Purification techniques for low energy
Radioactive Ion Beams at SPIRAL2

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Pierre Chauveau
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Pauline Ascher
Enrique Minaya
and the PIPERADE team
Outlook

1- Purification techniques for low energy RIB’s @ GANIL/SPIRAL2
   a- Magnetic spectrometer
   b- Multi-reflections time-of-flight spectrometer (MR-TOF-MS)
   c- Penning trap

2- Performances and Status of development of such devices @ GANIL/SPIRAL2
   a- HRS@DESIR
   b- PILGRIM @ S3-LEB
   c- PIPERADE@DESIR

3- Comparative performances / Complementarities

HRS : High Resolution Spectrometer
PILGRIM : Piège à Ion Linéaire du Ganil pour la Résolution des Isobares et leur mesure de Masse
PIPERADE: Piège de Penning pour les ions Radioactifs à DESir
1- Purification techniques for low energy RIB’s

Introduction

- The production methods of radioactive beams are non selective
  → powerful selection methods are mandatory

- The important criteria are:
  - the selectivity: the capability to separate the ions of interest from contaminants
  - the efficiency: keep the maximum of the ions of interest
  - the rapidity: the time needed to separate the ions of interest from contaminants

- Main beam characteristics:
  all nuclei are extracted from the source
  - with the same charged state (usually 1+)
  - with the same low energy (few to 60 keV)
    → no "universal" Z selection (depends of the source, use of lasers...)
    → need for an isobaric selection through mass/velocity
  - with “poor” optic qualities (emittance of few 10’s of \( \pi \).mm.mrad)
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

Principle: Mass separation by a magnet

\[ B_\rho = \frac{M \cdot v}{Q} \]
\[ Q = 1^+ \]

Different Masses \( \rightarrow \) different deviations

With "standard" systems \( \rightarrow \) \( R = \frac{M}{\Delta M} \approx 400 \)

- able to separate isotopes/isotones
  OK if Z selection
- not able to separate isobares

\( ^{132}\text{Sn} \): mass = 131.9178157
\( ^{132}\text{Sb} \): mass = 131.9144669

\( R = 39392 \) \( \rightarrow \) gain of \( \approx 100 \) needed on \( R \)

how to obtain this factor? \( \rightarrow \) HRS
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

- \( D \) : dispersion of the system
- \( 2x_{00} \) : beam size
- \( M \) : magnification
1- Purification techniques for low energy RIB’s

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\[ D \propto \frac{\Delta B}{B} : \text{magnet homogeneity} \]
\( \rho_M \) : magnet curvature
\( \theta_M \) : magnet angle
\( A_M \) : "filled" area of the magnet
...

Stéphane Grévy
Spiral2 Week 2014 - October 7th
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

- \( 2x_{00} \): beam size
- \( M \): magnification
- \( D \): dispersion of the system

standard 0.005m (5mm)
standard \( M=1 \)
standard 2m (2cm/%)

\[ R = \frac{2}{0.005 \times 1} = 400 \]
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

- \( 2x_{00} \): beam size
- \( M \): magnification
- \( D \): dispersion of the system

\[ R = \frac{2}{0.005 \times 1} = 400 \]

HRS \( \cdot 2x_{00} \): 1mm

\[ R = \frac{2}{0.001 \times 1} = 2000 \]

→ need to cool the beam before the HRS: RFQ SHIRaC
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

2\(x_{00} \): beam size

M : magnification

D : dispersion of the system

\[ R = \frac{2}{0.005 \cdot 1} = 400 \]

HRS • 2\(x_{00} \): 1mm

• "used area" : *3 \(\rightarrow\) "dedicated" optics between SHIRaC and the first magnet

\[ R = \frac{2 \cdot 3}{0.001 \cdot 1} = 6000 \]
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

2\(x_{00}\) : beam size

M : magnification

D : dispersion of the system

\[ R = \frac{2}{0.005 \times 1} = 400 \]

HRS

• \(2x_{00}\) : 1mm
  • "used area" : *3
  • \(\rho\) : *1.7

\[ R = \frac{2 \times 3 \times 1.7}{0.001 \times 1} = 10200 \]
1- Purification techniques for low energy RIB’s

a- Magnetic spectrometer

\[ R = \frac{D}{2x_{00} \cdot M} \]

2\(x_{00}\) : beam size

M : magnification

D : dispersion of the system

\[ R = \frac{2}{0.005 \cdot 1} = 400 \]

