Menu

- Objectives
- Status of the project
SPES Radioactive Ion Beam facility at LNL and EDM search
Giacomo de Angelis
INFN - LNL

Menu
• Objectives
• Status of the project

SPES – NuSPRASEN workshop
“Probing fundamental symmetries and interactions by low energy excitations with RIBs” Pisa 1-2 February 2018
SPES project goals

- Second generation ISOL facility for nuclear physics as part of the EURISOL_DF initiative (ESFRI_2020): Production & re-acceleration of exotic beams
- Research and Production of Radio-Isotopes for Nuclear Medicine
- Accelerator-based neutron source (Proton and Neutron Facility for Applied Physics)
The SPES ISOL complex

35-70 MeV, 750 microA proton cyclotron

NEW concept developed for the SPES Direct Target:
**Multi-foil UCx** designed to sustain 10kW beam power to reach \(10^{13}\) f/s

(p beam: 200 microA, 40 MeV)
Operating facilities at Legnaro National Laboratories

SC_LINAC (ALPI)
XTU Tandem

ALPI SC_linac
RFQ
CB - MRMS

ISOL FACILITY and reacceleration

Applications

Cyclotron
The Nuclear Landscape and the Big Questions

• Where did the atoms and atomic nuclei come from?
• How are the nuclei of atoms made and organized?
• What are the fundamental particles and forces at work inside atomic nuclei?
• What are practical and scientific uses of nuclei?
Which science drives physics with rare isotopes?

Origin of new elements, rare isotopes powering stellar explosions, neutron star crust.

Fundamental symmetries

Use of rare isotopes as laboratories where symmetry violations are amplified.

Nuclear Structure & Reactions

Limits of existence: what makes nuclei stable? New shapes, new collective behavior.

Materials, medical physics, reactors,..
Which science drives physics with rare isotopes?

Nuclear Astrophysics

Origin of new elements, rare isotopes powering stellar explosions, neutron star crust

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Nuclear Structure & Reactions

Limits of existence: what makes nuclei stable? New shapes, new collective behavior.

Materials, medical physics, reactors,..
Quantified input
Nuclear Forces from EFT

<table>
<thead>
<tr>
<th></th>
<th>NN</th>
<th>NNN</th>
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<tr>
<td>LO</td>
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<tr>
<td>NLO</td>
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<tr>
<td>N2LO</td>
<td><img src="image4" alt="Diagram" /></td>
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<tr>
<td>N3LO</td>
<td><img src="image6" alt="Diagram" /></td>
<td><img src="image7" alt="Diagram" /></td>
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</tbody>
</table>

Consistency with known data
Prediction

Comprehensive model of light and heavy nuclei
The frontier: calcium isotopes (where *ab-initio* and DFT meet)

New shell closures at $N = 32 \& 34$?

→ Shell closure at $Z=82 \ N=126$

Developing new nuclear paradigms

**Diagram:**
- **Graph (a):** Plot of $R_{ch}$ (fm) vs. Mass number $A$.
- **Graph (b):** Comparison of $\delta(\tau^2)_{48,52}$ for different theoretical calculations (Ab initio, DFT, CI) and experimental data.

**Citations:**
- Nature Physics 12, 594 (2016)
- Phys. Scripta 91, 053003 (2016)

**Authors:** G. de Angelis 2017
The N=82 region via multinucleon transfer with n-rich secondary beams
Deep Inelastic with n-rich beams at HIE-ISOLDE

\[ ^{94}\text{Rb} - 2n \]
\[ ^{208}\text{Pb} + 2n \]

\[ ^{94}\text{Rb} + ^{208}\text{Pb} @ 5.5 \text{ MeV/n} \]

\[ ^{210}\text{Pb} \gamma \gamma \]

\[ ^{210}\text{Pb} \gamma \]
Which science drives physics with rare isotopes?

**Nuclear Astrophysics**

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**Fundamental symmetries**

- Use of rare isotopes as laboratories where symmetry violations are amplified.

