Fundamental interactions studies by laser trapping methods

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Sezione di Fisica

SPES-Nusprasen Workshop, Pisa – February 2, 2018
Outline

Laser Spectroscopy as a precision tool for fundamental and nuclear physics

Laser trapping of radioactive neutral isotopes

Perspectives (and proposals?)
À la découverte des Observables

Meetup HumanTalks Paris Décembre 2017
List of atomic observables for nuclear studies

→ Hyperfine structure

\[ \Delta E_{\text{HFS}} = \Delta E_{\text{dipole}} + \Delta E_{\text{quadrupole}} \]

\[ = \frac{A}{C} + \frac{B}{4} \left( \frac{C}{2} (C+1) - 2JJ\left(J+1\right)\left(J+1\right) - \frac{I}{I} \left(2I-1\right)\left(2I-1\right) \right) \]

\[ C = F(F+1) - J(J+1) - I(I+1) \]

\[ A = \frac{\mu I B_e(0)}{J J I} \]

\[ B = q_e Q_S \left\langle \frac{\partial^2 V}{\partial z^2} \right\rangle \]

Optics Letters

Observation of 7p^2P_{3/2} \rightarrow 7d^2D optical transitions in 209 and 210 francium isotopes

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List of atomic observables for nuclear studies

→ **Hyperfine anomalies**

\[ A = A_{\text{point}} \left( 1 + \epsilon_{BR} \right) \left( 1 + \epsilon_{BW} \right) \]

\[
\frac{A}{A'} = \frac{A_{\text{point}} \left( 1 + \epsilon_{BW} \right) \left( 1 + \epsilon_{BR} \right)}{A'_{\text{point}} \left( 1 + \epsilon'_{BW} \right) \left( 1 + \epsilon'_{BR} \right)} \approx \frac{\mu l'}{\mu' l} \left( 1 + A \Delta A' \right)
\]

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**Hyperfine anomalies in Fr: boundaries of the spherical single particle model**


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(Dated: July 2, 2015)

We have measured the hyperfine splitting of the \( 7F_{1/2} \) state at the 100 ppm level in Fr isotopes \((206g, 206m, 207, 209, 213, 219)\) near the closed neutron shell \((N = 126)\) in \( ^{213}\text{Fr} \). The measurements in five isotopes and a nuclear isomeric state of francium, combined with previous determinations of the \( 7S_{1/2} \) splittings, reveal the spatial distribution of the nuclear magnetization, i.e. the Bohr-Weisskopf effect. We compare our results with a simple shell model consisting of unpaired single valence nucleons orbiting a spherical nucleus, and find good agreement over a range of neutron-deficient isotopes \((207-213)\). Also, we find near-constant proton anomalies for several even-\( N \) isotopes. This identifies a set of Fr isotopes whose nuclear structure can be understood well enough for the extraction of weak interaction parameters from parity non-conservation studies.
List of atomic observables for nuclear studies

- Isotope shift
- Mean square nuclear charge radii

\[ \delta V_{AA'} = \delta V_{m, AA'} \text{ mass shift} + \delta V_{f, AA'} \text{ field shift} \]

\[ \delta V_{m, AA'} \text{ mass shift} = \frac{m^{A'} - m^A}{m^A m^{A'}} (N + S) \]

\[ \delta V_{f, AA'} \text{ field shift} = \frac{Z e^2}{6 \hbar c_0} \delta \langle r^2 \rangle_{AA'} \]

\[ \langle r^2 \rangle = \frac{3}{5} r_0^2 A^{2/3} \]

\[ \langle r^2 \rangle \approx \langle r^2 \rangle_0 \left(1 + \frac{5}{4\pi} \beta_2^2 \right) \]

\[ Q_s = \frac{3 \Omega^2 - I(I + 1)}{(I + 1)(2I + 3)} Q_0 \]

\[ Q_0 = \frac{3}{\sqrt{5\pi}} \frac{Z e R^2}{\langle \beta_2 \rangle} (1 + 0.36 \langle \beta_2 \rangle) \]
List of atomic observables for nuclear studies
List of atomic observables for nuclear studies

