On reaction mechanisms involved in the deuteron-induced surrogate reactions on actinides

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Nuclear Data Request

- ITER, IFMIF, SPIRAL2

Deuteron cross section measurements & theoretical frame completion required for:

Al [1], Cu [2], Nb [3], Fe [4,5], Ni, Cr, Co, Mn, C …. (E_d ~ 60 MeV)

Reliable gas production cross-section data (H, He)
Dosimetry data file for E > 20 MeV (IRDF)

Surrogate Reactions

an indirect approach for determining cross sections for the interaction processes difficult or impossible to measure

Complementary analysis for (d,f) on actinides [6]

Surrogate reactions method

$^{237}\text{Np}(n,\gamma)^{238}\text{Np}$ → Desired Reaction

A + a → C → B + b

$\sigma_{a,b}(E_a, E) = \sigma_a(E_a, E^*) P_b(E^*)$

D + d → C + C → B + b + c

$\sigma_{d,b}(E_d, E^*) = \sigma_d(E_d, E^*) P_b(E^*)$

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Compound-nuclear reaction cross sections from surrogate measurements

Jutta E. Fischer, Jason T. Burke, Frank S. Dietrich, Nicholas D. Saliba, Ian J. Thompson, and Wald Yones

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**Table 4** (Nuclear Physics A13 (1979) 283)

<table>
<thead>
<tr>
<th>Excitation energies of levels in $^{238}\text{Np}$, differential cross sections</th>
<th>135°</th>
<th>14°</th>
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<td>Assignment</td>
<td>1°</td>
<td>1°</td>
</tr>
<tr>
<td>0</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>26.5</td>
<td>5.0</td>
<td>12</td>
</tr>
<tr>
<td>62.0</td>
<td>7.0</td>
<td>12</td>
</tr>
<tr>
<td>88.0</td>
<td>7.0</td>
<td>12</td>
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<tr>
<td>107.0</td>
<td>5.0</td>
<td>13</td>
</tr>
<tr>
<td>132.0</td>
<td>5.0</td>
<td>13</td>
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<tr>
<td>152.0</td>
<td>2.0</td>
<td>10</td>
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<td>10</td>
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<td>319.2</td>
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<td>10</td>
</tr>
<tr>
<td>625.0</td>
<td>0.5</td>
<td>7.0</td>
</tr>
</tbody>
</table>

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**Nuclear Levels in $^{213}\text{Np}$**

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**Nuclear Reactions** $^{238}\text{Np}(n, \gamma) E = 17-650, 2500-5500$ keV; measured $E_1, I_1$; deduced $Q$. $^{213}\text{Np}(d, p) E = 4.7$ MeV; measured $E_2, I_2$. $^{213}\text{Np}$ deduced levels, $K, J, z$, Nilson configurations.
E_d = 15 MeV (C.M. ~ 14 MeV)

BU: deuteron breakup
- Deuteron binding energy: B_d = 2.225 MeV
- \( \varepsilon_{p_{\text{max}}} = E_d - B_d \sim 11.8 \text{ MeV} \)
- BU threshold \( \sim 11.8 \text{ MeV} \)

ST: deuteron stripping (d,p)
- \( Q_{\text{Al(d,p)}} = 5.5 \text{ MeV} \)
- \( \varepsilon_{p_{\text{max}}} \sim E_d + Q_{\text{Al(d,p)}} = 19.5 \text{ MeV} \)

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: \( \cdots \cdots \), sum CN + PE: \( - - - \)) and \( n_0 = 4 \) (PE part: \( \cdots \cdots \cdots \), sum CN + PE: \( \cdots \cdots \cdots \)). The arrow indicates the BU threshold separating the BU and Stripping energy regions.
BREAKUP

\[ d \text{ breakup involvement: } d + ^{93}\text{Nb} \rightarrow ^{95}\text{Mo}^* \]

- Elastic: \(^{93}\text{Nb} + d \rightarrow ^{93}\text{Nb} + n + p\)
- Inelastic: \((^{93}\text{Nb} + n) + p \rightarrow ^{94}\text{Nb} + p\)
- Inelastic: \((^{93}\text{Nb} + p) + n \rightarrow ^{94}\text{Mo} + n\)

Inelastic breakup enhancement:
- \(^{94}\text{Nb} + y + p \rightarrow \text{( }\gamma p \text{ ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{93}\text{Nb} + n + p \rightarrow \text{(np ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{93}\text{Zr} + p + p \rightarrow \text{(2p ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{90}\text{Y} + \alpha + p \rightarrow \text{(ap ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{94}\text{Mo} + y + n \rightarrow \text{(yn ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{93}\text{Mo} + n + n \rightarrow \text{(2n ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{93}\text{Nb} + p + n \rightarrow \text{(pn ch. of } ^{95}\text{Mo}^*\text{)}\)
- \(^{90}\text{Zr} + \alpha + n \rightarrow \text{(an ch. of } ^{95}\text{Mo}^*\text{)}\)
TENDL (PE+CN) 2012, 2013 predictions for d+^{93}Nb


