Long-lived Fission Product Transmutation

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RIKEN Nishina Center
RI Beam Factory

5 cyclotrons + 2 linacs
3 in-flight separators

Super-heavy Element Science

113th Nh "Nihonium" Z=106 (Sg) Chemistry

Physics with Exotic Nuclei

New Isotopes
Shell evolutions
R-process path
EOS
Nucleon correlation
Application Programs at RIBF

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(1) Nuclear Transmutation Program
(2) Radioactive Isotope Productions
(3) Heavy-ion breeding
(4) Irradiation test of space-use semiconductors

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High-Level Nuclear Waste Problems

Nuclear Waste has long-lived fission products (FP) and minor actinoid (MA).

In case of geological disposal, nuclear waste has a potential risk over a few ten thousands years.

Site of geological disposal is hardly selected.

It is hard to guess how structures of ground layers will be changed for the coming ten thousands years.

Nuclear waste could be efficiently transmuted into harmless materials?

No leaving waste for next generation
**Geological Disposal and/or Reprocessing**

In Japan, before Fukushima Incident 2011, ~ 800t U / year (~75% operation of 50 LWR)

- **New Fuel**
  - $^{235}$U
  - $^{238}$U

- **Spent Fuel**
  - $^{238}$U
  - $^{235}$U
  - Pu
  - MA + FP
  - 768t
  - 32t
  - 744t
  - 8t
  - 8t
  - 40t

- **Direct Disposal**
  - USA, Canada, Finland, Sweden

- **Reprocessing + Disposal**
  - France, Japan ...

- **Reprocessing as fuel**

- **Geological disposal**
Further Partitioning and Reprocessing

R&D efforts to minimize risk of radioactive materials in future

MA (Np, Am, Cm)  1t  
FP  39t  
Platinum Group (4t) Pt, Pd, ...
> re-used

Cs/Sr (5t) (heat generator)
Other FP (30t)

How about accelerator system to reduce radioactivity of FP?

A variety of reactions

Nuclear Reactions
Beam species, energy
Target material & system.....

Facility building cost
operation cost ...

Lack of nuclear reaction data for FP (so far, n-capture only)
First targets are Cs-137 and Sr-90, to study spallation reaction induced by proton and deuteron.

Cs-137 and Sr-90 have a large weight fraction of FP.
- Half-life is about 30 years.
- At the present policy, “cooling” time needs about 300 years.

The thermal neutron capture cross sections are small.
- 0.27 b for Cs-137, 0.01 b for Sr-90

Total cross sections of spallation reaction could be expected larger than 1 b.

Production cross section of each fragment gives half-life distributions of fragments.

RIBF provides a unique opportunity to get reaction data.
Nuclear Reaction Study via Inverse Reaction Method

Inverse reaction method to take nuclear reaction data

Stable/short-lived nuclei
- neutron
- gamma

LLFP target (① proton, ② deuteron)

Spectrometer/detector (PID of reaction products, etc)

LLFP RI-beam
- ① proton
- ② deuteron (neutron + proton)

Nuclear transmutation setup

Stable/short-lived nuclei
- neutron
- gamma

LLFP target
- ① proton beam
- ②' neutron beam

① proton beam
②' neutron beam
World’s First and Strongest K2600MeV Superconducting Ring Cyclotron

400 MeV/u Light-ion beam
345 MeV/u Uranium beam

World’s Largest Acceptance
9 Tm
Superconducting RI beam Separator

~250-300 MeV/nucleon RIB
Transmutation for LLFP: The First Challenge

April, 2014

<table>
<thead>
<tr>
<th>Beam species</th>
<th>Beam energy [MeV/u]</th>
<th>Intensity [/s/10pnA]</th>
<th>Purity [%]</th>
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<tbody>
<tr>
<td>$^{137}$Cs</td>
<td>186</td>
<td>1200</td>
<td>14</td>
</tr>
<tr>
<td>$^{90}$Sr</td>
<td>187</td>
<td>7100</td>
<td>28</td>
</tr>
</tbody>
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U-238 Acceleration at Super-Conducting Cyclotron

