Recent activity of Neutronics related IFMIF

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IEA International Work Shop on Fusion Neutronics
5 September, 2002
Dresden, Germany

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○ Experimental Data on Neutron Yield by Deuteron-Lithium Reaction
○ Neutron Source Term Model
○ Experiment Plan on Activation by Deuteron Bombardment
Problems to be studied.

(1) Reaction cross sections of lithium and neutron
    For neutronics design surrounding Li target

(2) Reliability on neutron activation cross section up to 50 MeV
    For safety analysis
    Integral test on benchmark experiment

(3) Reaction data for deuteron bombardment
    For the structural design surrounding deuteron beam (Present report)
Problems for deuteron beam

(1) Estimation of neutron source term
   Necessary data:
   Neutron yield cross section
   Neutron yield factor per deuteron for thick layer
   (Integrated over angle and energy)
   Measurement: Neutron spectrum of d-\(^7\)Li reaction at
                Tandem (JAERI) and CYRIC (Tohoku Univ.)
   Simulation: Neutron source model for MCNP code
                (JAERI)

(2) Activation by beam bombardment
   Necessary data: Material(d,x) activation cross section
   Measurement: Planned at TIARA (JAERI)
Cyclotron and Radioisotope Center, Tohoku University (CYRIC)

Performance of new K=110 AVF cyclotron
- Protons 10-90 MeV
- Deuterons 10-65 MeV
- $^3$He 20-170 MeV
- $^4$He 20-130 MeV
- etc.

This measurements
Deuteron 25 MeV ~5nA
At Target-room NO.5
With Beam-swinger system

Layout of CYRIC
D\(^{(7}{\text{Li,n}}\)) at E\(^{(7}{\text{Li}}\)=60MeV: neutron time-of-flight spectra

\[ \theta_{\text{n,lab}}=0\text{deg} \]

\[ \theta_{\text{n,lab}}=15\text{deg} \]

Flight path
3m, 5cm\(\phi\) x 5cm thick NE213

D(\(^{7}\text{Li,n}\)) at E(\(^{7}\text{Li}\))=60MeV: neutron time-of-flight spectra

\[ \theta_{\text{n,lab}}=0\text{deg} \]

\[ \theta_{\text{n,lab}}=15\text{deg} \]

Flight Path
8.2m, 20cm\(\phi\) x 25cm thick NE213 (with time compensation)
D($^7\text{Li,n}$) at E($^7\text{Li}$)=60MeV: neutron production cross sections

- $\theta_{\text{n,lab}}=0\text{deg}$
- $\theta_{\text{n,lab}}=15\text{deg}$
- $\theta_{\text{n,lab}}=60\text{deg}$
- $\theta_{\text{n,lab}}=90\text{deg}$
$^{nat}$Li(d,xn) spectra  \( (E_d = 25 \text{ MeV}) \)

Neutron yields \( [\text{MeV}^{-1}\text{sr}^{-1}\mu\text{C}^{-1}] \)

Neutron energy \( [\text{MeV}] \)

- 0-deg
- 5-deg
- 10-deg
- 15-deg
- 20-deg
- 25-deg
- 30-deg
- 40-deg
- 60-deg
- 90-deg
Individual excitation levels of $^8$Be up to 17MeV and continuum background due to 3-body breakup channels can be identified with the help of $D(^7$Li,n) results.
Decomposition of produced neutron spectra into $^7\text{Li}(d,n)^8\text{Be}^*$, $^6\text{Li}(d,n)^7\text{Be}^*$, and kinematically allowed 3-body breakup channels: $^7\text{Li}(d,n\alpha)^4\text{He}$, $^7\text{Li}(d,2n)^7\text{Be}$, $^7\text{Li}(d,nd)^6\text{Li}$, and $^7\text{Li}(d,np)^7\text{Li}$; the last one is the origin of forward peak component around 7MeV (described by “Serber” model).
At this energy, forward peak ("Serber") component is small and practically it can be interpreted as the enhancement of some $^7\text{Li}(d, n)^8\text{Be}^*$ channels.
Outline of the Neutron source model

Neutron source model has been studied for the estimation of activation of devices and design of neutron shielding.

(1) Proton stripping model for $^7$Li(d,n)$^8$Be$	extsuperscript{*}$
   Direct process and evaporation model

(2) Modified Serber model in direct process
   To describe intense forward angular distribution
   Modified for lithium target

(3) Three-body break-up model
   Neutron spectrum based on phase space density
   $^7$Li(d,n$\alpha$)$^4$He/ $^7$Li(d,2n)$^7$Be/ $^7$Li(d,np)$^7$Li/ $^7$Li(d,nd)$^6$Li
   Branching ratio for models (1) through (3) is studied.
Neutron source model (1)

- Phase space density distributions of 3-body breakup channels that generate neutrons: \(^7\text{Li}(d,n\alpha)^4\text{He}, \(^7\text{Li}(d,2n)^7\text{Be}, \(^7\text{Li}(d,np)^7\text{Li}, \(^7\text{Li}(d,nd)^6\text{Li} are used to describe the continuum background component of measured neutron source spectra (\(E_d=8,16,24,25,32,35\) and 40-MeV)

