MUON AND FFAGS

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EXTINCTION OF NUCLEAR WASTE

Is ADS/FR nuclear transmutation really useful?

• Fast neutron can reduce of long-lived nuclear toxicity. ADS/FR can provide fast neutrons.

• But, ADS/FR needs fissile nuclear fuels, U, Pu, Th, etc. ADS/FR can reduce but not completely.

Still we need deep geological storages.

Difficult to get public consensas.

Radio toxicity cannot be extinct. Still need a geological storage!
Transmutation System Approach

Once-Through Fuel Cycle

Single-Tier Transmutation System

Dual-Tier Transmutation System

Tier 0

Tier 1

Tier 2

High-Level Waste Repository

LWR

Spent Nuclear Fuel

TRU

MOX

MA

Pu Burner

ADS or FR

HLW

HLW

None zero!
FR or ADS recycling in reality

Waste Management Objective: Radiotoxicity Reduction

Deep geological storage is essential, even with FR/ADS nuclear-transmutation!

- Continuous recycle required for significant reduction of radiotoxicity
- Continuous recycle strategy can significantly improve the basic nature of nuclear waste disposal (thermal load and isolation time frame)

MUON NUCLEAR TRANSMUTATION µ-NTM

• Nuclear transmutation with **weak interaction**
\[
\mu^- + p \rightarrow n + \nu_\mu
\]

• Production of $^{99m}$Tc : medical RI tracer \(\rightarrow\) very useful

\(\Rightarrow\) µ-NTM proposed by **K.Nagamine**.

\[
\mu^- + ^{100}\text{Ru} \rightarrow ^{99m}\text{Tc} + n
\]

• 500MeV-3mA(1.5MW) proton driver (Cyclotron : Nagamine) can provide

\(\Rightarrow\) 3.3x10^{12} \(\mu/\text{sec}\) \(\mu^-\). \(\rightarrow\) **1kCi-6days** $^{99m}$Tc : Total consumption in Japan

• How about µ-NTM for nuclear wastes?

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The reaction of stopped negative muons with protons is given as:

\[ \mu^- + p \rightarrow n + \nu_\mu \]

with 95% efficiency! by K.Nagamine.

But, slow muons (<MeV/c) are needed.

Nuclear transmutation with stopped negative muon:

- Phenomena taking place in the matter after stopping of “heavy electron” like negative muons:
  1. Formation of excited states of small atom by penetrating electrons surrounding nucleus.
  2. Transition within ns to the atomic ground state which has a radius of 270/Z x 10^{-13} cm for Z nuclei; In^{100}Ru (Z=44) 6.13 x 10^{-13} cm.
  3. Strong capture reaction of \( \mu^- \) via weak interaction (\( \mu^- + p \rightarrow n + \nu_\mu \)) since atomic radius becomes comparable to the nuclear radius which is 1.2(A)^{1/3} x 10^{-13} cm; for^{100}Ru, 5.37 x 10^{-13} cm. The nuclear capture process is competing with a free decay (\( \mu^- \rightarrow e^- + \nu_\mu + \nu_e \)); in^{100}Ru (Z=44), nuclear capture is 95% and free decay is 5%.
  4. After nuclear capture to highly excited (close to 100 MeV), particle (mainly neutron) emission takes place to produce a unique process of element transmutation.

Most of the stopping \( \mu^- \) makes nuclear transmutation.
EXTINCTION OF NUCLEAR WASTES WITH $\mu$-NTM

• NTM based on FR/ADS can reduce radio-toxicity but not completely.

• $\mu$-NTM convert TRU to U or less Z-element: Proton converts neutron with weak interaction.

• Free from radio-toxicity perfectly!
NUCLEAR WASTES FROM NUCLEAR POWER PLANT

• Production of nuclear wastes from Uranium fuel (3% enriched U; 1 ton @ 1 GWe nuclear power plant, operation in 1 year

  • Pu 10 kg
  • Pt 2 kg
  • Short-lived FP 26 kg
  • Long-lived FP 1.3 kg
  • Minor Actinides (Np, Am, Cm) 0.6 kg

• 1 GWe nuclear power plant for 40 years operation:

  • Nuclear fuel charging: 10 tons/10 years

If μNT can treat LL-FP and MA with 2-4 mol/year, a deep geological storage (GS) may not be necessary. *ADS or FR cannot treat all MA and need GS.
PRODUCTION OF STOPPED NEGATIVE MUONS

• To get stopped negative muons;
  • $p(<500\text{MeV}) + n \rightarrow p + \pi^-$ : Low energy proton
  • $\pi^-$ (~200MeV/c) capture & degradation $\rightarrow$ MeV/c
  • $\pi^- \rightarrow \mu^-$ degradation & stopped.

