NUCLEAR REACTION MODELS FOR SYSTEMATIC ANALYSIS OF FAST NEUTRON INDUCED (n,p) REACTION CROSS SECTIONS

M.Odsuren, J.Badamsambuu, G.Khuukhenkhuu

Nuclear Research Center, National University of Mongolia, Ulaanbaatar, Mongolia
MOTIVATION

Investigation of fast neutron induced charged particle emission reactions is important:

1. Fundamental nuclear physics study:
   - The study of nuclear reactions mechanisms
   - Nuclear structure

2. Fission and fusion reactors technology:
   - Radiation damage
   - Residual radioactivity
   - Hydrogen and helium gas production

Systematical analysis of neutron cross sections is of interest:

1. To evaluate of neutron cross sections
2. To estimate of authenticity for experimental data
Empirical formula $\sigma(n,p)$ and $\sigma(n,\alpha)$ at $E_n=14-15$ MeV

$$\sigma(n, p) = C \pi r_0^2 \left(1 + A^{1/3}\right)^2 e^{-K \frac{N-Z}{A}}$$

Here: $C=0.73$ and, $K=33$ are fitting parameters.

G.Khuukhenkhuu, JINR preprint. E3-93-205, Dubna, 1993
Statistical Model:

\[ \sigma_{np}^{\text{com}} = C \pi (R + \hat{\lambda})^2 e^{-K \frac{N-Z+1}{A}} \] (1)

\[ C = \exp \left( \frac{1}{\Theta} \left( \gamma \frac{2Z-1}{A^{1/3}} + \frac{\Delta}{A^{3/4}} - V_p \right) \right) \]

\[ K = \frac{4 \xi}{\Theta} \]

Here:

- \( R, Z, N \) and \( A \) - radius, proton, neutron and mass numbers of target nuclei
- \( \hat{\lambda} \) - Wavelength of incident neutrons divided by \( 2\pi \)
- \( V_p \) - Coulomb potential for protons
- \( \Theta \) - Thermodynamic temperature of nuclei
- \( \xi \) and \( \Delta = \delta_i - \delta_f \) - Constants of Weizsacker's formula.
– **Exciton Model:**

\[ \sigma_{np}^{pre} = 68.3 \frac{\pi^6}{\hbar^2} R^2 \sigma_r(E_n) \frac{2M_p}{K_0A} \left[ \frac{(E_n + Q_{np}) - V_p}{(E_n + B_n)^3} \right]^3 \]  

Where:
- \( \sigma_r(E_n) \) - Neutron induced reaction total cross section
- \( M_p \) - Mass of proton
- \( K_0 \approx 400 \text{ MeV}^3 \)
- \( E_n \) and \( B_n \) - Kinetic and binding energy of neutron
- \( Q_{np} \) - Reaction energy

\[ \sigma_{np}^{dir} = C_0 \pi R^2 \sqrt{1 + \frac{Q_{np}}{E_n}} \]  

Where \( C_0 \) can be determined as best fitting the experimental data parameter.

**Theoretical total (n,p) cross section:**

\[ \sigma_{np}^{tot} = \sigma_{np}^{com} + \sigma_{np}^{pre} + \sigma_{np}^{dir} \]
### SYSTEMATICS OF THE (n,p) REACTION CROSS SECTIONS

#### Table

<table>
<thead>
<tr>
<th>$E_n$ (MeV)</th>
<th>$K$</th>
<th>$C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>75.2</td>
<td>17.5</td>
</tr>
<tr>
<td>8</td>
<td>62.8</td>
<td>11.9</td>
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<tr>
<td>10</td>
<td>52.1</td>
<td>6.80</td>
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<tr>
<td>13</td>
<td>38.8</td>
<td>2.74</td>
</tr>
<tr>
<td>14.5</td>
<td>37.3</td>
<td>2.43</td>
</tr>
<tr>
<td>16</td>
<td>33.5</td>
<td>1.42</td>
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<tr>
<td>18</td>
<td>22.4</td>
<td>0.39</td>
</tr>
<tr>
<td>20</td>
<td>17.9</td>
<td>0.25</td>
</tr>
</tbody>
</table>

