Pulsed laser technique applied to rare isotopes

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Challenge and goals

Scientific challenge
• Validate the theoretical framework for calculating neutron capture cross sections important for defense science, advanced reactor concepts, transmutation of radioactive waste and other stewardship-related research areas
• The size of a nucleus is an important input to constrain theoretical framework.
• Our approach is to determine the charge radii of rare (short-lived) isotopes using laser spectroscopy techniques.
• A pulsed laser technique is being implemented to enhance sensitivity of laser spectroscopy for rare isotopes.

Project goals
• Develop and apply the pulsed laser techniques
• Train a postdoc and a graduate student
• Procure laser systems to be integrated into an existing laser system
• Collaborate with scientists at Oak Ridge National Laboratory (ORNL)
• Use the existing pulsed laser system at ORNL for training postdoc and student
Project overview

Personnel supported on grant
- Dr. David Garand, Research Associate, 100% salary (left May 2018) and travel support
- Mr. Jeremy Lantis, Graduate Students, 100% salary (2018) and travel support
- Mr. Andrew Miller, Graduate Students, travel support
- Prof. Paul Mantica, PI, travel support
- Prof. Kei Minamisono, co-PI, travel support

Number of peer-reviewed publications: 3
- J. Lantis et al., “Electronic population manipulation in RFQ ion trap ...”, Hyperfine Interactions, under review.

Interactions with national laboratories
- Collaboration meetings were held between ORNL and MSU participants at ORNL in July 2016 and January 2018
- Two hands-on training sessions for pulsed laser operations were held at ORNL in conjunction with the collaboration meetings
- ORNL collaborator Dr. Yuan Liu participated in on-line collinear laser spectroscopy experiments at NSCL in February 2016, September 2017 and April 2018
- Collaboration meeting for pulsed laser light transport in April 2018
Achievement in year 3

• A post-doctoral researcher and graduate student continue to work on the project

• Last year of the project

• No cost extension has been requested and granted to complete remaining tasks (red items below)

• Laser frequency 4th harmonic light generation
  • Procurement completed
  • installation/commissioning scheduled in May

• Laser light transport system
  • Design completed
  • Procurement of material, safety system completed
  • Fabrication completed
  • Installation is being done as of now

• Commissioning tests of the technique is planned in the summer

• New resonant ionization schemes identified for stable zirconium isotopes in experiments at ORNL
Detailed knowledge of the nuclear size and shape can be used to constrain parameters of nuclear theories to calculate neutron capture cross sections, which are important for accurately model the neutron capture networks relevant to stockpile stewardship.

Laser spectroscopy can be used to precisely determine charge radii/nuclear size.

To better constrain theoretical parameters, radii of neighboring isotopes even further away from stable isotopes are important.

Example: charge radii of Ca isotopes

Ca radii show a very intricate pattern.

Example: charge radii of Ca isotopes

Theory does good job, but some discrepancy, and predicts very large radii for light Ca.

We measured very small radii for light Ca.
Example: charge radii of Ca isotopes

Driven by our data, improved theory reproduces the overall trend better.

Isotope shift of atomic hyperfine structure

\[ \delta \nu^A, A' = \nu^{A'} - \nu^A = \frac{k(M' - M)}{M'M} + F \times \delta \langle r^2 \rangle^A, A' \]

Laser probes orbital electron that sees nucleus.
BECOLA facility @ NSCL/MSU
- Bunched beam collinear laser spectroscopy -

Injection of pulsed laser light into ion trap: **NEW**

K. Minamisono et al, NIMA 709, 85 (2013);
For a ground state transitions, if:
- No narrow line width laser light available and/or
- Transition not suitable to deduce nuclear properties

population manipulation in RFQ ion trap with pulsed laser light
- Long interaction time in the trap
- Easy to generate deep UV light with high power density of pulsed light

See poster presentation by J. Lantis

Atomic population manipulation in RFQ ion trap

- Commissioning tests planned on Zr isotope
  - After completion of the light transport system
  - Summer 2019