• Difficulties:
  • Large $dE/dx \rightarrow$ thin target(10cm C)
  • Small cross section of $\pi^-$ production $\sim$mb
  • $\pi^-$/proton $\sim 10^{-4}$ $\leftarrow$ $<10^{-3}$ times smaller than request!
MUON NUCLEAR TRANS_MUTATION

μ-NTM

• Total LLFP and MA from 1GWe nuclear power plant for 40 years (lifetime) operation. → 160 mol.

• If μ-NTM can treat LL-FP and MP with 2mol/year, 80 years for complete extinction . → Nice!

80 years μNTM

“0”

40 years operation
NUMBERS OF STOPPED NEGATIVE MUONS REQUIRED FOR NUCLEAR WASTES TREATMENT

• Stopped $\mu^-$ intensity required to treat LLFP and MA with a rate of 2 mol/year,

$$\Rightarrow 2[\text{mol}] \times NA / \varepsilon(\mu^-+p\rightarrow n+n\nu_\mu) \sim 1.2 \times 10^{24} \, \text{[muons/year]} = 3.8 \times 10^{16} \, [\mu^-/\text{sec}] :$$

• cf. $\sim 1 \times 10^{12}$ (J-PARC) $\times 38,000$ !
MUON YIELD

To get $3.8 \times 10^{16} \mu^-/\text{sec}$ with $\pi/p>0.5$ (Proton beam current : $I_p>12\text{mA cw}$)

- **Need thick enough pion production target**: $t \sim 100\text{m} ; \sigma=1\text{mb} @400\text{MeV}$: $\times 1000$
  - Ordinary $\pi/\mu$ production target $\rightarrow$ thickness $\sim 10\text{cm}$ for $E=500\text{MeV}$
  - Overcome the energy loss caused by stopping power
  - Energy recovery $\rightarrow$ “ERIT”

- **Efficiency of muon capture $> 0.5$**: 6-D capture with strong magnetic field ($B\sim 2T$): $\times 10$
  - Energy of $\mu^- < 200\text{MeV}/c$ ($q<0.33\text{m}$)
    - Deuteron(proton) beam energy $\sim 400\text{MeV}/u$

- **Proton driver beam power**: $4.8\text{MW}$ ($400\text{MeV} - 12\text{mA}$): $\times 5$
ERIT FOR MUON PRODUCTION

- ERIT: Emittance Recovery Internal Target in storage ring.

- Figure of merit
  - E threshold >300 MeV/u
  - Energy recovering.
  - $FOM = \frac{NL}{\int_{E}^{300 \text{ MeV}}} \left( \frac{dE}{dx} \right)^{-1} dE$
  - 500 MeV/u deuteron
    - $\langle \varepsilon \rangle_{\text{rms}} \sim 462 \text{ mm.mrad}$!
  - $\Delta E \sim 2.5 \text{ MeV} @0.5\text{cm C}$
  - N~20000 turns $\rightarrow$ 100m target equiv.

- Carbon: $t=0.5\text{cm}$

- Internal target
- RF cavity re-acceleration
- Beam

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- beam energy 11MeV
- circ. beam current 70mA
- beam life (# of turns) 500-1000 turns

- acceptance $\Delta v > 3000 \text{mm.mrad}$
- $\frac{dp}{p} > +5\% (\text{full})$

$\nu_x, \nu_y$ 1.77, 2.27

Neutron Yield $> 10^{13} \text{n/sec}$
μERIT - ERIT FOR MUON PRODUCTION

• Place a $\pi$-production target in the magnetic field.

  1. $\pi$ capture and decay $\rightarrow$ Need high $B (>1T)$ and distance.

  2. $\mu$ transport and degradation $\rightarrow$ Need high $B(>1T)$ and material.

