

Consistent Analysis of the Nuclear Reaction Mechanisms Involved in Deuteron-induced Activation at Low and Medium Energies

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A complete analysis of the nuclear reaction mechanisms involved within $^{nat}\text{Fe}(d, x)^{55}\text{Co}$ reaction, *i.e.* the breakup, stripping, pick-up, pre-equilibrium emission, and evaporation from fully equilibrated compound nucleus, is presented in order to highlight the importance of direct mechanisms that are not appropriately considered in the evaluation procedure. The overall agreement between the measured data and model calculations confirms the correctness of nuclear mechanism description taken into account stressing out the omissions of the evaluation procedures.

I. INTRODUCTION

Description of the deuteron interaction process is still a challenge for the basic research, while the accurate activation cross sections are highly requested by several ongoing strategic research programs as ITER (International Thermonuclear Experimental Reactor) [1], IFMIF (International Fusion Material Irradiation Facility) [2], and SPIRAL-2 (Système de Production d'Ions Radioactifs en Ligne - generation 2) [3]. Actually, it is critical for selecting and validating the best structural materials and a number of key technologies. Since the actual experimental and evaluated data for deuteron-induced reactions are less extensive and accurate than for neutrons, further measurements are presently planned. Improved model calculations should describe as well the experimental data and bring the deuteron data libraries at the standard of the neutron data files.

The deuteron interaction at incident energies below and around the Coulomb barrier proceeds largely through direct reaction (DR) mechanisms of stripping and pick-up, while the pre-equilibrium emission (PE) and evaporation from fully equilibrated compound nucleus (CN) become important with the increase of the incident energy. Moreover, in addition to these well known reaction mechanisms, the specific deuteron breakup (BU) process plays an important role that increases the complexity of the deuteron interaction analysis in the whole incident energy range due to the large variety of reactions initiated by the breakup nucleons [4–10]. The intricate nuclear model analysis of the $^{nat}\text{Fe}(d, xn)^{55}\text{Co}$ reaction represents a good example in this respect, in order to

illustrate the multifaceted of the deuteron interactions involving breakup, stripping, PE and CN reaction mechanisms. Due to the energy thresholds for the rest of the Fe isotopes, the reaction $^{54}\text{Fe}(d, n)^{55}\text{Co}$ is the only contributing to the $^{nat}\text{Fe}(d, xn)^{55}\text{Co}$ excitation function for incident energies ≤ 18.3 MeV. Therefore the effects of breakup and stripping mechanisms are better emphasized in the absence of strong contributions coming from the 91.8% most abundant ^{56}Fe isotope. On the other hand, the comparison of the experimental data with the predictions of the most recent TENDL-2012 library [11] has pointed out the weaker treatment of the direct interactions (DI), namely the breakup, stripping and pick-up processes.

II. BREAKUP CROSS SECTIONS

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

The former parameterization of the total neutrons, σ_{BU}^n , and protons, σ_{BU}^p , emission breakup cross sections, was given as a function of the deuteron incident energy E_d and atomic number A of the target nucleus by Kalbach [12, 13] (Fig. 1).

Additional features of the breakup cross section parameterization have been considered by Avrigeanu *et al.* [4], as the dependence on the target charge number Z and deuteron reaction cross section σ_R , while distinct forms

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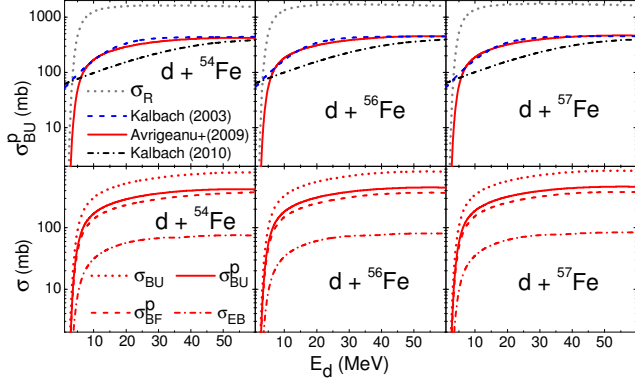


FIG. 1. The energy dependence of (top) the deuteron total reaction cross sections (dotted curves) [14] and BU proton-emission cross sections given by parameterizations of Refs. [4] (solid curves), [12] (dashed curves), and [13] (dash-dotted curves), and (bottom) the total BU (dotted curves), BU nucleon-emission (solid curves), BF (dashed curves) and EB (dash-dotted curves) cross sections [4], for deuteron interactions with $^{54,56,57}\text{Fe}$ nuclei.

are provided for the total BU nucleon emission, $\sigma_{BU}^{p/n}$, as well as the elastic (EB), σ_{EB} . Assuming equal breakup cross sections for proton and neutron emission, results the inelastic (BF) components, $\sigma_{BF}^{p/n}$ [4]

$$\sigma_{BF}^{(p/n)} = \sigma_{BU}^{(p/n)} - \sigma_{EB}, \quad (1)$$

leading to the total breakup (BU) cross section

$$\sigma_{BU} = \sigma_{EB} + 2\sigma_{BF}^{p/n}. \quad (2)$$

The latest breakup parameterization, given by Kalbach within the FENDL-3 project [13], considers also equal BU cross sections for proton and neutron emission.

