The adventures of radioactive ions
between production and measurement

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Contents

• Orientation: what’s all this about?

• Production of exotic nuclei

• Selection: overview
  building blocks
  examples

• Manipulation: overview
  building blocks
  examples

• Summary
An on-line experiment

after production target measurement requires products of interest selection & manipulation

products of interest ●
other products ● ● ●
primary beam ● ● ● ● ● ●

selection & manipulation

selection

manipulation
Special needs for radioactive ions

selection and manipulation techniques need to be

• fast (short half-life)
  down to µs
  ᐅ “on-line”

• efficient (small cross section)
  aim for 100 %
### Producing exotic nuclei

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Product Energy</th>
<th>Product Multiplicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fragmentation</td>
<td>few MeV/u</td>
<td>up to 1000</td>
</tr>
<tr>
<td>Spallation</td>
<td>few MeV/u</td>
<td>up to 1000</td>
</tr>
<tr>
<td>Fission</td>
<td>~1 MeV/u</td>
<td>few 100</td>
</tr>
<tr>
<td>Fusion-Evaporation</td>
<td>( E_R = \frac{m_p}{m_p + m_t} E_P )</td>
<td>few (≤ 20)</td>
</tr>
</tbody>
</table>
Selection techniques: 2 types

- Separation
  - separator
  - measurement

- Identification
  - or ?
  - correlation
  - measurement
## Selection: building blocks

<table>
<thead>
<tr>
<th>Separation</th>
<th>High Energy Beam</th>
<th>Thermal Energy Cloud</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>magnetic dipole</td>
<td>ionization</td>
</tr>
<tr>
<td></td>
<td>electric dipole</td>
<td>ion trap</td>
</tr>
<tr>
<td></td>
<td>velocity filter</td>
<td></td>
</tr>
<tr>
<td></td>
<td>energy degrader</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Identification</th>
<th>Time-of-flight (TOF)</th>
<th>Total Energy</th>
<th>Energy Loss ($\Delta E$)</th>
<th>Magnetic Rigidity</th>
<th>Stopping Range</th>
<th>Radioactive Decay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**In-flight**

**Stop & go (ISOL)**
Separation at high energy

magnetic dipole

\[
\vec{F} = q \vec{v} \times \vec{B}
\]

\[
B \rho = \frac{m v}{q} \left[ \text{T} \cdot \text{m} \right]
\]
magnetic rigidity

electric dipole

\[
\vec{F} = q \vec{E}
\]

\[
E \rho = \frac{m v^2}{q} \left[ \frac{\text{J}}{\text{C}} \right]
\]
dispersion

electric rigidity
Separation at high energy

velocity filter
Wien filter, E-cross-B filter

charged particles with velocity \( v = \frac{E}{B} \) are not deflected
Energy degrader

A, Z, ν

\[ S \equiv -\frac{dE}{dx} \propto \frac{Z^2}{v^2} \propto \frac{A Z^2}{E} \]

→ straggling (spread) in energy and angle
Momentum-loss achromatic fragment separator

element: FRS @ GSI

A/Z separation

momentum loss separation

target

$q = Ze$

~constant $v$

energy degrader

non-Liouvillean optics

\[
\begin{align*}
(B\rho)_1 & \propto \frac{Z + N}{Z} \\
v_2^2 & = v_1^2 - d \frac{Z^2}{Z + N} \\
v_2 & = v_1 \frac{(B\rho)_2}{(B\rho)_1}
\end{align*}
\]

\[Z = a \cdot N \]

\[Z = b - N \]
Identification at high energy

measured quantities

time-of-flight (TOF) \[ T = \frac{L}{v} \]

total energy \[ E = \frac{1}{2} m v^2 = \frac{1}{2} K A v^2 \]
magnetic rigidity \[ B \rho = \frac{m v}{q} = K \frac{A v}{q} \]

energy loss \[ \Delta E \propto \frac{A Z^2}{E} \]

relationships

\[ A = \frac{2}{K} \frac{E T^2}{L^2} \]

\[ \frac{q^2}{A} = 2 K \frac{E}{(B \rho)^2} \]

\[ \frac{A}{q} = \frac{1}{K} \frac{B \rho T}{L} \]

\[ q = 2 \frac{E T}{L B \rho} \]

A and q are discrete!
Example: LISE 3 at GANIL
Example: LISE 3 at GANIL

- Target
- 1\textsuperscript{st} dispersive plane
- 1\textsuperscript{st} focal point
- 2\textsuperscript{nd} dispersive plane
- 2\textsuperscript{nd} focal point
- Wien filter
- Final focal point
- Si detector telescope
- Beam pulse (cyclotron RF)
- Position sensitive PPAC
- TOF
- $\Delta E, E, t$
Identification plot: discovery of \(^{48}\text{Ni}\)


\[115 \text{ pnA} \ 74.5 \text{ A MeV} \ ^{58}\text{Ni}^{26+} + 230 \text{ mg/cm}^2 \ ^{\text{natNi}}\]

one \(^{48}\text{Ni}\) observed for every \(10^{17}\) primary beam particles!