Fig. 6.8 Experimental setup for the isotope shift measurements of He isotopes (left) as explained in the text. The upper plot (a) at the right shows the very first spectrum recorded solely with the first $^8$He atom in the MOT obtained within 0.4 s. The lower figure (b) shows an integrated spectrum over 30 atoms, resulting in a line center fitting uncertainty of 110 kHz and a $\chi^2 = 0.87$ assuming a simple Gaussian profile. Figure modified from [18], ©The Royal Swedish Academy of Sciences. Reproduced by permission of IOP Publishing. All rights reserved.
RADIOACTIVE ATOM TRAPPING

Atom trapping and Recoil Ion Spectrometry for $\beta$-decay (and other BSM) studies

H.W. Wilschut, KVI, Groningen

Or why it is easier to measure things standing still
Atom trap features

<table>
<thead>
<tr>
<th>Typical MOT parameters:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of Laser Beams</td>
</tr>
<tr>
<td>Power/Laser Beam</td>
</tr>
<tr>
<td>Detuning of Laser Frequency</td>
</tr>
<tr>
<td>Magnetic Field Gradient</td>
</tr>
</tbody>
</table>

- Number of trapped Atoms: $10^9$
- Peak Density of trapped Atoms (Limited by Fluorescence): $10^{11} \text{ atoms/cm}^3$
- Temperature (below Doppler Limit): $10 \text{ } \mu \text{K}$
- Phase Space Density $\rho \Lambda^3$: $10^{-6}$

(trapped atoms)
Why to trap radioactive atoms?

A) Because it is a way of studying nuclear physics and fundamental processes by atomic physics tools

→ β DECAY

B) Because it becomes possible to perform spectroscopy on rare species

→ ATOMIC PARITY NON CONSERVATION

→ STANDARD MODEL CHECK
Trapped radioactive isotopes

-The Fr experiment at CYRC. Sendai is now going on, and last year, we finally observe the Fr-MOT at last, although the estimated number of Fr atoms was still limited compared with your experiment at LNL.

<table>
<thead>
<tr>
<th>Element</th>
<th>Group/facility</th>
<th>Measurement</th>
<th>Trapped atom number</th>
</tr>
</thead>
<tbody>
<tr>
<td>^8He</td>
<td>Berkeley</td>
<td>Halo structure</td>
<td></td>
</tr>
<tr>
<td>^23Na</td>
<td>Berkeley</td>
<td>β decay asymmetry parameter</td>
<td>4 \times 10^4</td>
</tr>
<tr>
<td>^27,28K</td>
<td>TISOL - TRIUMF</td>
<td>β decay asymmetry parameter</td>
<td>6 \times 10^2</td>
</tr>
<tr>
<td>^39K</td>
<td>Wisconsin</td>
<td>β decay asymmetry parameter</td>
<td>-</td>
</tr>
<tr>
<td>^39Rb</td>
<td>Stony Brook</td>
<td>Preparation of Fr experiment</td>
<td>80</td>
</tr>
<tr>
<td>^82Rb</td>
<td>Los Alamos</td>
<td>Beta – spin correlation function</td>
<td>10^6</td>
</tr>
<tr>
<td>^84Rb</td>
<td>Los Alamos</td>
<td>fermion–fermion and fermion–boson collision dynamics at T=0</td>
<td></td>
</tr>
<tr>
<td>^81Kr</td>
<td>Berkeley</td>
<td>Map of groundwater movement</td>
<td></td>
</tr>
<tr>
<td>^133,137Cs</td>
<td>Los Alamos</td>
<td>Ultrasensitive detection</td>
<td></td>
</tr>
<tr>
<td>^209-211Fr</td>
<td>Stony Brook</td>
<td>Atomic Parity Violation</td>
<td>10^4</td>
</tr>
<tr>
<td>^209-211Fr</td>
<td>LNL</td>
<td>Atomic Parity Violation</td>
<td>10^4</td>
</tr>
<tr>
<td>^209-211Fr</td>
<td>CYRIC/RIKEN</td>
<td>Electron Electric-Dipole-Moment Search</td>
<td>?</td>
</tr>
<tr>
<td>^221Fr</td>
<td>Colorado/LBNL</td>
<td>Atomic Parity Violation/EDM</td>
<td>10^2</td>
</tr>
<tr>
<td>^204g,206m,207,209,213,221Fr</td>
<td>TRIUMF</td>
<td>Hyperfine anomaly</td>
<td>Max 10^5</td>
</tr>
<tr>
<td>^225Ra</td>
<td>Tripp/KVI</td>
<td>Permanent EDM</td>
<td></td>
</tr>
<tr>
<td>^222Rb</td>
<td>Argonne</td>
<td>Atomic EDM</td>
<td></td>
</tr>
</tbody>
</table>

