Resonance ionization schemes for high resolution and high efficiency study of exotic nuclei at the CRIS experiment

Agi Koszorus
EMIS XVIII
CERN Geneva/ Switzerland / 16-21 September 2018
Contents

• Motivation: Need for suitable techniques
• Challenges:
  • High efficiency and high resolution
  • Precision and accuracy
• CRIS: Laser lab
• Results: Selected Resonance Ionization Schemes
• Summery and Outlook
Motivation: Need for suitable techniques

- Nuclear spin \( l \)
- Magnetic dipole moment \( \mu \)
- Electric quadrupole moment \( Q \)
- Changes in the mean square charge radii \( \delta \langle r^2 \rangle \)

of the ground state and long lived isomeric states of exotic isotopes

- High resolution
- High efficiency

- The distance between the peaks carries the magnetic moment information
- The centroid (relative to the reference) gives us the changes in the \( m_s \) in the chain
- Spin assignment: number/relative intensities/ratio of HF parameters/…
Motivation: Need for new techniques

Model independent study of the
- Nuclear spin $I$
- Magnetic dipole moment $\mu$
- Electric quadrupole moment $Q$
- Changes in the mean square charge radii $\delta<r^2>$

of the ground state and long lived isomeric states of exotic isotopes

High resolution – collinear laser spectroscopy
High efficiency – In-source RIS

$\rightarrow$ CRIS
Principle of CRIS
Principle of CRIS

A.R. Vernon et al. in preparation
Principle of CRIS

Resonantly ionized atoms and Nonresonant background
Lowest limit 1 count/h background rate (dark count rate)

Figure by A. R. Vernon*
Principle of CRIS

Resonantly ionized atoms and Nonresonant background
Least limit 1 count/h background rate (dark count rate)
Challenges:

High efficiency and high resolution
- Resolution
  - Narrow band lasers
  - Remove power broadening
  - Laser atom related line shape distortion and shifts
- Efficiency = \( \varepsilon_{\text{TRANS}} \times \varepsilon_{\text{CEC}} \times \varepsilon_{\text{RIS}} \times \varepsilon_{\text{DET}} \)
  - Particle detection
  - Efficient RIS
  - 1% \( \rightarrow \) 100 ions/s before ISCOOL = 1 count/s signal

Isobaric/nonresonant background suppression
- Ultra high vacuum in the interaction region
- Reduction of non-resonant ionization rate
- Suppression of 1:10\(^6\) \( \rightarrow \) 10\(^6\) ions/s beam = 1 count/s background

Precision and accuracy in case of light systems
- Precision of laser scanning and frequency measurement

High resolution CRIS studies performed since 2014

- 16 nuclear states
  - 19\(^K\)
  - 17 nuclear states
  - 21\(^Sc\)
  - >60 nuclear states
  - 29\(^Cu\)
  - 31\(^Ga\)
  - 49\(^In\)
  - 50\(^Sn\)
  - 87\(^Fr\)
  - 88\(^Ra\)
  - 101-131\(^In\)
  - 203, 206, 207, 219, 221\(^Fr\)

- 38-52\(^K\)
- 63-66, 68-78\(^Cu\)
- 101-131\(^In\)
- 203, 206, 207, 219, 221\(^Fr\)
Details of the laser lab can be found in the PhD thesis of Dr. Shane G. Wilkins.
### Narrow band laser in at CRIS

<table>
<thead>
<tr>
<th>Laser</th>
<th>Type</th>
<th>Bandwidth</th>
<th>Power/Energy</th>
<th>SHG</th>
<th>THG</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSquared</td>
<td>Ti:sa</td>
<td>CW</td>
<td>&lt;1 MHz</td>
<td>5 W</td>
<td>Y</td>
</tr>
<tr>
<td>Matisse</td>
<td>Ti:sa</td>
<td>CW</td>
<td>&lt; 1 MHz</td>
<td>2.5 W</td>
<td>Y</td>
</tr>
<tr>
<td>Dye</td>
<td>CW</td>
<td>&lt;1 MHz</td>
<td>2.5 W</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Injection-locked(^2)</td>
<td>Ti:sa</td>
<td>Pulsed</td>
<td>~ 20 MHz</td>
<td>~ 300 uJ(^1)</td>
<td>Y</td>
</tr>
</tbody>
</table>