- Stripping process to unbound states \(^6,7\text{Li}(d,n)^7,8\text{Be}^* is analyzed and decomposed from the neutron spectra subtracted the 3-body breakup processes

- Obtained forward peak component (normally described by “Serber” model) is explained using \(^7\text{Li}(d,np)^7\text{Li phase space and transition matrix estimated by distorted-wave impulse approximation of quasi-free knockout model
Neutron source model (2)

Distorted Waves:
Optical potentials for 
\( d + ^7\text{Li}, n + ^7\text{Li}, p + ^7\text{Li} \)

Effective Interactions:
Scattering amplitudes of 
\( n + ^7\text{Li}, p + ^7\text{Li} \)

Cross sections
\[ = (\text{Kinematical Factors including Phase Space Density}) \times |\text{Transition Amplitude}|^2 \]

**DWIA**
Transition amplitude =
(Angular Momentum Coupling Factor) \times
(Overlapping integral for Distorted Wave and Effective Interaction)

Either \( n \) or \( p \) is spectator

Diagram:
- Entrance channel: \( d \) → \( ^7\text{Li} \)
- Exit channel: \( n \) or \( p \)
- \( ^7\text{Li} \) is the target nucleus.
Neutron source model (3)

- **Neutron source term for MCNP is provided** in the form of input data stream with the standard format:
  - To be version independent
  - To apply standard variance reduction techniques
  - To analyze sensitivity to the source term and
  - To derive uncertainty of the results

- **A preparation code is used to generate the input data stream** from nuclear reaction data and stopping power formula:
  - To obtain track length of ions at defined energies along the trajectories
  - To obtain double-differential neutron production yield by integrating over ion energy (and integrated over positions for the purpose of shielding calculation)
IFMIF Activation by Deuteron Bombardment
(Experimental Plan at TIARA)

Background

Intense deuteron beam: 40MeV, 250mA

Deuteron-induced radio-activity in structural materials is high.

The activation data is not enough for the design.

The (d,x) activation cross sections will be measured in 20-40 MeV energy range.
Experimental Condition

- D^+ beam Energy point
  - 35, 50 MeV
- Stacked foil activation method
- Energy Range: 20-50 MeV
- Beam monitor reaction
  - ^27Al(d,x)^22Na, ^24Na
- Irradiation time
  - 10m – 1h
- Irradiation port
  - Light Ion Room 1
- d beam current
  - < 1µA

TIARA: Takasaki Ion Accelerators for advanced Radiation Application
Target Arrangement

- Deuteron Beam
- Cooling water
- He gas
- Ti foil: 0.1mm
- Sample holder
- Stacked foils
- Transport system
- Sample Set
- Measurement by a HPGe detector

Cell

15mm
### Objective Materials and Reactions

<table>
<thead>
<tr>
<th>(1) Beam Transport System Materials</th>
<th>Cu, Al, Fe, Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu(d,x)$^{65}$Zn $T_{1/2}$=244d,</td>
<td>Cu(d,x)$^{62}$Cu $T_{1/2}$=9.2h,</td>
</tr>
<tr>
<td>Cu(d,x)$^{61}$Zn $T_{1/2}$=3.3h,</td>
<td>Cu(d,x)$^{63}$Zn $T_{1/2}$=38m,</td>
</tr>
<tr>
<td>(2) Beam Dump, Beam Aperture Materials</td>
<td>W, Ta</td>
</tr>
<tr>
<td>W(d,x)$^{184m,g}$Re $T_{1/2}$=169d, 38d,</td>
<td>W(d,x)$^{183}$Re $T_{1/2}$=70d</td>
</tr>
<tr>
<td>W(d,x)$^{186}$Re $T_{1/2}$=3.78d,</td>
<td>W(d,x)$^{182m,g}$Re $T_{1/2}$=12.7h, 2.7d,</td>
</tr>
<tr>
<td>W(d,x)$^{187}$W $T_{1/2}$=23.7h,</td>
<td>W(d,x)$^{181}$Re $T_{1/2}$=19.9h,</td>
</tr>
<tr>
<td>(3) Target Material</td>
<td>Li</td>
</tr>
<tr>
<td>Li(d,x)$^{7}$Be $T_{1/2}$=53d</td>
<td></td>
</tr>
</tbody>
</table>
Summary

The activity for neutronics design of IFMIF is summarized as below.

1. Neutron yield data through deuteron-lithium reaction has been accumulated with Tandem accelerator of JAERI and CYRIC facility at Tohoku University.

2. Neutron source model has been constructed to describe experimental data. Source program for MCNP code now under study will simulate the D-Li reaction, and be used for the structural design around the target.

3. Important activation data by direct reaction of deuteron beam with structural materials will be measured with TIARA facility at JAERI-Takasaki Establishment.