Direct processes effects on deuteron activation cross sections

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Abstract. An extended analysis of reaction mechanisms involved in deuterons interaction with target nuclei from $^{27}$Al till $^{231}$Pa, at incident energies up to 60 MeV, is presented. Increased attention is devoted to direct processes, concerning the breakup, stripping, and pick–up contributions to the deuteron activation cross sections. Finally, the pre-equilibrium and evaporation cross sections, corrected for the initial flux leakage towards direct processes, have completed the deuteron interaction analysis. The overall agreement of the measured data and model calculations proves the correctness of nuclear mechanism description.

1. Introduction

The request of the accurate activation cross sections by several on-going strategic research programmes for international large-scale facilities as ITER [1], IFMIF [2], and SPIRAL-2 [3] focus the attention on the deuteron data, less extensive and mature than the neutron ones. Description of the deuteron interaction process is still a challenge for basic research, the difficulties to describe the complex deuteron–induced reaction data in terms of the usual reaction mechanism models being the result of the high enhancement of a variety of reactions, even at low bombarding energies, induced by the deuteron–breakup nucleons. An increased attention is devoted in the present work to direct interactions, namely the breakup, stripping, and pick–up mechanisms (e.g., Refs. [4, 5, 6, 7, 8, 9, 10]), usually neglected or very poorly taken into account in spite of their importance. For energies below and around the Coulomb barrier, the interaction of deuterons with target nuclei proceeds largely through direct reactions (DR) mechanism, while pre-equilibrium (PE) and evaporation (CN) processes become more important with the incident energy increase. Moreover, the deuteron breakup (BU) mechanism is quite important along the whole incident-energy range [5, 6, 7, 9, 10].

2. Deuteron breakup

The physical picture of the deuteron breakup, in the Coulomb and nuclear fields of the target nucleus, considers two distinct chains. These are the elastic–breakup (EB) in which the target nucleus remains in its ground state and none of the deuteron nucleons interacts with it, and the inelastic–breakup or breakup fusion (BF), where one of the deuteron nucleons interacts with the target nucleus while the remaining one is detected.

An empirical parametrization of the total proton-emission breakup fraction of the deuteron total reaction cross section $\sigma_R$, $f_{BU}^{(p)} = \sigma_{BU}^{p}/\sigma_R$, and elastic breakup fraction, $f_{EB} = \sigma_{EB}/\sigma_R$, have been obtained [4] by analysis of the experimental systematic [11] of the proton-emission
Figure 1. Comparison of measured deuteron activation cross sections ([5, 7, 10, 9] and references therein), complete analysis results (thick solid curves) taking into account the BF enhancement (dashed curves) and PE+CN contributions (thin solid curves), and the TENDL-2012 evaluations (dotted curves) (see text).

spectra and angular distributions of deuteron–induced reactions on target nuclei from Al to Pb, at incident energies from 15 to 80 MeV. Their dependence with respect to the charge \( Z \) and atomic number \( A \) of the target nucleus, as well as deuteron incident energy \( E \) is [4]:

\[
\frac{f^{(p)}_{BU}}{\sigma} = 0.087 - 0.0066Z + 0.00163Z A^{1/3} + 0.0017A^{1/3} E - 0.000002Z E^2, \tag{1}
\]

\[
\frac{f_{EB}}{\sigma} = 0.031 - 0.0028Z + 0.00051Z A^{1/3} + 0.0005A^{1/3} E - 0.000001Z E^2. \tag{2}
\]

Consequently, it results the inelastic–breakup fraction \( f^{\sigma}_{BF} = f^{\sigma}_{BU} - f_{EB} \).

Overall, there are actually two opposite effects of the deuteron breakup on the deuteron activation cross sections that should be considered. Firstly, the reaction cross section \( \sigma_R \), that is shared among different outgoing channels, is reduced by the value of the total breakup cross section \( \sigma_{BU} \). On the other hand, the BF component, where one of deuteron constituents interacts with the target nucleus leading to a secondary composite nucleus, brings contributions to different reaction channels [4, 5, 6, 7, 9]. Thus, the absorbed proton or neutron, following the deuteron breakup, contribute to the enhancement of the corresponding \((d, xn)\), respectively \((d, xp)\) reaction cross sections.