1. Energy /pulse
2. Mikael Reponen Poster 97

**Power/ Energy**

- **SHG**: Single-Harmonic Generation
- **THG**: Triple-Harmonic Generation

**Laser Types**

- **CW**: Continuous Wave
- **Pulsed**: Pulsed

**Frequency Bands**

- **1064 nm**
- **532 nm**
- **355 nm**
- **Other**

**Types of Laser**

- **Ti:sapphire (Ti:sa)**
- **Dye**

**Inj.-locked**: Injection-locked

**Cavities**

- **Z cavity**

**Litron**

**DL PRO**

**WSU2**

**Millenia**

**Sprout**

**Matisse**

**MSquared**

**WS6**

**Brilliant**

**LEE**

**PDL**

**COBRA**

**Pulsed**

- **CW**: Continuous Wave
- **Pulsed**: Pulsed
## Broadband lasers at CRIS

<table>
<thead>
<tr>
<th>Laser</th>
<th>Type</th>
<th>Rep.rate</th>
<th>Bandwidth</th>
<th>Energy</th>
<th>SHG</th>
<th>THG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z cavity</td>
<td>Ti:sa</td>
<td>1 kHz</td>
<td>6 GHz</td>
<td>260 uJ</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>PDL</td>
<td>Dye</td>
<td>100 Hz</td>
<td>~10 GHz</td>
<td>0.5-4 mJ</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>COBRA</td>
<td>Dye</td>
<td>100 Hz</td>
<td>1.8 GHz</td>
<td>6 mJ</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Litron</td>
<td>Nd:YAG</td>
<td>100 Hz</td>
<td></td>
<td>80 mJ</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Litron</td>
<td>Nd:YAG</td>
<td>100 Hz</td>
<td></td>
<td>250 mJ</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Brillinat</td>
<td>Nd:YAG</td>
<td>20 Hz</td>
<td></td>
<td>850 mJ</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>
**CRIS: Laser lab**

**Wavelength meters**
WSU2: 2 MHz absolute accuracy
4 channel switchbox

WS6: absolute accuracy 600 MHz

Both recorded in the CRIS DAQ, CRISTAL*

**Frequency references**
HeNe (temperature stabilized)
DL PRO 780 → Toptica diode laser locked to a hyperfine transition in Rb

*Developed by R.P. de Groote
Poster 122
High resolution resonance ionization spectroscopy

RIS:
- Chopped cw light (25 mW) + 1064 nm
  - Reduce optical pumping
  - 20(1) MHz FWHM
- Delayed ionization
  - AC Stark effect

Efficiency $\sim 1:1000$
Isobaric/nonresonant background suppression $1:10^5$

<table>
<thead>
<tr>
<th>Contamination @ mass 202</th>
<th>$\sim 10^5$ ion/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{202}$Fr yields</td>
<td>$\sim 100$ ion/s</td>
</tr>
</tbody>
</table>
High resolution and highest efficiency – $^{29}\text{Cu}$

**High resolution and efficiency**

RIS:
- Injection-locked laser and THG (~ 1mW @ 1 kHz)
- 60 MHz FWHM
- Delayed ionization
- Autoionizing (AI) state

**Efficiency 1:100**

Background suppression 1:10$^7$
- Background of 1 count in every 400 s
- Background free spectra

<table>
<thead>
<tr>
<th>Contamination @ mass 78</th>
<th>$\sim 10^5$ ion/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{78}\text{Cu}$ yields</td>
<td>$\sim 20$ ion/s</td>
</tr>
</tbody>
</table>
RIS:
- Injection-locked laser and THG
  - 60 MHz FWHM (~0.5 mW @ 1kHz rate)
- Delayed ionization
- 1064 nm ionizing step

Efficiency 1:2000
Isobaric/nonresonant background suppression 1:10⁷
- 10⁻¹⁰ mbar in the interaction region
- High non-resonant background due to
  - non resonant 1064 step
  - collisional background

<table>
<thead>
<tr>
<th>Contamination @ mass 131</th>
<th>10⁷</th>
</tr>
</thead>
<tbody>
<tr>
<td>^{131}\text{In yields}</td>
<td>10³ ion/s</td>
</tr>
</tbody>
</table>
Lessons we learned:

Background suppression needs to be improved

- High power nonresonant ionization introduced background → Use AI when possible
- 1064 nm laser pulse fired before the RIS steps to clean the beam (30% times lower background in In)
- Field ionization of Rydberg atoms before the IR (3 times less background in In)
- Different mass regions have different contributions to background

- Cross section for collisional ionization?
- Laser ionization?
- Role of molecular beams?
High sensitivity $^{19}$K

RIS:
- Chopped cw light + Dye + 1064 nm
- Delayed ionization – efficiency loss

Efficiency 1:1500

Isobaric/nonresonant background suppression 1:10$^7$
- Rydberg atoms removed $\rightarrow$ 8 times lower background
- 1064 nm related background $\rightarrow$ 2 times lower background
- Still, high collisional background rate (stable Cr)
- Beta detection

<table>
<thead>
<tr>
<th>Contamination @ mass 52</th>
<th>~ 10$^7$ ion/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{52}$K yields</td>
<td>~300 ion/s</td>
</tr>
</tbody>
</table>

*Wasn’t the first time decay spectroscopy was used at CRIS (Phys. Rev. X 4, 011055 – Published 28 March 2014)
Precision and accuracy

