Overview of
the RI Beam Facility (RIBF)

Daisuke Suzuki
Riken Nishina Center
daisuke.suzuki@ribf.riken.jp
+81-(0)48-467-4958
Laboratory on Earth

Modified from GenshikakuKenkyu Vol.56 Suppl.3
Recipe of RI beams: Four questions

- How to produce?
- How to accelerate?
- How to separate?
- How to identify?
Basic elements of ion-beam facility

Ion source

Acceleration

Transport

Ion source

Cathode

Cs+ focus

Ionizer

Extractor

Oven

http://www.pelletron.com/

Riken Ring Cyclotron

Layout of RARF (RIKEN Accelerator Research Facility)
ISOL (Isotope Separation On Line)

- Uranium fission ($e^-, n$)
- Spallation ($p \sim 1$ GeV)
- Light beam and heavy thick target
In-flight method

- Projectile fragmentation reaction
- Uranium fission
- Heavy beam and light thin target (Be, C)
RIBF (Radioactive Isotope Beam Factory)

- 3 injectors + 4 cyclotrons
- A variety of primary beam up to U
- Energy up to 345 MeV/nucleon

Primary target for RI beam production
World-leading producer of RI beam

As of June 2016

- RI beam Produced (416) for 125 Experiments
- Production Yield Measured (1481)
- New isotope 2011
- New isotope 2012
- New isotope 2013
- New isotope 2014
- New isotope 2015

238U In-flight fission

Courtesy Y. Shimizu
How to accelerate?

SRC (Superconducting Ring Cyclotron)

- K2500MeV
  - 345 MeV/nucleon for U beam
  - 400 MeV/nucleon for Light-ion beam
- Self magnetic shield
  - Up to 8 Tm

Diameter : 18.4m
Weight : 8,300 tons
Production of exotic nuclei at relativistic energies

Projectile Fragmentation

Nucleon-nucleon collisions, abrasion, ablation

\[ \vec{V}_f \approx \vec{V}_p \]

Projectile Fission

Electromagnetic excitation, fission in flight

\[ \vec{V}_f \approx \vec{V}_p + \vec{V}_\text{fission} \]

Sn isotope production

K. Sümmerer

EUROSCHOOL lectures 2011-08-24-25
BigRIPS: How to separate and identify?

Primary target for RI beam production

RIPS: precursor of BigRIPS

RIPS: T. Kubo et al., Nucl. Instr. Meth. B 70, 309 ('92)
1\textsuperscript{st} stage selection

Momentum-dispersive focal plane

1\textsuperscript{st} selection

\begin{align*}
qvB &= m \frac{v^2}{\rho} \\
\nu &= \nu_{\text{beam}} \text{ for all fragments} \\
ZevB &= Am_{\text{nucl}} \frac{v^2}{\rho} \\
B\rho &= \frac{A}{Z} \frac{p_{\text{nucl}}}{e}
\end{align*}
Isotope separation (stage1)
Between 1\textsuperscript{st} and 2\textsuperscript{nd} selections

Momentum-dispersive focal plane

Stopping range

\[ R \approx k \frac{A}{Z^2} \left( \frac{E}{A} \right)^\gamma \]

\[ \gamma = 1.75 \] (at intermediate beam energies)

\[ = k' \frac{Z^{2\gamma-1}}{A^{2\gamma-2}} (B\rho)^{2\gamma} \]

Material

Degradation range

Primary beam from RRC

Secondary beams

Production target
Double-achromatic focal plane

\[ B \rho_2 = B \rho_1 \left( 1 - \frac{d}{R} \right)^{\frac{1}{2\gamma}} \]

\[ = B \rho_1 \left( 1 - \frac{d}{k'} \frac{A^{2\gamma-1}}{Z^{2\gamma-2}} (B \rho_1)^{2\gamma} \right)^{\frac{1}{2\gamma}} \]

\[ \Rightarrow B \rho_2 \propto \frac{A^{2\gamma-1}}{Z^{2\gamma-2}} = \frac{A^{2.5}}{Z^{1.5}} \]
Isotope separation (stage 2)
BigRIPS configuration

Momentum-dispersive focal planes

Double-achromatic focal planes
Isotope separation

BigRIPS 1st stage
Particle identification

BigRIPS 2nd stage

TOF (time of flight): $\beta$

$B \rho$ with track reconstruction

$B \rho_{35}$

$B \rho_{57}$

TOF-B$\rho$-$\Delta$E method

$$\frac{A}{Q} = \frac{B \rho}{\gamma \beta m_{\text{nucl}}} \frac{c}{\gamma \beta m_{\text{nucl}}}$$

$Z \leftarrow \Delta E = f(Z, \beta)$

Bethe-Bloch formula
Example of PID plot

$^{238}\text{U} + \text{Be} (5\text{mm})$ at 345 MeV/nucl, F1-slit: $\pm 2\text{mm}$, Brho: $^{76}\text{Ni}$

Time of Flight (F3-F7) [ns] vs. $\Delta E$ at F7 [MeV]
Different physics require ...