transmission efficiency: 10 \% $\rightarrow$ cross section = \(5 \times 10^{-14} \text{ b}\)
Separation at thermal energy: target-ion source systems

the ISOL method
Isotope Separator On-Line

Separation at thermal energy:
target-ion source systems

target-ion “sourcery”

target-ion source systems can have:

• chemical selectivity
  based on e.g. melting point, diffusion constant, ionization energy, oxidation state in compounds

• isotopic/isomeric selectivity
  laser ionization
Laser ionization

technically not feasible

1 step

2(3)-step resonant

resonant step gives selectivity
- chemical (=Z)
- isotopic (=Z, ≠A)
- isomeric (=Z, =A, ≠E*)

autoionising state

Rydberg state
Selectivity in laser ionization

\[
\begin{array}{cccc}
\text{E}^* \quad (\text{keV}) & T_{1/2} \quad (\text{s}) & \pi & \\
107^{m}\text{Ag} & 93 & 44 & 7/2^+ \\
107^{g}\text{Ag} & 0 & \text{stable} & 1/2^- \\
\end{array}
\]

ISOLDE-CERN
**Manipulation of radioactive ions**

<table>
<thead>
<tr>
<th>Manipulation of ion group properties</th>
<th>Manipulation of ion properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam, cloud</td>
<td>charge state ionization</td>
</tr>
<tr>
<td>energy</td>
<td>energy degrading</td>
</tr>
<tr>
<td>stopping, trapping acceleration</td>
<td>ionic/atomic state</td>
</tr>
<tr>
<td>energy spread cooling, trapping</td>
<td>spin direction alignment</td>
</tr>
<tr>
<td>emittance cooling</td>
<td>polarization</td>
</tr>
<tr>
<td>size cooling, trapping</td>
<td></td>
</tr>
<tr>
<td>time structure pulsing bunching</td>
<td></td>
</tr>
</tbody>
</table>

“ion beam cooler”  
(gas-filled RF quadrupole)

“charge breeder”  
(ECRIS & EBIS)
Ion beam cooler: principle

- reducing beam size, emittance, energy spread
- storing
- bunching

**the output does not depend on the input!**

**principle**

- reducing energy spread:
  - thermalization in (helium) gas
- confinement by electric fields
  - RF multipole
  - end electrodes
Ion beam cooler: RF confinement

Mathieu parameter

\[ q = \frac{4 Q V_{RF}}{m r_0^2 \Omega_{RF}^2} \]

Ion motion is stable when \( 0 < q < 0.91 \)
Ion beam cooler: axial field

Axial field due to segmentation of quadrupole rods
- speeds up transmission
- allows storing and bunching

Jyväskylä ion beam cooler

- [Graph showing counts over time with and without axial field]
  - Red line: Without axial field
  - Black line: With axial field
  - Separator beam on
  - Separator beam off
Ion beam cooler: storing and bunching

potential along z-axis

- separator beam on: $t = 0 - 1000 \, \mu s$
- cooler end plate voltage down $t = 3300-4000 \, \mu s$

$+2 \, V \quad +1 \, V \quad +0.5 \, V$

$+70 \, V \text{ (collect)}$
$0 \, V \text{ (release)}$

DC level (V)

-1V

$Z$

[Graph showing ion beam cooler with potential along the z-axis and a timeline of events.]
The Jyväskylä IGISOL facility

Specific features

- fast (sub ms)
- chemically non-selective → access to all elements including refractory metals

maximum yield ↑↓
high energy spread ↓
on-line cooler-buncher
Charge state breeding: basics

What?
from singly charged to multiply charged ions

"1+ → n+"

Why?
post-acceleration

In principle
electron impact stepwise ionization

requirements
1) high enough electron energy
2) suitable combination of:
   • ionization time (→ confinement)
   • high electron density
   • good vacuum

In practice
ECRIS
electron cyclotron resonance ion source

EBIS
electron beam ion source

E = qV
(cyclotron: $E = K \frac{q^2}{A}$)
Charge state breeding: ECRIS vs. EBIS

**ECRIS**
*Electron Cyclotron Resonance Ion Source*

- Confinement: magnetic bottle / e⁻-ion plasma
  - minimum-B field
  - axial: solenoid, radial: multipole

- Electron energy: microwaves

**EBIS**
*Electron Beam Ion Source*

- Confinement: electrostatic / ions
  - axial: potentials on drift tubes
  - radial: electron beam space charge

- Electron energy: electron gun

![Diagram of ECRIS and EBIS](image-url)
REX-ISOLDE

- Production
- Cooling bunching
- Charge breeding
- Selection
- Acceleration
- Measurement

- Target - ion source
- Proton beam (1 GeV)
- Analysing magnet
- q/A
- 60 keV
- EBIS
- TRAP
- n^+
- m/q = 4-5
- RFQ
- IH
- 7-Gap Resonators
- 0.8-2.2 MeV/u
many “building blocks” are available

studying exotic nuclei requires a clever combination of several building blocks

has to be fast and efficient!