- Delayed ionization efficiency loss
- Background
- Rydberg atoms removed
- Beta detection

**Figure:**

- Photodiode detection of FPI transmission peaks during each $^{47}\text{K}$ scan.
- Hyperfine structure of $^{47}\text{K}$

**Legend:**

- PD: Photodiode
- M: Mirror
- $\lambda/2$: Half-wave plate
- PBS: Polarising beam-splitter cube
- FL: Fiber launch
- Fiber
- Laser beam
- COSY: Saturation spectroscopy module

- a) FPI transmission peaks detected using photodiodes during each $^{47}\text{K}$ scan.
- b) Hyperfine structure of $^{47}\text{K}$
Precision and accuracy

- Precision of the wavelength measurement
  - \( \sigma = 0.77 \text{ MHz} \)
- Consistency of hyperfine parameters
  - In good agreement with literature

References:
- Kreim et al, PLB 731 97 (2014)
Precision and accuracy

- AC Stark shift
  - Asymmetric peaks
  - Higher efficiency
- Consistency of hyperfine parameters
- Centroid shifts
  - Different for different isotopes
  - Increase with laser power
Summary and Outlook

- **High resolution** and **high efficiency** achieved at CRIS → Weak transition \((A \sim 10^6 \text{ s})\) and delayed ionization
- **Background suppression** → ultra high vacuum \(10^{-10}\)
  - Ionization from Rydberg states after the CEC
  - 1064 nm for cleaning
  
  **Understanding source of background rates is the key to sensitive measurements**

- **Laser atom interaction** investigated (better understood) → delayed ionization solves the problem of line shape distortion
  - Frequency shifts have to be investigated in light systems

- **Precision less than 1 MHz**

- **Isobaric/nonresonant** background suppression still the bottleneck:
  - AI
  - Field ionization
  - Decay spectroscopy
  - Energy filter?
  - Electron ion coincidence?
Thank you for your attention!

The University of Manchester
Institut de Physique Nucléaire d'Orsay
CERN
Department of Physics, New York University
Institut für Physik, Johannes Gutenberg-Universität
Peking University
University of Jyvaskyla
KU Leuven, Instituut voor Kern- en Stralingsfysica

Our work was supported by ERC Consolidator Grant No.648381; GOA 15/010 from KU Leuven; the FWO Vlaanderen (Belgium) and the European Unions Seventh Framework Programme for Research and Technological Development under Grant Agreement 654002 (ENSAR2). We acknowledge the financial aid from the Ed Schneiderman Fund at New York University. B.K.S. acknowledges financial support from Chinese Academy Science through the PIFI fellowship under the project number 2017VMB0023 and partly by the TDP project of Physical Research Laboratory (PRL), Ahmedabad and the computations were carried out using the Vikram-100 HPC cluster of PRL. We would like to thank the ISOLDE technical group for their support and assistance, and the University of Jyvaskyla for the use of the injection-locked cavity.
Ra experiment 2016
- 25(2) MHz FWHM
- Delayed ionization
- RIS full of surprises – online developments
- Chopped and cw light both worked
- Importance of RIS developments

**Selected RIS:**

<table>
<thead>
<tr>
<th>No.</th>
<th>Scheme [nm]</th>
<th>PDL [cm$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>714+783+555</td>
<td>17971</td>
</tr>
<tr>
<td>2</td>
<td>714+783+555</td>
<td>17971</td>
</tr>
<tr>
<td>3</td>
<td>714+555+555</td>
<td>17994</td>
</tr>
<tr>
<td>4</td>
<td>714+783+555</td>
<td>18001</td>
</tr>
<tr>
<td>5</td>
<td>714+555+555</td>
<td>18001</td>
</tr>
</tbody>
</table>

IP: 42573.36(2) cm$^{-1}$
AI: 31993.40 cm$^{-1}$
Motivation: Need for new techniques

- High efficiency: in-source
- High resolution: collinear lasers
- High sensitivity

(far from a complete survey)
High resolution and high efficiency

- Chopped cw light for weak transitions
- Pulsed light for strong transitions

Weakness:
- Spectral range of cw light
  - Production of UV light
  - Photons density
Technique
Collinear Resonance Ionization Spectroscopy

As a function of the laser frequency we measure beta particles emitted by $^{52}$K and its daughters.

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}$</th>
<th>$Q_{\beta}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{52}$K</td>
<td>110 ms</td>
<td>17.130</td>
</tr>
<tr>
<td>$^{52}$Ca</td>
<td>4.6 s</td>
<td>6.1</td>
</tr>
<tr>
<td>$^{52}$Sc</td>
<td>200 ms</td>
<td>9</td>
</tr>
<tr>
<td>$^{52}$Ti</td>
<td>1.7 min</td>
<td>1.9</td>
</tr>
<tr>
<td>$^{52}$V</td>
<td>3.7 min</td>
<td>3.9</td>
</tr>
</tbody>
</table>