• V_FFAG looks interesting!
B \sim \exp\left(\frac{m}{\rho^* y}\right)

ERIT_V-FFAG

d beam

B > 1T

Target
BETATRON MOTION AROUND CIRCULAR ORBIT

Eqs. of motion

\[ \frac{d^2x}{d\theta^2} + \left[ \frac{e}{p} B_y (\rho + x) - 1 \right] (\rho + x) = 0, \]

\[ \frac{d^2y}{d\theta^2} - \left[ \frac{e}{p} B_x (\rho + x)^2 \right] = 0. \]

Linearization

\[ \frac{d^2x}{d\theta^2} + x + \frac{\rho}{B_0} \left[ \left( \frac{\partial B_y}{\partial x} \right) x + \left( \frac{\partial B_y}{\partial y} \right) y \right] = 0, \]

\[ \frac{d^2y}{d\theta^2} - \frac{\rho}{B_0} \left[ \left( \frac{\partial B_x}{\partial x} \right) x + \left( \frac{\partial B_x}{\partial y} \right) y \right] = 0. \]

---

normal

skew
MAGNETIC FIELD FOR ZERO CHROMATICITY

(1) Ring

a) Normal: H-FFAG
\[ \frac{R}{\rho} = \text{const.} \quad \& \quad \frac{R}{B_y} \left( \frac{\partial B_y}{\partial x} \right) = k \rightarrow B_y = B_y^0 \left( \frac{R}{R_0} \right)^k \]

b) Skew: V-FFAG
\[ R, \rho = \text{const.} \quad \& \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial y} \right) = n \rightarrow B_y = B_y^0 \left( \frac{n}{\rho} \right) \]

(2) Straight line

a) Normal: H-FFAG
\[ \rho = \text{const.} \quad \& \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial x} \right) = n \rightarrow B_y = B_y^0 \exp \left( \frac{n}{\rho x} \right) \]

b) Skew: V-FFAG
\[ \rho = \text{const.} \quad \& \quad \frac{\rho}{B_y} \left( \frac{\partial B_y}{\partial y} \right) = n \rightarrow B_y = B_y^0 \exp \left( \frac{n}{\rho y} \right) \]
V_FFAG : LINEAR MODEL

- Betatron equations of V_FFAG: x-y coupled.
  \[ \frac{d^2 x}{d\theta^2} + x + ny = 0, \]
  \[ \frac{d^2 y}{d\theta^2} + nx = 0. \]

- Normal mode: diagonalization

\[
M = T^{-1} \begin{pmatrix} U & 0 \\ 0 & V \end{pmatrix} T, T = \begin{pmatrix} \mu I & SR^T S \\ R & \mu I \end{pmatrix}.
\]

\[
U = I \cos \psi_u + J_u \sin \psi_u, \quad J_u,v = \begin{pmatrix} \alpha_{u,v} & \beta_{u,v} \\ -\gamma_{u,v} & -\alpha_{u,v} \end{pmatrix},
\]

\[
V = I \cos \psi_v + J_v \sin \psi_v.
\]
STABILITY-AG FOCUSING

(1) $m(=n/\rho)$ - edge angle ($\xi_{\text{ent}}=\xi_{\text{ex}}$)

(2) $\xi_{\text{ent}}$ - $\xi_{\text{ex}}$ for 8-cell ring
\(\mu\)-ERIT\_\textit{v}\_FFAG

- **D-(H-) beam**
- **Carbon target 0.5cm**
- **RF cavity V>5MV**

<table>
<thead>
<tr>
<th>Type</th>
<th>\textit{v}_FFAG</th>
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<tbody>
<tr>
<td>Energy</td>
<td>500[MeV/u]</td>
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<tr>
<td>Numbers of cells</td>
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<tr>
<td>Packing factor</td>
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<tr>
<td>Radius</td>
<td>2(4) [m]</td>
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<td>Magnetic field</td>
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<tr>
<td>Edge angle (ent-ext)</td>
<td>50-50 [degree]</td>
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SUMMARY

• **Intense low energy muon source with ERIT using v_FFAG is proposed.**
  
  • Very long production target can be effectively realized with ERIT scheme, which is good for production of slow $\pi-/\mu$-.

  ➞ Efficiency x1000

  • $\pi-/\mu$- are captured and transported by strong magnetic field of v_FFAG.
  
  • $\mu$- yield $\sim 1\times10^{16}$ muons/sec

• **Technical (many) issues;**

  • Nuclear reactions (elastic scattering)
  
  • Target heating
  
  • Radiation (neutrons!)