As it can be seen in Fig.1, both Kalbach's parameterizations [12, 13] predict similar higher values of total proton breakup cross sections at the lowest incident energies, exceeding σ_R , the latest one [13] providing also too lower values for E_d from ~ 10 to ~ 40 MeV. Regardless the differences between Kalbach [12] and Avrigeanu *et al.* [4] predictions at low deuteron energies, it results a similar trend of the two approaches for the total protons breakup excitation functions within the energy range ~ 10 –60 MeV.

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 σ_R , that is shared among different outgoing channels, is reduced by the value of the total breakup cross section σ_{BU} . On the other hand, the inelastic-breakup 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, 7–10]. Thus, the absorbed proton or neutron following the deuteron breakup, contributes

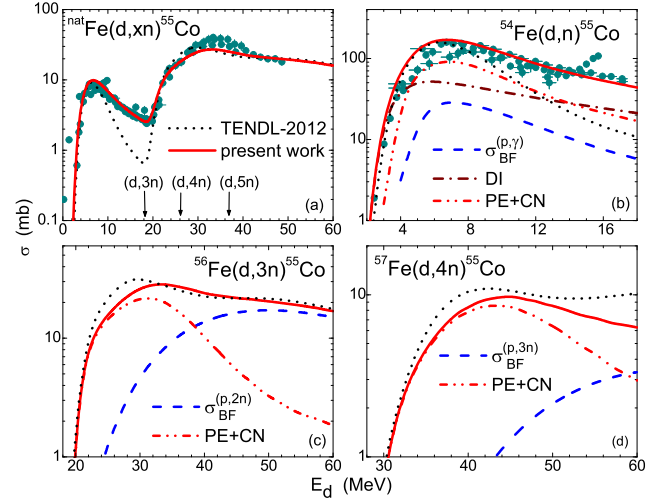


FIG. 2. Comparison of the measured [15], TENDL-2012 predicted (dotted curves), and presently calculated cross sections (solid curves) including the inelastic breakup enhancement (dashed curves), for (a) the $^{nat}\text{Fe}(d,x)^{55}\text{Co}$, (b) $^{54}\text{Fe}(d,n)^{55}\text{Co}$, (c) $^{56}\text{Fe}(d,3n)^{55}\text{Co}$, and (d) $^{57}\text{Fe}(d,4n)^{55}\text{Co}$ reactions.

to the enhancement of the corresponding (d,xn) , respectively (d, xp) reaction cross sections. In order to calculate the inelastic breakup enhancement of, *e.g.*, the (d,xn) reaction cross sections, the proton inelastic-breakup cross section, σ_{BF}^p , [4, 5, 7–10] should be multiplied by the ratios $\sigma_{(p,x)}/\sigma_R^p$, corresponding to the above-mentioned enhancing 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 protons energy led the inelastic breakup enhancement cross section [7–10]

$$\sigma_{BF}^{p,x}(E_d) = \sigma_{BF}^p(E_d) \int_0^{E_{BU}^{max}} dE_p \frac{\sigma_{(p,x)}(E_p)}{\sigma_R^p} \frac{1}{(2\pi)^{\frac{1}{2}}w} \exp\left[-\frac{(E_p - E_p^0(E_d))^2}{2w^2}\right], \quad (3)$$

where σ_R^p is the proton total reaction cross section, x stands for various, *e.g.*, γ , n , d , or α , outgoing channels, while E_p^0 and w are the centroid and standard deviation, respectively, of the above-mentioned BU proton-energy Gaussian distribution [12].

The inelastic breakup enhancements brought by BU protons during the deuteron interaction with the target nucleus ^{nat}Fe (Fig. 2), namely through the $^{54}\text{Fe}(p,\gamma)^{55}\text{Co}$, $^{56}\text{Fe}(p,2n)^{55}\text{Co}$, and $^{57}\text{Fe}(p,3n)^{55}\text{Co}$ reactions that populates the residual nucleus ^{55}Co are shown in Figs. 2(b,c,d). The Gaussian distributions of the breakup proton energies have been used as given by Kalbach [12] related parameters.

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