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\[ ^{93}\text{Nb}(d,p)^{94}\text{Nb}^{m} \]
\[ \text{[3+, 6.263min]} \]

\[ ^{93}\text{Nb}(d,x)^{92}\text{Nb}^{m} \]
\[ \text{[2+, 10.15d]} \]

\[ ^{93}\text{Nb}(d,p\alpha)^{90}\text{Y}^{m} \]
\[ \text{[7+, 3.19 h]} \]

\[ ^{93}\text{Nb}(d,2n)^{91}\text{Nb}^{m} \]
\[ \text{[1/2-, 60.86 d]} \]

\[ ^{93}\text{Nb}(d,p\alpha)^{90}\text{Y}^{m} \]
\[ \text{[7+, 3.19 h]} \]
Breakup Cross Sections Parametrizations

Kalbach (2003)

\[ \sigma_{BU}^{p/n} = K_{d,(p,n)} \left( \frac{A^{1/3} + 0.8}{1 + \exp\left(\frac{13 - E_d}{5}\right)} \right)^2, \quad K_{d,p} = 21, \quad K_{d,n} = 18 \]

Avrigeanu+ (2009)

\[ \sigma_{BU}^{p/n} = (0.087 - 0.0066Z + 0.00163ZA^{1/3} + 0.0017A^{1/3}E_d - 0.000002ZE_d^2) \sigma_R \]
\[ \sigma_{EB}^{p/n} = (0.031 - 0.0028Z + 0.00051ZA^{1/3} + 0.0005A^{1/3}E_d - 0.000001ZE_d^2) \sigma_R \]

Kalbach (2010)

\[ \sigma_{BU}^{p/n} = 5.4(D_0)^2 \exp\left(\frac{E_d}{170}\right)[1 + \exp\left(\frac{42 - E_d}{14}\right)]^{-1}, \quad D_0 = 1.2 \frac{5A^{1/3}}{1 + \exp\left(\frac{E_d}{50}\right)} + 1.2 \]


www.tunl.duke.edu/publications/tunlprogress/2003/

Importance of Deuteron Breakup mechanism

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Carpathian Summer School of Physics, July 13 - 26, 2014 @ Sinaia, Romania

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\[ \text{d} + ^{231}\text{Pa}: \ \text{d breakup involvement} \]

\[ ^{231}\text{Pa}(d,3n)^{230}\text{U} \]

\[ E_{th}^{d,3n} = 9.347 \text{ MeV} \]

\[ \sigma \ (\text{mb}) \]

\[ 10^0 \ 10^1 \ 10^2 \]

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

\[ 10 \ 12 \ 14 \ 16 \ 18 \ 20 \]

\[ \text{d breakup: } \text{d} + ^{231}\text{Pa} \]

\[ E_{p,n}(E_d) = 0.5 \frac{A+1}{A+2} E_d + 0.5 \frac{A+1}{A} (-B_d \pm \frac{Z}{9.5}) \]

\[ Morgenstern et al. (2009) \]

\[ ^{231}\text{Pa}(p,2n)^{230}\text{U} \]

\[ E_{th}^{p2n} = 7.073 \text{ MeV} \]

\[ \sigma \ (\text{mb}) \]

\[ 10^0 \ 10^1 \ 10^2 \]

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

\[ 10 \ 12 \ 14 \ 16 \ 18 \ 20 \ 22 \ 24 \]

\[ \text{Morgenstern et al. (2008)} \]

\[ ^{231}\text{Pa+d} \rightarrow ^{231}\text{Pa} + n + \gamma \]

\[ 232\text{U}^* \rightarrow 2n \rightarrow 230\text{U} \]
Breakup deuteron effects on $^{231}\text{Pa}(d,3n)^{230}\text{U}$ reaction

Investigation of deuteron breakup and deuteron-induced fission on actinide nuclei at low incident energies

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The dominance of the deuteron breakup mechanism around the Coulomb barrier is shown by an analysis of the $^{231}\text{Pa}(d,3n)^{230}\text{U}$ reaction excitation function, while the same attribute was found within a former assessment.