"The Fr experiment at CYRC. Sendai is now going on, and last year, we finally observe the Fr-MOT at last, although the estimated number of Fr atoms was still limited compared with your experiment at LNL."
ATOMIC PARITY NON CONSERVATION
Atomic parity violation

RELEVANT ELECTRON - HADRON PROCESSES

\[ A_{em} \propto \frac{e^2}{p^2} \]

\[ A_{W} \propto \frac{e^2}{p^2 + M_{Z0}^2 c^2} \]

\( p \) is the momentum transfer
(inversely proportional to the Bohr radius)

\[ p \sim m_e \alpha c \]
Different transition probabilities for two mirror-image experiments

The amplitude $A_w$ contains a part that is odd under space reflection and gives rise to a left-right asymmetry $A_{LR}$ by interference with $A_{em}$.

$$ P_{L/R} = \left| A_{em} \pm A_w^{odd} \right|^2 $$

$$ A_{LR} = \frac{P_L - P_R}{P_L + P_R} \approx 2 \text{Re} \frac{A_w^{odd}}{A_{em}} $$

$$ \alpha^2 \left( \frac{m_{e^-}}{M_{Z_0}} \right)^2 \sim 10^{-15} $$
Completely hopeless? No!

There are 2 factors of enhancement:

A. The so-called Z³ law

- For valence electrons belonging to penetrating orbitals, the orbitals are deformed in the vicinity of the nucleus, where electrons “see” a Coulomb potential generated by a charge Ze. The orbital radius is given by \( a_0/Z \), in such a way that \( p^2 \) is enhanced by \( Z^2 \).
- The various nucleons add for their contributions coherently: the number of nucleons grows as \( Z \)
B. The second source comes from the possibility of exciting highly forbidden transitions like
\[ nS_{1/2} \Rightarrow (n+1)S_{1/2} \]
in alkalis. The electromagnetic selection rules strictly forbid the electric dipole transition; dipole magnetic transitions \( M_1 \) are allowed by the symmetry, not by the change in radial number.

\[ M_1 \approx 4 \times 10^{-5} \frac{\mu_B}{C} \]

The weak interaction associated with the boson exchange breaks this rule and gives rise to a parity violating electric dipole amplitude \( E_{1}^{(PV)} \):
\[ E_1^{PV} \approx 10^{-11} ea_0 \]

\[ Im \frac{E_1^{PV}}{M_1} \approx 0.5 \times 10^{-4} \]
Nuclear parameters deducible by laser spectroscopy

→ **Nuclear anapole moment**

→ **Weak charge**

---

**Nuclear anapole moment (NAM)**

1959: Concept of Nuclear Anapole Moment:
(Ya. B. Zel’dovich & V. G. Vaks)

1980: Detectable through atoms and molecules
(V. V. Flambaum, I. B. Khriplovich & O. P. Sushkov)

1997: Reported to be observed in Cs PNC
(C. S. Wood et al, Science 275, 1759 (1997))

Current distribution seen by an electron has definite chirality due to spin helix:

\[
\overline{A}(R) = \frac{1}{c} \int \frac{\vec{j}(\vec{r})}{|\vec{R} - \vec{r}|} \, d^3 r
\]