HRS

- 2\(x_{00}\) : 1mm
- "used area" : *3
- \(\rho_M\) : *1.72
- \(\theta_M\) : *3

\[ R = \frac{2 \cdot 3 \cdot 1.7}{0.001 \cdot 1} = 31000 \]
1- Purification techniques for low energy RIB’s

b- MR-TOF-MS

Principle: Time-of-Flight separation in a linear trap

Nuclei extracted with the same energy $\rightarrow \Delta M \leftrightarrow \Delta v$

$^{132}\text{Sn} : \text{mass} = 131.9178157 \rightarrow v = 0.0209486 \text{cm/ns}$

$^{132}\text{Sb} : \text{mass} = 131.9144669 \rightarrow v = 0.0209488 \text{cm/ns}$

@ 5 keV

In 10 msec $\rightarrow$ - Flight pass: 2 km ! $\rightarrow$ multi reflections (~4000) in a trap

- $\Delta_L : 2 \text{ cm}$
- $\Delta_{TOF} : 100 \text{ ns}$

From RFQ cooler

• Injection
• Trapping
• ToF separation
• Ejection
1- Purification techniques for low energy RIB’s

**b- MR-TOF-MS**

- Energy spread → need "time focussing"

**Generalization**: Mirrors optimization to have a Flight time independant from:

- energy
- transverse position
- divergence

**Need**: Nuclei with higher energy to have longer revolution time
→ adjustment of the slope of the mirror voltage

$$E$$

$$E + \delta E$$

"optimized" resolution power
1- Purification techniques for low energy RIB’s

c- Penning trap

Principle: Mass separation in a trap

1) trapping in x, y and z

- use of a quadrupolar potential
- Laplace law: \( \Delta \phi = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} = 0 \)

→ cannot confine in all the directions with a single potential (escape axis)

\[ \phi(z, r) = \frac{U_{dc}}{2d^2} \left( z^2 - \frac{1}{2} r^2 \right) \]

\[ \frac{d^2 x}{dt^2} = \omega_c \frac{dy}{dt} + \frac{\omega_{0z}^2}{2} x \]
\[ \frac{d^2 y}{dt^2} = -\omega_c \frac{dx}{dt} + \frac{\omega_{0z}^2}{2} y \]

harmonic oscillation in z

\[ \omega_{0z} = \sqrt{\frac{2qU}{m r_0^2}} \]
1- Purification techniques for low energy RIB’s

2) purification

Mass selection by sideband buffer gas cooling:

- Dipolar excitation at the magnetron frequency: \[ \omega_- = \frac{\omega_c}{2} - \sqrt{\frac{\omega_c^2}{4} - \frac{\omega_z^2}{2}} \]
  - mass independant \( \rightarrow \) all ions to a higher radius

- Combining the effect of buffer gas and a quadrupolar excitation at \( (\omega_+ + \omega_z) \)
  - buffer gas: cyclotron motion is cooled, magnetron motion increases
  - quadrupolar excitation: coupling the two radial modes
    \( \rightarrow \) radii of both motions are cooled
    \( \rightarrow \) mass-selective centering
Outlook

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3- Comparative performances / Complementarities
2- Performances and Status of development of such devices @ GANIL/SPIRAL2
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a- SHIRaC+HRS@DESIR

- Goal: "on-line" isobar purification
- Intensity: up to 1μA
- Cooling time ~ msec
- Design resolution: $M/\Delta M = 31\,000$
  + Misalignments $\Rightarrow M/\Delta M > 20\,000$

<table>
<thead>
<tr>
<th></th>
<th>X shift (mm)</th>
<th>Y shift (mm)</th>
<th>X Tilt (mrad)</th>
<th>Y Tilt (mrad)</th>
<th>Θ (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QQ1</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±3.5</td>
<td>±3.5</td>
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<td>±0.35</td>
<td>±3.5</td>
<td>±3.5</td>
</tr>
<tr>
<td>D1</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.35</td>
<td>±3.5</td>
<td>±3.5</td>
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<tr>
<td>M</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±3.5</td>
<td>±3.5</td>
<td>±3.5</td>
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<tr>
<td>D2</td>
<td>±0.1</td>
<td>±0.1</td>
<td>±0.35</td>
<td>±3.5</td>
<td>±3.5</td>
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2 - Performances and Status of development of such devices @ GANIL/SPIRAL2

a - SHIRaC+HRS@DESIR

Shiracq RFQ

- New measurements for emittances and energy spread
  - Transmission: above 70%
  - Emittance: 2 π.mm.mrad @60 keV and up to 1 μA
  - Energy spread: around 1.5 eV for 1 μA
- Gas recycling tested. To be implemented
- Modifications of design to fulfil 'ALARA' environment to be done