#### Graphs

- **$E_n = 6$ MeV**
  - $C = 17.5$
  - $K = 75.2$

- **$E_n = 14.5$ MeV**
  - $C = 2.43$
  - $K = 37.3$

- **$E_n = 20$ MeV**
  - $C = 0.25$
  - $K = 17.9$
COMPARISON OF EXPERIMENTAL AND THEORETICAL (n,p) CROSS SECTIONS

Statistical model (n,p) cross sections and experimental data:

\[ \sigma_{np}^{\text{comp}} = C \pi (R + \hat{\lambda})^2 e^{-K \frac{N-Z+1}{A}} \]
Exciton model \((n,p)\) cross sections and experimental data:

\[ \sigma_{np}^{pre} = 68.3 \frac{\pi^6}{\hbar^2} R^2 \sigma \left( E_n \right) \frac{2M_p}{K_0 A} \left[ \frac{Q_{np} - V_p}{E_n + B_n} \right] \]

\[ E_n = 6 \text{ MeV} \]

\[ E_n = 14.5 \text{ MeV} \]

\[ E_n = 20 \text{ MeV} \]
PWBA (n,p) cross sections and experimental data:

\[ \sigma_{np}^{dir} = C_0 \pi R^2 \sqrt{1 + \frac{Q_{np}}{E_n}} \]
The total (n,p) cross section

\[ \sigma_{np}^{tot} = \sigma_{np}^{com} + \sigma_{np}^{pre} + \sigma_{np}^{dir} \]

The theoretical total (n,p) cross sections are satisfactorily in agreement with experimental values for \( E_n = 6, 14.5 \) and 20 MeV. Also, in the case of \( E_n = 8, 10, 13, 16 \) and 18 MeV neutrons we have almost the same results.
CONCLUSION

1. Using the statistical model, exciton model and PWBA are deduced formulae for the fast neutron induced \((n,p)\) reaction cross sections.

2. The formulae were used for systematical analysis of fast neutron induced \((n,p)\) reaction cross sections.

3. It was shown that the theoretical and experimental total \((n,p)\) cross sections for \(E_n=6-20\) MeV are satisfactorily in agreement.
Thank you for your attention
MONGOLIA
TERRITORY: 1 500 000 km², POPULATION: 2 500 000
ULAANBAATAR is Capital of Mongolia

Inhabitants - 1 300 000
National University of Mongolia
1942
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NEUTRON GENERATOR

$E = 14 \text{MeV}$

$F = 10^{10} \text{s}^{-1}$
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$^{252}\text{Cf-NEUTRON SOURCE}$

\[ F = 10^9 \text{ n/s} \]
\[ E_{e}^{\text{max}} = 22\text{MeV} \]
\[ I_{e} = 20\mu\text{A} \]
\[ Y_{\gamma} = 10^{3} \gamma/\text{s} \]
\[ F_{n} = 10^{8} \text{n/cm}^{2}\text{s} \]
$T = -196^0 C$

productivity $= 8 \frac{l}{h}$
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TOTAL REFLECTION X-RAY SPECTROMETER

resolution = 180eV
at 5.9 KeV

sensitivity = 10 − 100 $\frac{\mu g}{l}$
NUCLEAR RESEARCH CENTER
X-RAY SPECTROMETER

resolution = 185eV
sensitivity = 1 – 15%
Микротрон MT-22

\[ V \rightarrow 22 \text{ млн вольт} \]

\[ E_e = 2.2 \text{ МэВ} \]
\[ I_e = 10 - 20 \text{ мкА} \]
\[ \Delta r_e = 3 \text{ мкс} \]
\[ \Phi_i = 2.5 \cdot 10^{13} \text{ н/см}^2 \cdot \text{с} \]
\[ \Phi_n = 10^4 - 10^8 \text{ н/см}^2 \cdot \text{с} \]
\[ N_n = 10^{11} \text{ н/с} \]