**Nuclear Structure & Reactions**

- Limits of existence: what makes nuclei stable?
  - New shapes, new collective behavior.

**Materials, medical physics, reactors,**
Indeed, in many cases, nuclear modeling MUST involve massive extrapolations...

Impact of Nuclear Mass Uncertainties on the r Process

Measurements of astrophysical relevant reactions induced by alpha, protons and neutrons at the Gamow peak using the Trojan Horse method

Observation of 1808.65 keV $\gamma$-rays from the decay of $^{26}\text{Al}$ to $^{26}\text{Mg}$ in the interstellar medium demonstrated that $^{26}\text{Al}$ nucleosynthesis does occur in the present Galaxy.

Meteorites formed before the birth of the solar system show excesses in $^{26}\text{Mg}$, pointing to $^{26}\text{Al}/^{27}\text{Al}$ at least 100 times larger than the solar value.

The radioisotopes $^{26}\text{Al}$ (T1/2 = $7.17 \times 10^5$ yr) and $^{26}\text{Al}^m$ (T1/2 = 6.34 s) are of outstanding importance in astrophysics.

$r$-process reactions can be studied as well

$^{26}\text{Al}^*(n,\alpha)^{23}\text{Na}$ via $^{26}\text{Al}^*(d,\alpha^{23}\text{Na})p$

$^{26}\text{Al}^*(n,p)^{26}\text{Mg}$ via $^{26}\text{Al}^*(d,p^{26}\text{Mg})p$

M. La Cognata, S. Palmerini and the ASFIN collaboration LNS

SPES phase 1 (using silicon carbide as primary target) can supply $^{26}\text{Al}^m$ beam

→ Isomeric state at 228 keV with a lifetime of 6.34 s cannot be as target in neutron induced reactions

→ The THM can be used to transfer a neutron and deduce the cross sections of astrophysical interest at astrophysical energies (0-2 MeV)

$^{26}\text{Al}$ beam @ 5AMeV

$10^4$ pps a 5 $\mu$A

$^4\text{He}/p$

$^{23}\text{Na}/^{26}\text{Mg}$
Which science drives physics with rare isotopes?

Origin of new elements, rare isotopes powering stellar explosions, neutron star crust

Nuclear Astrophysics

Fundamental symmetries

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Nuclear Structure & Reactions

Limits of existence: what makes nuclei stable? New shapes, new collective behavior.

Materials, medical physics, reactors,..
Nuclear Structure and EDM search

• Explanations of the Baryon Asymmetry of the Universe require additional CP violation
• Permanent EDM of fundamental spin systems are the most sensitive probes for beyond Standard Model CP violation
• Axion like Dark Matter probe?

Observed:
\[(n_B - n_{\bar{B}})/n_\gamma = 6 \times 10^{-10}\]

SM expectation:
\[(n_B - n_{\bar{B}})/n_\gamma \sim 10^{-18}\]

Sakharov 1967:
B-violation
C & CP-violation
non-equilibrium
JETP Lett. 5(1967)24
**Electric Dipole Moment (EDM) Violates Both P and T**

A permanent EDM violates both time-reversal symmetry and parity.

![Diagram showing EDM and spin](image)

<table>
<thead>
<tr>
<th>Sector</th>
<th>Exp Limit (e-cm)</th>
<th>Location</th>
<th>Method</th>
<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$9 \times 10^{-29}$</td>
<td>Harvard (ACME)</td>
<td>ThO molecules in a beam</td>
<td>$10^{-38}$</td>
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<tr>
<td>Neutron</td>
<td>$3 \times 10^{-26}$</td>
<td>ILL</td>
<td>UCN in a bottle</td>
<td>$10^{-31}$</td>
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<tr>
<td>Nuclear</td>
<td>$7 \times 10^{-30}$</td>
<td>U. Washington</td>
<td>$^{199}$Hg atoms in a cell</td>
<td>$10^{-33}$</td>
</tr>
</tbody>
</table>
The Seattle EDM Measurement