HRS

- Global optical design published
- Performance of the HRS considering misalignment/positioning precision of different elements
  m/Δm = 20,000 for a 3π mm mrad 60keV beam and energy spread ~1 eV.
- Mechanical design and integration ready
- Dipoles delivered @ GANIL (july2014)
- Magnetic field mapping scheduled for 2015
- Manufacturing of other elements by CENBG
- Setup completed @ CENBG end of 2015
- Tests @ CENBG up to 2018
2- Performances and Status of development of such devices @ GANIL/SPIRAL2

b- PILGRIM @ S3-LEB

- goal: isobar purification + mass measurement
- intensity: $10^3$ ions/pulse
- cycle time: 10 msec
- Design resolution: $M/\Delta M = 10^5$ and $\sigma M/M \approx 5.10^{-7}$

Simulations on SIMION:
- Potentials
- Geometry

<table>
<thead>
<tr>
<th>Geometry</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
<td>B.Kansal</td>
<td>2226.5</td>
</tr>
<tr>
<td>P.Chauveau</td>
<td>29048.0</td>
</tr>
<tr>
<td></td>
<td>42181.4</td>
</tr>
</tbody>
</table>

$R > 3.10^5$ have been obtained in simulation for realistic beams (B.Kansal)
b- PILGRIM @ S3-LEB

Planning

PILGRIM:

- 10/2015: end of mechanical design
- 10->12/2015: production/purchase of mechanical parts
- 01->06/2016: assembly of PILGRIM
- 09->12/2016: tests at LIRAT?
c- PIPERADE@DESIR

- goal: isobaric purification + accumulation for precision measurements
- intensity: up to $10^6$ ions/pulse
- cycle time: 100-300 msec
- Design resolution: $M/\Delta M > 10^5$

Increasing the number of ions makes the re-centering inefficient

Additional potential created by the cloud itself
→ f-shifts, peak broadening, screening effects

Alternative techniques...
- simulations @ CSNSM and MPIK
- experimental tests @ MPIK
- Performances and Status of development of such devices @ GANIL/SPIRAL2

**c- PIPERADE@DESIR**

- **Febiad Ion source:**
  - renovation completed (SPIRAL2 compatible)
  - emittance characterized

- **General Purpose Ion Buncher:**
  - mechanics and electronics completed
  - ready to be tested

- **Penning Trap**
  - simulations underway
  - mechanical design ready
  - construction beginning of 2015
  - magnet ordered (delivery expected 10/15)
  - tests@CENBG in 2016
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### 3- Comparative performances / Complementarities

- HRS and MR-TOF-MS/Penning Trap have different philosophy
- MR-TOF-MS and Penning Trap are complementary

<table>
<thead>
<tr>
<th></th>
<th>HRS</th>
<th>MR-TOF-MS PILGRIM</th>
<th>Penning Trap PIPERADE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Goals</strong></td>
<td>Isobaric purification</td>
<td>Isobaric purification Mass measurement</td>
<td>Isobaric/Isomeric purification and accumulation</td>
</tr>
<tr>
<td><strong>Intensity</strong></td>
<td>$10^{13}$ pps</td>
<td>$10^3$ ions/pulse - 100Hz</td>
<td>$10^5$ ions/pulse - 5/10Hz</td>
</tr>
<tr>
<td><strong>Timing</strong></td>
<td>N/A</td>
<td>10 msec</td>
<td>100-200 msec</td>
</tr>
<tr>
<td><strong>Resolution M/ΔM</strong></td>
<td>$&gt;20000$</td>
<td>$10^5$</td>
<td>$&gt;10^5$</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>100%</td>
<td>$&gt;50$%</td>
<td>$&gt;50$%</td>
</tr>
<tr>
<td><strong>Possible developments</strong></td>
<td>N/A</td>
<td>identification device (&quot;tagging&quot;)</td>
<td>In trap decay spectroscopy ...</td>
</tr>
</tbody>
</table>

Rq1 : HRS would be able to make a "pre"-purification before PIPERADE
Rq2 : a MR-TOF-MS device could be installed in the DESIR hall in the future