On deuteron interactions in surrogate (d,pɤɤ) reactions

Marilena Avrigeanu and Vlad Avrigeanu

National Institute for Physics & Nuclear Engineering (IFIN--HH), Bucharest, Romania

1. Calculation tools: Nuclear Models & CODES
2. Direct Interactions (DI): breakup, stripping & pick-up
3. Effects of DI on Deuteron Surrogate Reactions
4. Conclusions
Deuteron interaction analysis: Nuclear Models & CODES

Motivation: Nuclear Data Needs (FENDL, EURATOM, F4E, EUROfusion)

- **ITER, IFMIF, SPIRAL2, Breeder Reactors**

- **REQUIRED** deuteron reaction cross sections measurements & calculations
  (E ~ 50 MeV): [Al, Cu, Nb, Co, Mn, Fe, Cr, Ni, C... Th, U]
  Reliable gas production cross-section data (H, He)
  Dosimetry data file for E > 20 MeV (IRDF)
  Surrogate reactions (d,pɣ), (d,pf) on Th, U...

- **Deuteron breakup**
  **BREAKUP** [M. Avrigeanu, V. Avrigeanu]
  - total, elastic and inelastic breakup c.s.: M. Avrigeanu et al., Fusion. Eng. Design, 84, 418 (2009);
    E. Šimečková et al., Phys. Rev. C 84, 014605 (2011);
    M. Avrigeanu et al., Phys. Rev. C 85, 034603 (2012); 88, 014612 (2013);
    89, 044613 (2014); 92, 02160(R) (2015), 94, 0146-6 (2016).

- **Direct reactions**
  **FRESCO** (Version FRES 2.9, September 2011) [I.J. Thompson]
  - stripping & pick-up: (d,p), (d,n), (d,t ), (d,α)

- **Composite system equilibration for both deuteron and breakup nucleon reactions**
  **STAPRE-H95** [V. Avrigeanu, M. Avrigeanu] (updated)
  - OMP: SCAT2000; preequilibrium: GDH / EXCITON; evaporation: Hauser-Feshbach
  **TALYS - 1.4 - 1.8** [A. Koning, S. Hilaire, M. Duijvestijn]
  - OMP: ECIS’97; breakup, preequilibrium: MSD / EXCITON; evaporation: Hauser-Feshbach
Empirical parametrization versus microscopic predictions

Marilena Avrigeanu

6th Workshop on Nuclear Level Density & Gamma Strength, Oslo, May 8 - 12, 2017

Proton BU fractions

\[ f_{BU} = \frac{\sigma_{BU}}{\sigma_R} \]

\[ f_{EB} = \frac{\sigma_{EB}}{\sigma_R} \]

\[ \frac{\sigma}{mb} \]

\[ d + ^{232}_{90}Th \]

\[ \sigma_{Reaction} \]

\[ \sigma_{BU} \]

\[ E_d ~ V_c \]

breakup dominance for heavy nuclei and E_d ~ V_c

for deuteron-induced reactions

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Published 27 October 2016

deuteron-induced reactions. A reaction model space, where A is the target nucleus, and the nucleon-target on an effective nucleon-nucleon interaction in nuclear body scattering wave function in the model space is (CDCC) method, and the eikonal reaction of neutron removal cross at several energy.
REACTION MECHANISMS INVOLVED in $^{nat}$Cu(d,x)$^{64}$Cu PROCESS

\[ \sigma (b) \]

$^{nat}$Cu(d,x)$^{64}$Cu

- Gilly+ (1963)
- Fulmer+ (1970)
- Okamura+ (1971)
- Takacs+ (2006)
- Simeckova+ (2011)
- Khandaker+ (2014)

- BF: $^{63}$Cu(n,\(\gamma\))$^{64}$Cu
- BF: $^{65}$Cu(n,2n)$^{64}$Cu + $^{65}$Cu(p,d)$^{64}$Cu
- DR, stripping: $^{63}$Cu(d,p)$^{64}$Cu
- DR, pick-up: $^{65}$Cu(d,t)$^{64}$Cu
- PE+CN: $^{63}$Cu(d,p)$^{64}$Cu
- PE+CN: $^{65}$Cu(d,x)$^{64}$Cu
- BF + DR + PE +CN
- TENDL-2015