$^{199}\text{Hg}$ is stable, high Z, $J = 0$, $I = \frac{1}{2}$, high vapor pressure.

\[ f_+ = \frac{2\mu B + 2dE}{\hbar} \approx 15 \text{ Hz} \]
\[ f_- = \frac{2\mu B - 2dE}{\hbar} \approx 15 \text{ Hz} \]
\[ |f_+ - f_-| < 0.2 \text{ nHz} \]

The best limit on atomic EDM

EDM ($^{199}\text{Hg}$) < $7.4 \times 10^{-30}$ e-cm


Courtesy of Michael Romalis

Unit EDM

Courtesy of Savard
Atomic EDM proportional to Schiff moment

- No atomic EDM due to EDM of the nucleus – Schiff’s Theorem
  – Electrons screen applied electric field

- $d(\text{Hg})$ is due to finite nuclear size
  – nuclear Schiff moment $S$ – Difference between mean square radius of the charge distribution and electric dipole moment distribution

$$S = \frac{2\pi}{5} \int dx^3 \rho(x) \left( x^2 x - \frac{5}{3} \langle r^2 \rangle_{ch} x \right)$$

Recent work by Haxton, Flambaum on form of Schiff moment operator

- Schiff moment induces parity mixing of atomic states, giving an atomic EDM:

$$d_a = R_A S$$

- $R_A$ - from atomic wavefunction calculations, uncertainty 50%
Octupole Enhancement

\[ \Psi^+ = \frac{(|+\rangle + |-\rangle)}{\sqrt{2}} \]
\[ \Psi^- = \frac{(|+\rangle - |-\rangle)}{\sqrt{2}} \]

\[ \Delta E \]

\[ S_{\text{intr}} \sim e Z A^{1/2} \beta_2 \beta_3 \]
\[ S_{\text{lab}} \sim e Z A^{2/3} \beta_2 \beta_3^2 / \Delta E \]

\[ \beta_2, \beta_3 \sim 0.1 \]

\[ \Psi^+ = \frac{(1+\alpha)|+\rangle + (1-\alpha)|-\rangle}{\sqrt{2}} \]
\[ \Psi^- = \frac{(1-\alpha)|+\rangle + (1+\alpha)|-\rangle}{\sqrt{2}} \]

\[ \alpha = \frac{\langle \Psi^- | \nu^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E} \]

Measured \( B(E3) \) values as a function of \( Z \)

- \( Z = 34 \) (\( ^{96}\text{Zr} \): 53(6) W.u.)
- \( Z = 56 \)
- \( Z = 88 \) (\( ^{152}\text{Gd} \): 52(17) W.u., \( N = 134 \), \( ^{226}\text{Ra} \): 54(3) W.u.)
- \( Z = 86 \)? (Rn)
Octupole enhanced atomic EDM moment

Schiff moment: \[ S = -2 \frac{\frac{J}{J+1} \langle \hat{S}_z \rangle \langle \hat{V}_{PT} \rangle}{\Delta E} \]

related to \( Q_3 \)

P,T-violating n-n interaction

Schiff moment enhanced by \( \sim 3 \) orders of magnitude in pear-shaped nuclei

Search candidates are odd-A Rn [TRIUMF] and Ra [Argonne, Groningen/ISOLDE]

Measure: \( Q_3 \) in even-A Rn, Ra

\( \Delta E \) in odd-A Rn
Signature of pear-shape: B(E3)

rigid deformation

radioactive targets

vibrational

$Q_2$ (efm$^2$)

$Q_3$ (efm$^3$)

Gaffney et al, Nature 497 (2013) 199
EDM measurement with $^{225}$Ra

Results and up-grades
2015 : $< 5 \times 10^{-22}$ e cm
2016 : $< 1.4 \times 10^{-23}$ e cm
New trap: $< 1.4 \times 10^{-26}$ e cm
FRIB: $< 3 \times 10^{-28}$ e cm