\[ \sigma_{\text{BF}}^p(E_d) = \sigma_{\text{BF}}^p(E_d) \int dE_p \frac{\sigma_{(p,x)}(E_p) \left( \frac{1}{2\pi} \right)^{1/2} \exp \left[ - \frac{(E_p - E_p^0(E_d))^2}{2w^2} \right]}{\sigma_R^p} \]
CONCLUSIONS

\[ ^{54}\text{Fe}(d,n)^{55}\text{Co} \]

\[ ^{58}\text{Fe}(d,p)^{59}\text{Fe} \]

\[ ^{27}\text{Co}(d,x)^{58}\text{Co} \]

\[ ^{93}\text{Nb}(d,p)^{94}\text{Nb}^m \]

\[ ^{59}\text{Co}(d,x)^{58}\text{Co} \]

\[ ^{93}\text{Nb}(d,x)^{92}\text{Nb}^m \]
Reduction factor due to DIRECT INTERACTIONS

The deuteron total reaction cross section that remains to be available for the PE+CN mechanisms has to be corrected for the incident flux leakage through DI processes, i.e. the breakup, stripping and pick-up, by a reduction factor:

\[
frac{1}{\sigma_R} = 1 - \frac{\sigma_{BU} + \sigma_{(d,n)} + \sigma_{(d,p)} + \sigma_{(d,t)} + \sigma_{(d,\alpha)}}{\sigma_R}
\]

\[= 1 - \frac{\sigma_{DI}}{\sigma_R}\]

\[(8)\]

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

\[\text{d+}^{54}_{26}\text{Fe} \quad \text{d+}^{56}_{26}\text{Fe} \quad \text{d+}^{57}_{26}\text{Fe} \quad \text{d+}^{58}_{26}\text{Fe}\]
ELASTIC BREAKUP

CHECKING the correctness of parameterization EXTRAPOLATION

PHYSICAL REVIEW C 82, 037601 (2010)

Improved deuteron elastic breakup energy dependence via the continuum-discretized coupled-channels method

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Experimental elastic-scattering angular distributions for deuteron interaction with $^{63}$Cu and $^{93}$Nb targets are compared with calculations performed within the continuum-discretized coupled-channels (CDCC) method, in which coupling to breakup channels is explicitly taken into account. The calculated elastic breakup cross sections are compared with the predictions of an empirical parametrization for a wide range of deuteron incident energies. The good agreement between the calculations and the systematics at the energies where data are available indicates that the CDCC method permits a useful assessment of empirical parametrizations and provides useful guidance for the extrapolation of these parametrizations beyond the energies formerly considered.
Elastic breakup: phenomenology versus CDCC

Three-body Hamiltonian
Two-body projectile - Target

\[ H = K_r + K_R + V_{np}(r) + U_n(R - r/2) + U_p(R + r/2), \]

Elastic breakup treated as an INELASTIC EXCITATION of the projectile (Nuclear & Coulomb interactions) through the Coupled Channels approach

Essence of CDCC
- truncated continuum spectrum at \( E^{\text{max}} \)
- divided into a finite number of bins: \( i = 0 \) (g.s.), \( N \)

Each bin represented by a single, averaged w.f.:

\[ \{ |\phi_i\rangle \}_{i=1}^N \xrightarrow{\text{ind}} \frac{1}{\sqrt{D_i}} \int_{\epsilon_{i-1}}^{\epsilon_i} |\phi(E)\rangle \, dE, \quad i = 1, \ldots, N, \]

\( (V_{np} = V_0 e^{-(r/r_d)^2}; \quad V_0 = 72.15 \text{ MeV}; \quad r_d = 1.484 \text{ fm}) \)

M. Kamimura et al., Prog. Theor. Phys. Suppl. 80 (1986) 1

\[ \Psi(\xi, R) = \sum_{i=0}^N |\phi_i(\xi), \chi_i(R)\rangle, \]

where

\( \chi_i(R) \) channel wave functions:
- \( i=0 \): elastic channel
- \( i>0 \): breakup channel
Elastic breakup: phenomenology versus CDCC

Total Wave Function

\[ |\Psi(\xi, R)\rangle = \sum_{i=0}^{N} |\phi_i(\xi), \chi_i(R)\rangle \]

Coupled Channels calculations:

\[ i=0: \text{elastic channel} \]
\[ \sum \sigma_i = \sigma_{\text{CDCC}}, \ i>0 \]

Marilena Avrigeanu

Nuclei Produced in Reactor

RED  Long-lived Minor Actinide
BLUE Fissile Nuclei

→ Decay within a few days

238Pu → 239Pu → 240Pu → 241Pu → 242Pu → 243Pu

236Np → 237Np → 238Np → 239Np

234U → 235U → 236U → 237U → 238U → 239U