- Shape coexistence
- Configuration Mixing
- Exotic decay mode (e.g. 2-p decay)
- p-n pairing
- Proton drip line
- Neutron drip line
- New magic number
- Island of inversion
- Nuclear force
- Fission Cluster decay
- Explosive nucleosynthesis
- 2-n correlation BEC BCS
- Multi-neutron halo
Different observables

- Mass
- Excitation energy
- Half-life
- Decay scheme
- Transition strength
- Charge distribution
- Cross sections
- Matter distribution
- Nuclear moment
- Charge radius
- Nuclear EOS
- Matter distribution
And different devices
ZDS (Zero-Degree Spectrometer)
ZDS (Zero-Degree Spectrometer)

Spectrometer for in-beam gamma-ray measurement

\[ ^{132}\text{Sn} \]

From BigRIPS

**Grape (Ge detectors):** S. Shimoura, Nucl. Instr. Meth. B 525, 188 (’04)

**DALI2 (NaI scintillators):** S. Takeuchi et al., Nucl. Instr. Meth. B 763, 596 (’14)
Evidence for a new nuclear ‘magic number’ from the level structure of $^{54}$Ca

D. Steppenbeck$^1$, S. Takeuchi$^2$, N. Aoi$^3$, P. Doornenbal$^2$, M. Matsushita$^1$, H. Wang$^2$, H. Baba$^2$, N. Fukuda$^2$, S. Go$^1$, M. Honma$^4$, J. Lee$^2$, K. Matsui$^5$, S. Michimasu$^1$, T. Motobayashi$^2$, D. Nishimura$^6$, T. Otsuka$^{1,5}$, H. Sakurai$^{2,5}$, Y. Shiga$^7$, P.-A. Söderström$^3$, T. Sumikama$^8$, H. Suzuki$^2$, R. Taniuchi$^5$, Y. Utsuno$^9$, J. J. Valiente-Dobón$^{10}$ & K. Yoneda$^2$

$^{55}$Sc/$^{56}$Ti on a 1.85 g/cm$^2$ Be target

40 hours of data taking

\[ E_x \text{ [MeV]} \]

ISOLDE ('85)
Minos (Maglc Numbers Off Stability)

Thick hydrogen target for in-beam γ-ray spectroscopy

- 1 g/cm² liquid hydrogen target
- Dopper-shift correction by locating vertex using a TPC (Time Projection Chamber)

A. Obertelli et al., Eur. Phys. J. A 50, 8 ('14)
“Island of Inversion” at $N = 40$

Eurica (EUroball RIken Cluster Array)

β-delayed γ-ray spectroscopy station at the end of ZDS

- 84 high-purity Ge crystals in 12 clusters
  - Resolution: 2.5 keV @1.3MeV
  - Efficiency: 13% @1MeV

- 8 double-sided strip silicon detector (DSSD)
  - 60 × 40 pixels
  - Detect β-ray from implanted radioactive nuclei
40 new half-lives!

Better understanding of r-process abundance

SAMURAI (Superconducting Analyzer for MUlti-particle from RAdioIsotope beams)
SAMURAI (Superconducting Analyzer for Multi-particle from RadioIsotope beams)

$^{27}\text{F} + \text{C} \rightarrow ^{26}\text{O} \rightarrow ^{24}\text{O} + 2n$

$^{27}\text{F} \sim 210\text{MeV/u (from BigRIPS)}$

First $2^+$ state of unbound $^{26}\text{O}$

- USDB cannot reproduce the $2^+$ energy of $^{26}\text{O}$
- Effect of $pf$ shell? and/or continuum? Or other effects (such as 3N forces, 2n correlation)

SPiRIT

SAMURAI Pion Reconstruction and Ion Tracker

Nuclear equation of state via $\pi^+/\pi^-$ production ratio in heavy RI collision

R. Shane et al., Nucl. Instr. Meth. A 784, 513 (’15)
$^{132}\text{Sn} @ 300 \text{ MeV/u} + ^{\text{nat.}}\text{Sn} (\text{May '05})$

$\pi^- \quad \pi^+ \quad p \quad d \quad t$

$dE/dX (\text{A.U.}) \quad p/Q (\text{MeV/c})$

Track reconstruction
Spectroscopy with High-resolution Analyzer of RadioActive Quantum beams
SHARAQ

Spectroscopy using RI beam as a reaction probe

T. Uesaka et al., Nucl. Instr. Meth. B 266, 4218 ('08)
T. Uesaka, S. Shimoura, and H. Sakai, Prog. Theor. Exp. Phys. 03C007 ('12)
Neutral nucleus ‘tetra-neutron’ candidate


R3 (Rare RI Ring)
R3 (Rare RI Ring)

Mass measurement in an ‘isochronous’ storage ring

\[ f_c = \frac{1}{2\pi} \frac{qB}{m} \]
SLOWRI

Slow (1 to 50 keV) and low emittance (∼πmm·rad) beam for trapping and laser spectroscopy