Statistical uncertainty:

$$\delta d = \frac{\hbar}{2E \sqrt{T} N \varepsilon T}$$

100 kV/cm
100 s $10^6$ 10%

$\delta d = 3 \times 10^{-28}$ e cm Phase II

- $^{225}$Ra / $^{199}$Hg enhance factor $\sim 10^2$
- $\delta d(^{199}$Hg$) = 1.5 \times 10^{-29}$ e cm

Courtesy of Savard

M. Bishof et al
PRC 94, 025501 (2016)
R.H. Parker et al.,
PRL 114 233002 (2015)
Octupole Enhancement

\[ \Psi^+ = \frac{|+\rangle + |-\rangle}{\sqrt{2}} \]
\[ \Psi^- = \frac{|+\rangle - |-\rangle}{\sqrt{2}} \]

\[ \Delta E \]

\[ \Psi^+ = \frac{(1+\alpha)|+\rangle + (1-\alpha)|-\rangle}{\sqrt{2}} \]
\[ \Psi^- = \frac{(1-\alpha)|+\rangle + (1+\alpha)|-\rangle}{\sqrt{2}} \]

\[ \alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E} \]

\[ S_{\text{intr}} \sim eZ\alpha^2 \beta_2 \beta_3 \]
\[ S_{\text{lab}} \sim eZ\alpha^2 A^{2/3} \beta_2 \beta_3^2 / \Delta E \]
\[ \beta_2, \beta_3 \sim 0.1 \]

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel; Dobaczewski & Engel

<table>
<thead>
<tr>
<th></th>
<th>$^{223}$Rn</th>
<th>$^{223}$Ra</th>
<th>$^{225}$Ra</th>
<th>$^{223}$Fr</th>
<th>$^{225}$Ac</th>
<th>$^{229}$Pa</th>
<th>$^{199}$Hg</th>
<th>$^{129}$Xe</th>
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<tr>
<td>$t_{1/2}$</td>
<td>23.2 m</td>
<td>11.4 d</td>
<td>14.9 d</td>
<td>22 m</td>
<td>10.0 d</td>
<td>1.5 d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I$</td>
<td>7/2</td>
<td>3/2</td>
<td>1/2</td>
<td>3/2</td>
<td>3/2</td>
<td>5/2</td>
<td>1/2</td>
<td>1/2</td>
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<tr>
<td>$\Delta e_{th}$ (keV)</td>
<td>37</td>
<td>170</td>
<td>47</td>
<td>75</td>
<td>49</td>
<td>5</td>
<td></td>
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<tr>
<td>$\Delta E_{exp}$ (keV)</td>
<td>--</td>
<td>50.2</td>
<td>55.2</td>
<td>160.5</td>
<td>40.1</td>
<td>0.22</td>
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<tr>
<td>$10^5 S$ (efm$^3$)</td>
<td>1000</td>
<td>400</td>
<td>300</td>
<td>500</td>
<td>900</td>
<td>12000</td>
<td>-1.4</td>
<td>1.75</td>
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<tr>
<td>$10^{28} d_A$ (e cm)</td>
<td><strong>2000</strong></td>
<td><strong>2700</strong></td>
<td><strong>2100</strong></td>
<td><strong>2800</strong></td>
<td></td>
<td></td>
<td>-5.6</td>
<td>0.8</td>
</tr>
</tbody>
</table>
HIE-ISOLDE for $^{223}$Fr ~ $2 \times 10^6$ s$^{-1}$

SPES for $^{229}$Pa by $^{232}$Th(p,4n)

$I \approx 10^{16}$ atoms in 10 days

SPIRAL2 (Linag) for $^{229}$Pa by $^{232}$Th(p,4n)

229Pa production at SPES?

