Radiation Evaluation in RIBF

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Outline

Introduction: RIBF accelerator facility
   Radioactive Isotope beam production
   Measurement and PHITS calc.

Radiation evaluation and comparison with PHITS calc.:
   A, Neutron dose
   B, Heat load
   C, Residual radioactivity
   D, Radioactivity at low energy beam

Future plan
Radioactive Isotope Beam Factory (RIBF)

- Operation of RIBF started in 2007.
- Maximum energy is ~350MeV/n for heavy ions up to $^{238}$U.
- Goal intensity is 1 μA (82kW at $^{238}$U) for all ions.
- Beam intensities increase year by year.
- 1/6 of Goal beam power is achieved.

→ generate variety of radioactive isotopes (RIs) to study nuclear, nuclear astrophysics and etc.
RI beam production

Proton or neutron-rich isotope beams, as $^{48}$Ca, $^{124}$Xe and $^{238}$U are useful to make intense RI beam!
Radiation Evaluation at RIBF over the past decade

**Beam intensity**
- 18GHz SC-ECRIS
- RILAC

**Neutron flux/dose**
- \(^{238}\text{U} + \text{He gas stripper}\)
  - Neutron flux (Bi sample): \(~1\)
  - Activation: \(0.5\sim2\)
- \(^{238}\text{U} + \text{Be, C}\)
  - Neutron flux (Bi sample): \(~2\sim3\) (H.Lee et al.)
  - Activation: \(~2\sim3\)

**Heat Load**
- \(^{238}\text{U} + \text{Be}\)
  - Heat load (Superconducting magnet): \(1\sim1.5\)
  - Activation: \(1\sim1.5\)
- \(^{238}\text{U} + \text{He, Cu dump}\)
  - Neutron dose (survey meter): \(2.1\)
  - Neutron flux (Bi sample 60,90 degree): \(~1\)

**Activation/residual dose**
- \(^{48}\text{Ca} + \text{Be, Cu dump}\)
- \(^{124}\text{Xe} + \text{Be, Cu dump}\)
- \(^{238}\text{U} + \text{Be}\)
- \(^{238}\text{U} + \text{He, gas stripper}\)
- \(^{238}\text{U} + \text{He, gas stripper}\)

**Beam, target**
- \(^{238}\text{U} + \text{He, gas stripper}\)
- \(^{124}\text{Xe} + \text{Be, Cu dump}\)
- \(^{238}\text{U} + \text{Be}\)
- \(^{238}\text{U} + \text{He, gas stripper}\)
- \(^{238}\text{U} + \text{Be}\)

**Evaluation**
- Neutron dose (survey meter)
- Neutron flux (Bi sample 60,90 degree)
- Heat load (Superconducting magnet)
- Activation
Radiation measurement: High energy 350MeV/u

Radiation measurement:
A, Neutron dose outside of shield
B, Heat load on STQ1
C, Radioactivity using samples near beam dump

Results are compared with PHITS calculation!
Calculation (PHITS ver 2.30-2.86)
Event: 1-10M ions irradiate target, 100~500 core, HOKUSAI GreatWave, 34560 core 1.0PFLOPS
Time: 0.5~1 day

Condition
Collision:
Heavy ion
JQMD1 + GEM (General Evaporation Model)
INCL+GEM for $^{238}$U + He

Neutron
$E > 20$MeV, JAM or INCL+GEM
$E \leq 20$MeV, nuclear data
ENDF/B-VII
A, Neutron dose

Measurement
ALOKA, TPS-451C (Polyethylene moderated $^3$He neutron detector, E=0.025eV-15MeV)

<table>
<thead>
<tr>
<th>Beam, target, B$_\rho$ 1</th>
<th>Spot</th>
<th>Dose rate (mSv/h) PHITS/exp.</th>
<th>Ratio PHITS/exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca 100pnA + Be 15 mm,</td>
<td>A</td>
<td>4 / 1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>$^{124}$Xe, 10pnA + Be 4 mm, 7.645Tm</td>
<td>A</td>
<td>0.5 / 0.36</td>
<td>1.4</td>
</tr>
<tr>
<td>$^{238}$U, 1pnA + Be 5 mm, 6.950Tm</td>
<td>A</td>
<td>0.15 / 0.13</td>
<td>1.2</td>
</tr>
</tbody>
</table>
B, Heat load


- Liq. He level is kept constant by varying the heater power with fixed supply and return valves
- Radiation heat load fluctuation is compensated by the heater power.
- Thus, the radiation heat load can be deduced by comparison of heater power for beam on / off
B, Heat load

