text{Au} \, ^{(18}\text{O},5n)^{210}\text{Fr}$ reactions/s
- $(6 \times 10^8$ total)

**197Au TARGET**
- $\Delta x = 1 \, \text{mg/cm}^2$
- $\Delta E = 1.5 \, \text{MeV/ion}$
- 240 W to dissipate

**RF BEAM POWER**
- $(1.5 \, \text{MV})(1.3 \, \text{mA})/8 = 240 \, \text{W}$

**Specific issues:**
- Charge state distributions
- Target heating
- Extraction
Conclusions

- Francium is one of the best candidates for studying violations of fundamental parity and time-reversal symmetries.
- The first European facility for Fr atomic traps has been built and commissioned at LNL (Legnaro, Italy).
- First results on high-precision laser spectroscopy were achieved.
- We’re looking forward to the next challenging phase of atomic parity-violation measurements in francium.

Thank you for your attention!