In order to calculate the BF enhancement of, e.g., the \((d, xn)\) reaction cross sections, the proton BF cross section should be multiplied by the ratios \( \sigma_{(p,xn)} / \sigma_R \) corresponding to this reaction, convoluted with the Gaussian line shape distribution of the breakup protons energy for a given deuteron incident energy \( E_d \). Finally the integration over the breakup proton energy,
Figure 2. Comparison of measured deuteron activation cross sections ([5, 7, 10] and references therein), complete analysis results (thick solid curves) taking into account the BF enhancement (dashed curves), DR (dot-dashed and dot-dot-dashed curves) and PE+CN contributions (thin solid curves), and the TENDL-2012 evaluations (dotted curves) (see text).

\[ E_p, \text{ led the corresponding BF enhancement cross section } [7, 6, 9]: \]

\[ \sigma^p_{BF}(E_d) = \sigma^p_{BF}(E_d) \int dE_p \frac{\sigma^{p,x}_{(p,x)}(E_p)}{\sigma_R} \frac{1}{2\pi w} \exp \left[-\frac{(E_p - E_0^p)(E_d)}{2w^2} \right], \]  

(3)

where \( \sigma^p_{BF} \) is the proton total reaction cross section, \( x \) stands for various \( \gamma, n, d \), or \( \alpha \) outgoing channels, while the Gaussian distribution parameters, \( w \) and \( E_0^p \), are given by Kalbach [12].

The BF enhancements brought by the breakup neutron and proton interactions with \(^{27}\)Al, \(^{54}\)Fe, \(^{63,65}\)Cu, \(^{93}\)Nb and \(^{231}\)Pa target nuclei are shown by dashed curves in Figs. 1 and 2.

### 3. Transfer reactions

Apart from the breakup contributions to deuteron interaction, an increased attention has to be devoted to the DR very poorly accounted so far in deuteron activation analysis. The calculations of the DR mechanisms contributions, like stripping and pick–up, that are important at the low energy side of the \((d, p)\), \((d, n)\), and \((d, t)\) excitation functions [4, 5, 6, 7, 8, 10], have been performed in the frame of the CRC formalism by using the code FRESCO [13]. The \( n-p \) interaction in deuteron [14] as well as \( d-n \) interaction in triton [15] are assumed to have a Gaussian shape, while the transferred nucleon bound states were generated in a Woods–Saxon real potential [4, 7, 10]. A particular note should concern the pick–up essential contribution to the total \((d, t)\) activation cross section, at the energies between its threshold and those for the \((d, nd)\) and \((d, 2np)\) reactions that lead to the same residual nucleus. Thus, the pick–up component of the \((d, t)\) excitation function is critical for the data description at deuteron.
incident energies lower than 10 MeV, where PE and CN contributions are almost negligible. The importance of the stripping and pick-up reactions for the deuteron interaction process is evidenced in Fig. 2.

4. Statistical particle emission
Following the decay path, the PE and CN reaction cross sections have been calculated by means of the code STAPRE-H [17], taking into account the breakup and DR results discussed above. A consistent local parameter set [5, 7, 10] has also been used. The mark BU, rather than BF, for the sum of various contributions to an activation cross section in Figs. 1 and 2 underlines the consideration of both breakup effects, i.e., the overall decrease of $\sigma_R$, as well as the BF enhancement. On the other hand, the apparent discrepancies between the experimental data and corresponding TENDL-2012 [16] evaluation, shown in Figs. 1 and 2 too, stress out the effects of disregarding the direct processes within TENDL.

5. Conclusions
The overall agreement between the measured data and model calculations supports the description of nuclear mechanisms taken into account for the deuteron-nucleus interaction. However, while the associated theoretical frames are already settled for DR, PE and CN mechanisms, an increased attention should be given to microscopical description of the BF component. The improvement of deuteron breakup description requires complementary experimental studies involving deuterons, protons and neutron induced reactions too.

Acknowledgments
This work was partly supported by a grant of the Romanian National Authority for Scientific Research, CNCS - UEFISCDI, project No. PN-II-ID-PCE-2011-3-0450, and by Fusion for Energy through the Specific Grant Agreement GRT-168.01.

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