---

**Weak charge**

Weak charges of quarks in the nucleus add coherently, therefore, at the tree level of SM:

\[
Q_{W}^{SM} = -N + Z \left(1 - 4 \sin^2 \theta_W \right) \approx -N
\]

With the permission of B. Sahoo
To obtain an observable that is first order in the APNC amplitude, it is possible to apply a dc electric field $E$ that also mixes $S$ and $P$ states. This field gives rise to a “Stark induced” E1 transition amplitude that is typically $10^5$ times larger than APNC and can interfere with it.

\[ R \propto \left| A_{\text{Stark}} + e^{i\theta} A_{\text{APNC}}^E \right|^2 \]

\[ \propto A_{\text{Stark}}^2 + k A_{\text{Stark}} \text{Im}(E_{\text{APNC}}^E) \]

Figure 4. Historical comparison of cesium PNC results. The squares are values for the 4-3 transition, the open circles are the 3-4 transition, and the solid circles are averages over the hyperfine transitions. The band is the standard-model prediction for the average, including radiative corrections. The ±1σ width shown is dominated by the uncertainty of the atomic structure.
Parity violation in atomic ytterbium: experimental sensitivity and systematics

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Advanced Light Source Division, Lawrence Berkeley National Laboratory, Berkeley CA 94720

Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720

(Dated: June 19, 2017)

We present a detailed description of the observation of parity violation in the $6s^2 1S_0 \rightarrow 5d6s^3D_1$ 408-nm forbidden transition of ytterbium, a brief report of which appeared earlier. Linearly polarized 408-nm light interacts with Yb atoms in crossed E- and B-fields. The probability of the 408-nm transition contains a parity violating term, proportional to $(\mathbf{E} \cdot \mathbf{B})|\mathbf{E} \times \mathbf{E}|$, arising from interference between the parity violating amplitude and the Stark amplitude due to the E-field ($\mathbf{E}$ is the electric field of the light). The transition probability is detected by measuring the population of the $^3P_0$ state, to which 65% of the atoms excited to the $^3D_1$ state spontaneously decay. The population of the $^3P_0$ state is determined by resonantly exciting the atoms with 649-nm light to the $6s^2 ^3S_1$ state and collecting the fluorescence resulting from its decay. Systematic corrections due to E-field and B-field imperfections are determined in auxiliary experiments. The statistical uncertainty is dominated by parasitic frequency excursions of the 408-nm excitation light due to imperfect stabilization of the optical reference with respect to the atomic resonance. The present uncertainties are 9% statistical and 8% systematic. Methods of improving the accuracy for the future experiments are discussed.

FIG. 8: (color online) The PV interference parameter $\zeta/\beta$. Mean value: $39(4)_{\text{stat}}(3)_{\text{syst.}}$ mV/cm, $|\zeta| = 8.7 \pm 1.4 \times 10^{-10}$ eV.
A possible experimental approach:

1. Capture Fr atoms in a MOT
2. Accumulate and cool in the MOT
3. Transfer to a second trap (purely optical)
4. Establish a “coordinate system” by dc electric field, dc magnetic field, k vector of the exciting laser
5. Excite 7S to 8S using a build up cavity and detect using the 7S to 7P transition.
6. Reverse the coordinate axis.
7. Change isotope.
Towards APV measurement

preliminary measurement of the ratios \( \alpha/\beta, \beta/M_1, M_1/M_{1hf} \): in the MOT cloud to “calibrate” APV
**Expected signal to noise ratio**

- Fr production rate in Legnaro: up to $10^6$ ions/s.
- Trapping efficiency $\sim 10^{-2} \Rightarrow N = 10000$ atoms in 1 mm$^3$ (0.01 mm$^3$) (optical dipole trap).
- **Laser intensity:** 100 mW/mm$^2$, enhanced by a factor $\zeta = 1000$ with a Fabry-Perot cavity (cf. Boulder) $\Rightarrow P/S = 10$ kW/cm$^2$.
- Fluorescence detection efficiency: $\eta \sim 10\%$.

$$
S/N = \xi m E_1^{pv} \left( \frac{4\pi 1 P}{3\hbar c \hbar \Gamma S} \right) \eta N \sqrt{t} = 0.009 \sqrt{t(s)} \quad (1 \text{ for } t = 3 \text{ hours})
$$

**How can we improve $S/N$?**

- Higher laser power, BUT: – heating due to photon scattering
  – photoionization from 8S and 7P.