\( E_d \) (MeV)

\( \sigma \) (b)

Marilena Avargeanu

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SURROGATE REACTIONS: STRONG EFFECTS OF THE DEUTERON BREAKUP (1)


**BU dominance**

Warning for d-surrogates analyzed in CN frame

Marilena Avrigeanu

6th Workshop on Nuclear Level Density & Gamma Strength, Oslo, May 8 - 12, 2017
Investigation of the $^{238}\text{U}(d,p)$ surrogate reaction via the simultaneous measurement of $\gamma$-decay and fission probabilities

Marilena Avri
6th Workshop on Nuclear Level Density & Gamma Strength, Oslo, May 8 - 12, 2017

**CN mechanism, too restrictive frame for d-surrogates**

**LARGE leakage of d flux through BU + DR before CN formation**

**INELASTIC BREAKUP ENHANCEMENT**

$^{238}\text{U}(n_{BF},\gamma)^{239}\text{U}$
Corrected $P_\gamma$ by d-flux leakage through DI \((\text{frac}=0.124)\)

\[
P_{d,p\gamma}(E_{ex}) = \sum J,\pi F_{d,p}^{CN}(E_{ex}, J, \pi) G_{\gamma}^{CN}(E_{ex}, J, \pi) \approx P_{d,p\gamma}^{exp}(E_{ex})
\]
CONCLUSIONS

Nuclear Reactions Analysis of deuteron induced reactions should consider **BREAKUP & STRIPPING / PICK-UP EFFECTS**

- **DIRECT INTERACTIONS** (DI) effects to $^d$ interactions
  - **BREAKUP**: DOMINANT for heavy targets at $E_d \sim V_c$ surrogate
  - **BREAKUP ENHANCEMENT** of activation C.S. surrogate
  - (d,t) pick-up exclusive contribution at low-energy EF part

- **PE & EVAPORATION** cross sections corrected for initial flux leakage towards **DIRECT INTERACTIONS**

- **UPDATE FOR DEUTERON SURROGATE MODEL**

Thank you!
Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production

Marilena Avrigeanu

Nuclear Data Week, OECD-NEA, 24-27 April, 2017, Paris

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Table 3: Cross-section studies of monitor reactions.

<table>
<thead>
<tr>
<th>Cross sections</th>
<th>Agreed responsibilities, status and actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}$Al(d,x)$^{22,24}$Na</td>
<td>Accept Pade 21 fit for $^{22}$Na up to 100 MeV. For $^{24}$Na, some points were excluded. Accept Pade 12 fit up to 100 MeV.</td>
</tr>
</tbody>
</table>

See FENDL-report: INDC(NDS)-0645, pp. 51, November 2013
Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production

Table 3: Cross-section studies of monitor reactions.

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<tr>
<td>$^{nat}$Cu(d,x)$^{62}$Zn</td>
<td>Accept Pade 9.</td>
</tr>
<tr>
<td>$^{nat}$Cu(d,x)$^{63}$Zn</td>
<td>CRP will not recommend due to deviation at 20 MeV and at 45 MeV. However, accept Pade 12.</td>
</tr>
<tr>
<td>$^{nat}$Cu(d,x)$^{65}$Zn</td>
<td>Accept Pade 13C, uncertainties to be increased to 6%.</td>
</tr>
</tbody>
</table>

VS.

See FENDL-report: INDC(NDS)-0645, pp. 48, November 2013
Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production

Table 3: Cross-section studies of monitor reactions.

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<tr>
<td>natFe(d,x)⁵⁶Co</td>
<td>Hermanne to de-select Nakua 2006 data, and re-send to Ignatyuk for re-fitting by July 1, 2016.</td>
</tr>
</tbody>
</table>

VS.