2ndary target
C, CH$_2$, CD$_2$

Inflight Separator to deliver intense RI beams: Cs-137, etc

PID at BigRIPS

Z

A/Q

(\textit{n, Xn}) Spallation
Charge exchange for p, d(n), C targets

PID at ZeroDegree

ZeroDegree Spectrometer

PID for reaction products to determine reaction channels.
Spallation reaction study for fission products in nuclear waste: Cross section measurements for $^{137}$Cs and $^{90}$Sr on proton and deuteron

H. Wang$^a$, H. Otsu$^a$, H. Sakurai$^a$, D.S. Ahn$^a$, M. Aikawa$^b$, P. Doornenbal$^a$, N. Fukuda$^a$, T. Isebe$^a$, S. Kawakami$^c$, S. Koyama$^d$, T. Kubo$^a$, S. Kubono$^a$, G. Lorusso$^a$, Y. Maeda$^c$, A. Makinaga$^e$, S. Momiyama$^d$, K. Nakano$^f$, M. Niikura$^d$, Y. Shiga$^g$, P.-A. Söderström$^a$, H. Suzuki$^a$, H. Takeda$^a$, S. Takeuchi$^a$, R. Taniuchi$^d$, Ya. Watanabe$^a$, Yu. Watanabe$^f$, H. Yamasaki$^d$, K. Yoshida$^a
Cross section data $^{137}$Cs + p, d

- **Ba (Z=56)**
- **Cs (Z=55)**
- **Xe (Z=54)**
- **I (Z=53)**
- **Te (Z=52)**
- **Sb (Z=51)**

**Graphs:**
- **A)**
- **B)**
- **C)**
- **D)**
- **E)**
- **F)**

The graphs show the cross section data for different elements. The x-axis represents the mass number (A), and the y-axis represents the cross section in mb (millibarns). The data is compared with PHITS simulations on D and H.
Cross section data $^{90}\text{Sr} + p, d$

![Graphs showing cross section data for different elements](image-url)
Comparison between d-induced and p-induced reactions

Deuteron is a particle formed of proton and neutron, but not an in-coherent composite of proton and neutron! It is hard to get “neutron”-induced components.

Deuteron gives higher energy deposits in targets.
Half-life Distributions of Fragments

Fragments of which half-life is longer than 30 years are less than several percent.
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To be upgraded for the coming a few years
**RIKEN RIs for application studies**

- **Development of RI production technologies at AVF, RRC, and RILAC**
  - RI application studies in the fields of physics, chemistry, biology, medicine, pharmaceutical and environmental sciences
  - Fee-based RI distribution to general public (FY2007–)
  - Platform for short-lived RI distribution (FY2016–)

- **Cu for nuclear medicine**

- **Sr: New product for fee-based RI distribution**

- **211At for nuclear medicine**

- **262Db, 265Sg, and 266Bh for SHE chemistry**

- *RIs produced with the gas-jet system.*
Production of promising therapeutic $^{211}\text{At}$ using $^{209}\text{Bi}(\alpha,2n)^{211}\text{At}$ at AVF

Toward mass production of $^{211}\text{At}$ with 0.5 mA $\alpha$ beam from RILAC

- Short range of $\alpha$ particle
- High LET
- Large cytotoxic effect, small effect for normal cell
- Effective for disseminative, blood, and spread cancers, and small cancer left after operation

$\rightarrow$ R&D of novel $^{211}\text{At}$ medicines in collaboration with Biofunctional Synthetic Chemistry Laboratory, Synthetic Cellular Chemistry Laboratory, RIKEN Center for Life Science Technologies, and RIKEN Innovation Center

$^{211}\text{At}$ production chamber

$^{209}\text{Bi}$ target

$\alpha$ decay (41.8%) $E_\alpha = 5.87 \text{ MeV}$

$\alpha$ decay (100%) $E_\alpha = 7.45 \text{ MeV}$

$^{211}\text{Po}$ EC decay (58.2%)

Chem. Y. : 70%

RIBF has started a new project to obtain LLFP nuclear reaction data via inverse reaction method. A bunch of reaction data are being obtained. A conceptual design for accelerator transmutation systems is being discussed under collaboration of domestic universities/institutes. e.g. Cyclotron, Linac, FFAG...

A project has started to deliver At-211 to chemists and biologists for development of new nuclear medicine.