- Higher Fr$^+$ Rate: $\geq 4 \cdot 10^9$ ions/s at the ISOLDE facility.

$\Rightarrow S/N = 0.55 \sqrt{t(s)}$

**In 9 hours we can get** $S/N = 100$
THE LNL EXPERIMENT
### (Bad) facts about francium

<table>
<thead>
<tr>
<th>Mass no. (A)</th>
<th>Half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>202</td>
<td>0.34 s</td>
</tr>
<tr>
<td>203</td>
<td>0.55 s</td>
</tr>
<tr>
<td>205</td>
<td>3.85 s</td>
</tr>
<tr>
<td>206</td>
<td>15.9 s</td>
</tr>
<tr>
<td>207</td>
<td>14.8 s</td>
</tr>
<tr>
<td>209</td>
<td>50 s</td>
</tr>
<tr>
<td>211</td>
<td>3.1 min</td>
</tr>
<tr>
<td>213</td>
<td>34.6 s</td>
</tr>
<tr>
<td>220</td>
<td>27.4 s</td>
</tr>
<tr>
<td>223</td>
<td>21.8 min</td>
</tr>
<tr>
<td>224</td>
<td>3.3 min</td>
</tr>
<tr>
<td>Fr</td>
<td></td>
</tr>
<tr>
<td>225</td>
<td>4.0 min</td>
</tr>
<tr>
<td>226</td>
<td>48 s</td>
</tr>
<tr>
<td>227</td>
<td>2.47 min</td>
</tr>
<tr>
<td>228</td>
<td>39 s</td>
</tr>
<tr>
<td>230</td>
<td>19.1 s</td>
</tr>
<tr>
<td>232</td>
<td>5 s</td>
</tr>
</tbody>
</table>

- Fr has no stable isotopes
- The longest lifetime is 22 min
- There is at most a tea spoon of francium in the whole Earth at any given time

$\Rightarrow$ continuos production and trapping for further studies is necessary
(Interesting) facts about francium

spectroscopically poorly known
“simple” electronic structure
several isotopes suitable for trapping
enhanced P and T violations (Z=87)
The “traprad”/“francium”/“wade” experiment

Fr production

\[ {^{197}\text{Au}} + {^{18}\text{O}} \rightarrow xn + {^{215-x}\text{Fr}} \]

Fr\(^+\) (and Rb\(^+\)) transport at 3 keV

The MOT cell

\[ \phi_{Au} = 5.1 \text{ eV} \]
\[ \phi_Y = 3.1 \text{ eV} \]
\[ I_{Fr} = 4.1 \text{ eV} \]

Further cooling in MOT to <1mK
Francium trapping

220 atoms

450 atoms

560 atoms

930 atoms

1100 atoms
Francium trapping

accumulation in the cold yttrium and fast release by suddenly switching on the heating of neutraliser up to 10000 atoms
Other Fr isotopes (209, 211)
PRECISION MEASUREMENTS ON THE FRANCIUM LEVELS
We compare the frequency of 2 lasers transmitted by a confocal FP cavity (finesse 200, FSR 2 GHz) ..... 