<table>
<thead>
<tr>
<th>Beam, target</th>
<th>Heat on Superconducting magnet (W) PHITS/exp.</th>
<th>Ratio PHITS/exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{18}\text{O}$ 190pnA + Be 60 mm</td>
<td>54 / 39</td>
<td>1.3</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$ 175pnA + Be 15 mm*</td>
<td>43 / 33</td>
<td>1.3</td>
</tr>
<tr>
<td>$^{70}\text{Zn}$ 70pnA + Be 10 mm</td>
<td>17 / 25</td>
<td>0.7</td>
</tr>
<tr>
<td>$^{124}\text{Xe}$ 10pnA + Be 4 mm</td>
<td>6.4 / 6</td>
<td>1.1</td>
</tr>
<tr>
<td>$^{238}\text{U}$ 10pnA + Be 3 mm</td>
<td>4.2 / 3</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Error: 20% mainly from beam current uncertainty

*T. Ohnish et al., Prog. Nucl. Sci. Tech. 2(2011) 416
C, Activation of sample materials

Radiation samples were set downward of the Cu beam dump, in the forward direction of the beam. Neutrons come from the beam dump, and samples were irradiated. Generated radioactive nuclide in samples were identified using a Ge detector and compared with PHITS calculation.

Radiation sample
(Fe, Cu, Al, Ni, Cr (stainless steel ~Fe+Cr+Ni))

![Diagram showing the setup of the experiment with beam dump, sample, and radiation shield]
Produced long lived nuclides

To eliminate background of short life RI, Radioactivities were measured after 90~140 days cooling

- $^{54}$Mn $T_{1/2} = 312$ d
- $^{46}$Sc $T_{1/2} = 84$ d
- $^{57}$Co $T_{1/2} = 272$ d
- $^{60}$Co $T_{1/2} = 5.3$ y
- $^{51}$Cr $T_{1/2} = 28$ d
- $^{56}$Co $T_{1/2} = 77$ d
- $^{58}$Co $T_{1/2} = 71$ d
- $^{22}$Na $T_{1/2} = 2.6$ y
- $^{57}$Co $T_{1/2} = 272$ d

Production ratio

- PHITS/exp.

Ratio for $^{48}$Ca ~ 2-3
- $^{124}$Xe, $^{238}$U ~ 1
D. Residual radioactivity at low energy to plan maintenance

11 MeV/u $^{238}$U beam + He gas

Al sample (chamber material) activation
First layer: fission product catcher
Second layer: Al activation by neutron from U beam
Third layer: Radioactive Bi isotopes corresponds to energy dependence of neutron flux
By PHITS calculation, both long and short lived nuclides were generated. But only long lived nuclides were observed by measurement. To compare the PHITS calc. result to exp. result, short lived were summed to long lived in calculation. 

$^{134}\text{Cs}$ and $^{124}\text{Sb}$ could be compared without other nuclides, respectively, because they don’t have parent nuclides.
Ratio of the produced nuclides to PHITS/exp.

Neutron threshold for $^{207}\text{Bi}$

Main error are 20% of beam current.

Neutron energy [MeV] by PHITS calculation

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<tr>
<th>Nuclide</th>
<th>Threshold (MeV)</th>
<th>Reaction</th>
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<tr>
<td>$^{207}\text{Bi}$</td>
<td>14.12</td>
<td>(n,3n)</td>
</tr>
<tr>
<td>$^{206}\text{Bi}$</td>
<td>22.55</td>
<td>(n,4n)</td>
</tr>
<tr>
<td>$^{205}\text{Bi}$</td>
<td>29.62</td>
<td>(n,5n)</td>
</tr>
<tr>
<td>$^{204}\text{Bi}$</td>
<td>38.13</td>
<td>(n,6n)</td>
</tr>
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Future plan for radiation evaluation in RIBF

Precise measurement of neutron yield for more high intense beam

- Current intensity of uranium beam is **70 pnA**.
- **Permission for uranium beam: 300 pnA.**  **Goal: 1000 pnA.**  Future • • • ?
- RIBF shield was designed at 1999 by empirical formula of mass dependence of “A*E^2” with $^{20}\text{Ne} + \text{Cu} 400\text{MeV/u}$ measurement.
- More than ten times surplus shield were applied.
- RIBF is in underground. Neuron yield for side direction as **45, 90 degrees** are also necessary.
Neutron yield measurement using TOF

Preliminary result for $^{238}\text{U} + \text{thick Cu target}$ at 345 MeV/u.

We will measure for thin Be, W target (RIBF target materials)

K. Sugihara and Kyushu univ.
Summary: Radiation Evaluation at RIBF over the past decade

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<tr>
<td>Activation/dose</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Activation</td>
<td>$2 \sim 3$</td>
<td></td>
</tr>
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18GHz SC-ECRIS

RILAC

Neutron flux/dose

Heat Load

Activation/residual dose
Thank you for attention