- Simulation code was developed, and indicates
  - Population in the 315 cm\(^{-1}\) state can be moved to the ground state
  - Increase population in the ground state from 70 to 90%

- Tests results will be fed back to the simulation
  - Improving predictive power of the simulation

Simulation with pump laser @ 361 nm
10 Hz, 25 mJ/pulse

Initial population

\[
\begin{align*}
361 \text{ nm} & : 25\% \\
315 \text{ cm}^{-1} & : 49\% \\
763 \text{ cm}^{-1} & : 26\% \\
70\% & : 25\% \\
0 \text{ cm}^{-1} & : 25\%
\end{align*}
\]

Other schemes available
**Laser light transport**

- Light needs to be transported approximately 15 meters
  - Design, procurement completed
  - Installation being done as of now

- In the RFQ ion trap, light must pass 2 meters through 7 mm diameter channel
  - Optics design (a telescope) completed using FRED optical engineering software
  - Procurement completed
  - Installation being done as of now

FRED: https://photonengr.com/fred-software/
Laser frequency 2\textsuperscript{nd} & 4\textsuperscript{th} harmonic light generation

For population manipulation

- Procured a pulsed laser system

For spectroscopy

- Procured a laser frequency doubler
  - To match with wide wavelength range of the pulsed laser
  - Together with existing system, it allows generation of deep UV light (205 – 235 nm)
  - Overall laser wavelength range of 205 – 1000 nm available at BECOLA
- Enhancing accessibility to wide range of elements and isotopes for charge radius measurements

### Pulsed Laser Properties

<table>
<thead>
<tr>
<th>Spectral Properties</th>
<th>197-900 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength Range</td>
<td>197-900 nm</td>
</tr>
<tr>
<td>Energy per Pulse</td>
<td>0.1 mJ for &lt; 200 nm</td>
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<tr>
<td></td>
<td>1 mJ for &gt; 200 nm</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Frequency Linewidth</td>
<td>10 μeV</td>
</tr>
</tbody>
</table>

Summary & prospects

- Appropriate progress toward final commissioning tests
  - Construction of light transport system
  - Installation of laser frequency doubler
- NCE has been requested and granted for commissioning of the system
- Students and post-doc (left 2018) actively engaged in research activities
- Collaboration with ORNL remains strong
  - Resonance ionization of Zr
- Commissioning experiments on Zr planned this summer

Thank you.
Need for data: radii of Zr isotopes

- Detailed knowledge of the nuclear size and shape can be used to constrain parameters of nuclear theories to calculate neutron capture cross sections, which are important for accurately model the neutron capture networks relevant to stockpile stewardship.

- Laser spectroscopy can be used to precisely determine charge radii/nuclear size.
- To better constrain theoretical parameters, radii of neighboring isotopes even further away from stable isotopes are important.

Unstable nuclei of interest for stockpile stewardship

<table>
<thead>
<tr>
<th>Loaded Element</th>
<th># of Isotopes</th>
<th># with half-life &gt; 10y</th>
<th># with half-life &lt; 1d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti</td>
<td>14</td>
<td>6</td>
<td>3</td>
</tr>
<tr>
<td>Cr</td>
<td>11</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Fe</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Br</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Kr</td>
<td>3</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Y</td>
<td>11</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>Zr</td>
<td>10</td>
<td>3</td>
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</tr>
<tr>
<td>Nb</td>
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</tr>
<tr>
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<tr>
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<td>14</td>
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<td>Ta</td>
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</tr>
<tr>
<td>Ir</td>
<td>21</td>
<td>3</td>
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</tr>
<tr>
<td>Bi</td>
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<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

BECOLA cryogenic cooler/buncher

- cryogenic (currently commissioned)
- separate cooling/bunching sections

B. R. Barquest et al., NIMA 866, 18 (2017).
Three-step resonance ionization of Zr at ORNL

- Zr is difficult to produce due to its refractory nature
- Laser resonance ionization of Zr was studied
  - Two schemes were newly developed
  - Ionization potential was precisely determined from Rydberg series (by a factor of 10 improvement)