....Measuring the beat signal with a frequency meter (accuracy better than 300 kHz)
Precision measurements

Secondary frequency standard: Rb $5S - 5D_{5/2}$ 2 photon transition (@ 778 nm) measured with 8 kHz accuracy

<table>
<thead>
<tr>
<th>Isotope</th>
<th>209</th>
<th>210</th>
<th>211</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trapping freq. (GHz)</td>
<td>417415.0914(90)</td>
<td>417412.4493(90)</td>
<td>417412.6303(90)</td>
</tr>
<tr>
<td>Repumping freq. (GHz)</td>
<td>366897.43(5)</td>
<td>366898.70(5)</td>
<td>366895.57(5)</td>
</tr>
</tbody>
</table>

Accuracy:
- Calibration: 5 MHz
- Fabry-Perot maxima: 2 MHz
- Refractive index of air: 2 MHz
- TOTAL: 9 MHz
DETECTION OF LINES BY CHANGE IN TRAPPED ATOM NUMBERS
Detection of excited level population transfer in an MOT through the measurement of trapped atom number

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Measurement Science and Technology's Outstanding Paper awards for 2013
http://iopscience.iop.org/0957-0233/25/7/070201
Detection results (Rb)

Figure 2. (Left) Relative variation of the trapped $^{85}$Rb atoms as a function of the Ti:Sa laser detuning with respect to the D$_1$ line involving hyperfine level $F_g = 3$. The black and red lines denote the signal obtained with 3.5 mW and 35 μW, respectively. (Right) A simplified scheme of the involved levels.

Figure 6. Variation of the trapped $^{85}$Rb atom number as a function of the Ti:Sa laser detuning with respect to the D$_2$ line involving hyperfine level $F_g = 2$. The curves in the graph shows the effect of increasing Ti:Sa intensity (from left to right) on the observed signal. Each 600 MHz wide scan of the Ti:Sa laser frequency is marked by black arrows.

Figure 9. (Top) Relative variation of the number of trapped $^{85}$Rb atoms as a function of the Ti:Sa laser detuning with respect to the $5P_{1/2}$ ($F_g = 4$) → $5D_{5/2}$ at 8 mW (black curve), 1 mW (grey curve) and 35 μW (red curve) (left). (Right) Simplified scheme of the involved Rb atom levels. (Bottom) Numerical simulation of occupation probability as a function of the probe laser detuning.
Detection results (Fr)

Observation of $7p^2P_{3/2} \rightarrow 7d^2D$ optical transitions in 209 and 210 francium isotopes

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Detection results (Fr)

**Fig. 3.** $^{210}$Fr $7p^2P_{3/2}(F = 15/2) \rightarrow 7d^2D_{5/2}(F' = 13/2, 15/2)$ optical transitions observed as MOT population depletion caused by a laser beam of the wavelength 968.9 nm, intensity 1.77 mW cm$^{-2}$. Inset: levels scheme according to [19,25,26].

**Table 1.** $^{209}$Fr $7p^2P_{3/2} \rightarrow 7d^2D_{5/2}$ Hyperfine Splittings

<table>
<thead>
<tr>
<th>Excited Level</th>
<th>Experiment (This Letter)</th>
<th>Theory (Eq. 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F' = 7$</td>
<td>$(-259 \pm 10)$ MHz</td>
<td>$(-260 \pm 15)$ MHz</td>
</tr>
<tr>
<td>$F' = 6$</td>
<td>$(-89 \pm 10)$ MHz</td>
<td>$(-73 \pm 7)$ MHz</td>
</tr>
<tr>
<td>$F' = 5$</td>
<td>$(+62 \pm 10)$ MHz</td>
<td>$(+61 \pm 7)$ MHz</td>
</tr>
</tbody>
</table>

**Fig. 4.** $^{209}$Fr $7p^2P_{3/2}(F = 6) \rightarrow 7d^2D_{5/2}(F' = 7, 6, 5)$ optical transitions observed as MOT population depletion caused by a laser beam of the wavelength 960.7 nm, intensity 2.1 mW cm$^{-2}$. Inset: levels scheme according to Eq. (1).
OPTIMIZATION OF TRAPPED ATOM NUMBERS
LIAD for MOTs

Fr LIAD MOT loading from Yttrium

FIG. 8. Application of LIAD to Francium MOT loading.
Enhanced Atomic Desorption of 209 and 210 Francium from Organic Coating