ThC$_X$ target

30000 more sensitive than $^{199}$Hg

EDM and Axions or Axions like particles

- The smallness of $\theta_{\text{QCD}}$ can be explained invoking axions
- Axions and ALPs are viable candidates for Dark Matter
- The neutron EDM is sensitive to axions and ALPs, some of which produce oscillating EDM values

Nuclear species with large Schiff moments can be used due to octupole enhancement and can be used for Axion-Gluon and Axion-Nucleon PSI results.

EDM limiting axions

Axion-Gluon and Axion-Nucleon
SPES building

- 50x60 m²
- -3 to +11 m height
- 24,000 m³ of concrete
- 1,150 tons iron
- 3-4 m shielding wall thick
The SPES building 2016
PLANTS: air and water

UTA air treatment cyclotron vault

Cyclotron cooling

Moduls for cooling water
Cyclotron and beam lines

- Proton beams (H⁻ acceleration)
- Dual beam extraction
- Variable Energy 35-70 MeV
- Total current 750 microA

Main Parameters

<table>
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<tr>
<th>Parameter</th>
<th>Description</th>
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<tbody>
<tr>
<td>Accelerator type</td>
<td>Cyclotron AVF with 4 sectors, Resistive Magnet</td>
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<tr>
<td>Particle</td>
<td>Protons (H⁻ accelerated)</td>
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<tr>
<td>Energy range</td>
<td>35-70 MeV</td>
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<tr>
<td>Max Current Intensity</td>
<td>700 µA (variable within the range 1µA-700µA)</td>
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<tr>
<td>Extraction</td>
<td>Dual stripping extraction</td>
</tr>
<tr>
<td>Max Magnetic Field</td>
<td>1.6 T (Bo = 1 T)</td>
</tr>
<tr>
<td>RF System</td>
<td>nr. 2 delta cavities; harmonic mode=4; f_{RF} =56 MHz; 70 kV peak voltage; 50 kW RF power (2 RF amplifiers)</td>
</tr>
<tr>
<td>Ion Source</td>
<td>Multi-cusp volume H⁻ source; I_{ext} =8mA; V_{ext}=40 kV; axial injection</td>
</tr>
<tr>
<td>Dimensions</td>
<td>Φ=4.5 m, h=2 m, W=190 tons</td>
</tr>
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</table>
Cyclotron commissioning

- May 30th 2016 → dual extraction 70 MeV beam – 3 µA
- Sept 9th 2016 → acceleration 70 MeV beam – 500 µA
- Oct Nov 2016 → preliminary endurance test 250 µA, 40 MeV
- End Nov 2016 → source HV transformer brakes before to complete Site Acceptance Test
- June - July 2017 → endurance test completed
- September 2017 → cyclotron accepted

Up to 500 µA current and 70 MeV energy proton beam (35 kW) delivered to the BD
Less than 1% beam loss

Very good Cyclotron vacuum performance
(8x10^-8 mbar with beam ON)
System under operation for source commissioning. (Following ISOLDE Design)
Final version updated for radiation hardness and maintenance is under construction.
**n+ Beam transport and reacceleration**

- **Pre-accelerator**: RFQ (700 keV/n)  
- **ECR_Charge Breeder**: from 1+ to n+  
- **Mass separator**: to clean the beam from CB contaminants
1. installation of Charge Breeder and related mass separator: ready in 2018

2. installation of ISOL and 1+ beam line up to the tape station: ready in 2019
   Experiments with non-reaccelerated beams

3. Installation of RFQ and 1+ beam line up to Charge Breeder: ready 2020

4. Reaccelerated beams: ready in 2021

✓ High resolution mass selection: ready in 2022
Our current understanding of nuclei has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allowed experiments to be performed with only a small number of atoms. Concurrent advances in theoretical approaches and computational science have led to a more detailed understanding and pointed toward which nuclei and what phenomena to study.

Profound intersections

- Nuclear Structure
- Astrophysics
- Fundamental Symmetries

How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

- Energy (fission, reactions, decays…)
- Security (stewardship, forensics, detection…)
- Isotopes (medicine, industry, defense, applied research…)

Thanks for Attention