M. Wada et al.
MRTOF @ GARIS-II for SHE-Mass project

FIG. 3: Time-of-flight spectrum observed using $^{165}$Ho target. Ions made n=148 laps in the MRTOF-MS. See text for details

<table>
<thead>
<tr>
<th>Species</th>
<th>$\rho'$</th>
<th>Mass Excess [keV]</th>
<th>$\Delta m$ [keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{201}$Bi</td>
<td>0.9803821(20)</td>
<td>-21450(385)(3)</td>
<td>-35(385)(3)</td>
</tr>
<tr>
<td>$^{203}$Po</td>
<td>0.98040785(39)</td>
<td>-16541(74)(3)</td>
<td>-16(74)(3)</td>
</tr>
<tr>
<td>$^{201}$At</td>
<td>0.98043619(23)</td>
<td>-11131(44)(3)</td>
<td>-342(45)(3)</td>
</tr>
<tr>
<td>$^{205}$Po</td>
<td>0.99990(10)</td>
<td>-18567(2050)</td>
<td>-1059(2050)</td>
</tr>
<tr>
<td>$^{205}$At</td>
<td>0.999939(22)</td>
<td>-12898(420)</td>
<td>73(420)</td>
</tr>
<tr>
<td>$^{205}$Rn</td>
<td>0.999967(16)</td>
<td>-7502(320)</td>
<td>212(320)</td>
</tr>
<tr>
<td>$^{206}$At</td>
<td>1.004819(11)</td>
<td>-12497(2150)(1)</td>
<td>-9(2150)(1)</td>
</tr>
<tr>
<td>$^{206}$Rn</td>
<td>1.0048400(30)</td>
<td>-8565(600)(1)</td>
<td>551(600)(1)</td>
</tr>
<tr>
<td>$^{206m}$Fr</td>
<td>1.00487892(55)</td>
<td>-1150(107)(1)</td>
<td>-98(118)(1)</td>
</tr>
</tbody>
</table>

May be $^{206m}$Fr, with deviation from literature of $\Delta m=-92(111)(1)$ keV

P. Schury et al., submitted
Construction will be completed in March 2017
From BigRIPS

$^{132}\text{Sn} \times 2.5 \times 10^6$ pps

RF cavity for smaller beam spot

200-250 MeV/u

Beam spot 20~30 mm FWHM

$5 \pm 1$ MeV/u

$1.7 \times 10^5$ pps

5 to 50 MeV/u RI beam for direct reactions

To SHARAQ

50 MeV/u

<20 MeV/u
SCRIT (Self Confining RI Ion Target)
SCoRT (Self Confining RI Ion Target)

Electron scattering off RI beam

M. Wakasugi et al., Nucl. Inst. Meth. A 532, 216 ('04)
M. Wakasugi et al., Phys. Rev. Lett. 100, 164801 ('08)
T. Ohnishi et al., Phys. Scr. T166, 014071 ('15)
CRIB (CNS Radio-Isotope Beam separator)
CRIB (CNS Radio-Isotope Beam separator)

Low-energy RI beams (<10MeV/u) for astrophysical reactions
Direct measurement of $^{11}$C($\alpha$,p) reaction

A reaction that bypasses the 3\(\alpha\) process in explosive hydrogen-burning

KISS (KEK ISotope Separator)
KISS (KEK ISotope Separator) RI beam with $N = 126$ for unexplored r-process path

H. Grawe et al., Rept. Prog. Phys. 70, 1525 (’07)

Y. Hirayama et al., Nucl. Instr. Meth. B 353, 4 (’15)

Multiple nucleons transfer reaction

Laser
Resonance ionization (Element selection)

$^{136}$Xe beam
$^{198}$Pt target
Ar gas
Measurement of $^{199}$Pt


Hyper-fine structure of $^{199}$Pt

$\mu = +0.63(13) \mu_N$

$F_{gs} = 9/2$

$F_{gs} = 11/2$

$F_{gs} = 7/2$

$F_{gs} = 5/2$

$F_{gs} = 3/2$

$F_{gs} = 1/2$
GARIS (GAs-filled Recoil Ion Separator)
GARIS (GAs-filled Recoil Ion Separator)

Search for super heavy elements
Nihonium (Nh) currently under public review

For Release 8 June 2016

**IUPAC is naming the four new elements nihonium, moscovium, tennessine, and oganesson**

Following earlier reports that the claims for discovery of these elements have been fulfilled [1, 2], the discoverers have been invited to propose names and the following are now disclosed for public review:

* Nihonium and symbol Nh, for the element 113,
* Moscovium and symbol Mc, for the element 115,
* Tennessine and symbol Ts, for the element 117, and
* Oganesson and symbol Og, for the element 118.

The IUPAC Inorganic Chemistry Division has reviewed and considered these proposals and recommends these for acceptance. A five-month public review is now set, expiring 8 November 2016, prior to the formal approval by the IUPAC Council.