Controlled atomic desorption from organic Poly-DiMethylSiloxane coating is demonstrated for improving the loading efficiency of $^{209,210}$Fr in magneto-optical traps. A three times increase in the cold atoms population is obtained with contact-less pulsed light-induced desorption, applied to different isotopes, either bosonic or fermionic, of Francium. A six times increase of $^{210}$Fr population is obtained with a desorption mechanism based on direct charge transfer from a triboelectric probe to the adatom-organic coating complex. Our findings provide new insight on the microscopic mechanisms of atomic desorption from organic coatings. Our results, obtained at room temperature so as to preserve ideal vacuum conditions, represent concrete alternatives, independent from the atomic species in use, for high-efficiency laser cooling in critical conditions.
Room temperature neutralizer trap!
1. New spectroscopic measurements

- ENERGY LEVEL DETERMINATION
- LIFETIMES MEASUREMENTS
- COLLISIONAL STUDIES
- DIMER FORMATION
2. Gamma Ray Laser proposal

Coherent gamma photon generation in a Bose–Einstein condensate of $^{135m}$Cs

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$^b$ Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom
2. Gamma Ray Laser proposal

Coherent gamma photon generation in a Bose–Einstein condensate of $^{135}\text{mCs}$

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$^a$ Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom
$^b$ Department of Physics, University of Surrey, Guildford GU2 7XH, United Kingdom

Our results demonstrate that a mechanism of collective decay occurs for a BEC of $^{135}\text{mCs}$ isomers. The collective nature of the phenomenon is highlighted by the exponential dependence of the number of emitted photons with respect to the initial isomer density. The collective de-excitation relies on the coherence of the condensate being transferred to $\gamma$ photons, and occurs at densities much lower than those required by the standard Dicke superradiance. The identified mechanism provides a promising route to the generation of coherent $\gamma$ radiation, as the associated process can be realized with available technology. $^{135}\text{mCs}$ ion beams can be generated by proton-induced fission of actinides. Afterwards, laser cooling and trapping can proceed as well established for $^{133}\text{Cs}$ and some of its isotopes [14]. The long lifetime of $^{135m}\text{Cs}$ allows for evaporation and creation of a BEC in an optical trap, along the lines of the procedure for stable cesium. As the collisional properties of ultra-cold $^{135m}\text{Cs}$ are not known, it is not possible to give an accurate estimate of the expected size of the BEC, and hence of the intensity of the $\gamma$ photons burst. However, the present results indicate that exponential photonic generation occurs for a wide range of BEC densities. We therefore expect coherent emission to occur over a broad range of BEC size, thus demonstrating the validity of the proposed approach for coherent gamma-ray generation.
### 3. Lasers at SPES

- **Surface Ionization Mechanism**
- **Laser Ionization Mechanism**
- **Electron Impact Ionization Mechanism**

#### Periodic Table of Elements

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3. Lasers at SPES

\[ M^*(E_k) + h\nu_2 \rightarrow M^+ + e^- + E_{\text{kin}} \]
\[ M^*(E_k) + 2h\nu_2 \rightarrow M^+ + e^- + E_{\text{kin}} (e^-) \]
3. Lasers at SPES

- Tin atom level scheme
- Table of isotopes:
  - Isotope: Sn, Mass: 119.90, Abundance: 0.97
  - Isotope: Sn, Mass: 113.90, Abundance: 0.66
  - Isotope: Sn, Mass: 114.90, Abundance: 0.34
  - Isotope: Sn, Mass: 115.90, Abundance: 14.54
  - Isotope: Sn, Mass: 116.90, Abundance: 7.68
  - Isotope: Sn, Mass: 117.90, Abundance: 24.22
  - Isotope: Sn, Mass: 118.90, Abundance: 8.59
  - Isotope: Sn, Mass: 119.90, Abundance: 32.58
  - Isotope: Sn, Mass: 120.90, Abundance: 4.63
  - Isotope: Sn, Mass: 123.91, Abundance: 5.79
4. Collinear laser spectroscopy proposal
4. Collinear laser spectroscopy proposal
SPES laser group
Thank you very much for the patience!

(SPES lasers after national elections)