Low energy deuteron-induced reactions on Fe isotopes

M. Avrigeanu,¹, ² V. Avrigeanu,¹ P. Bém,² U. Fischer,³ M. Honusek,² K. Katovsky,⁴ C. Mănăilescu,¹ J. Mrázek, ² E. Šimečková,², ³ and L. Závorka²

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This work: BU+DR+PE+CN
Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production

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<td>nat-Ni(d,x)56Co</td>
<td>CRP will recommend data up to 50 MeV.</td>
</tr>
<tr>
<td>nat-Ni(d,x)58Co</td>
<td>Accept Pade 11; fit uncertainties to be increased by Ignatyuk to at least 5%.</td>
</tr>
<tr>
<td>nat-Ni(d,x)61Cu</td>
<td>Accept Pade 12.</td>
</tr>
<tr>
<td></td>
<td>Potential systematic shifts due to use of different gamma lines were considered. Accept Pade 10.</td>
</tr>
</tbody>
</table>

NO accompanying figure

VS.

PHYSICAL REVIEW C 94, 014606 (2016)

Deuteron-induced reactions on Ni isotopes up to 60 MeV

Marilena Avrigeanu

Nuclear Data Week, OECD-NEA, 24-27 April, 2017, Paris
Conclusions of CRP on Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope production

Table 7: Cross-section studies for the production of therapeutic α emitters.

<table>
<thead>
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<th>Agreed responsibilities, status and actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>231Pa(d,3n)²³⁰U</td>
<td>Ignatyuk to refit up to 30 MeV based on additional supporting theoretical calculations.</td>
</tr>
</tbody>
</table>

See FENDL-report: INDC(NDS)-0645, pp. 50, November 2013

Marilena Avrigeanu
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Consistent Theoretical Calculations of deuteron induced reactions involving BREAKUP - STRIPPING - PICK-UP - PE - CN should be recommended instead of PADE APPROXIMATIONS as long as exist Powerful Computers and Available Dedicated Codes

Should be correlated various international projects involving deuteron interaction process analysis, e.g. FENDL, F4E, CHARPAR, EUROfusion
Breakup versus Stripping

\[ E_d = 15 \text{ MeV (C.M. } \sim 14 \text{ MeV)} \]

**BU: deuteron breakup**
- deuteron binding energy: \( B_d = 2.225 \text{ MeV} \)
- \( \varepsilon_p^{\text{max}} = E_d - B_d \approx 11.8 \text{ MeV} \)
- \( \text{BU threshold } \approx 11.8 \text{ MeV} \)

**ST: deuteron stripping**
- \((d,p)\) reaction
- \( Q_{\text{Al}(d,p)} = 5.5 \text{ MeV} \)
- \( \varepsilon_p^{\text{max}} \approx E_d + Q_{\text{Al}(d,p)} = 19.5 \text{ MeV} \)

\[ \varepsilon_p^{\text{max - stripping}} - \varepsilon_p^{\text{max - breakup}} = Q_{d,p} + B_d \]

Fig. 3. Decomposition of the experimental angle-averaged proton spectrum (thick full curve) into MSC and MSD type contributions. The thin full curve is derived from the spectrum at 128° by means of eq. (11) and represents the MSC contribution. It is compared with theoretical CN + PE calculations (see text) with \( n_0 = 3 \) (PE part: \( \cdots \cdots \cdots \cdots \cdot \) sum CN + PE: \( \cdots \cdots \cdots \cdots \cdot \)). The arrow indicates the BU threshold separating the BU and \$ \text{Stripping energy regions} \$.
Direct Interactions: BU + stripping + pick-up

\[
\sigma_{\text{DI}} = \sigma_{\text{BU}} + \sigma_{d,p} + \sigma_{d,n}
\]

\[
\sigma_{\text{BU}} = \sigma_{(d,p)} + \sigma_{(d,n)} + \sigma_{(d,\alpha)} + \sigma_{(d,t)}
\]

\[
\sigma_{(d,p)} = \sigma_{(d,p)} + \sigma_{(d,n)}
\]

\[
\sigma_{(d,n)} = \sigma_{(d,n)} + \sigma_{(d,\alpha)} + \sigma_{(d,t)}
\]

\[
\sigma_{(d,\alpha)} = \sigma_{(d,\alpha)} + \sigma_{(d,t)}
\]

\[
\sigma_{(d,t)} = \sigma_{(d,t)} + \sigma_{(d,\alpha)}
\]

\[
\sigma = 10^{\sigma_{\text{DI}}}\text{mb}
\]

\[
E (\text{MeV})
\]

\[
\text{Marilena Avrigeanu}
\]

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