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Role of breakup and direct processes in deuteron-induced reactions at low energies

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Background: Recent studies of deuteron-induced reactions around the Coulomb barrier B pointed out that numerical calculations for deuteron-induced reactions are beyond current capabilities. The statistical model of nuclear reactions was used in this respect since the compound-nucleus (CN) mechanism was considered to be responsible for most of the total-reaction cross section σ_R in this energy range. However, specific noncompound processes such as the breakup (BU) and direct reactions (DR) should be also considered for the deuteron-induced reactions, making them different from reactions with other incident particles.
Purpose: The unitary and consistent BU and DR consideration in deuteron-induced reactions is proved to yield results at variance with the assumption of negligible noncompound components.
Method: The CN fractions of σ_R obtained by analysis of measured neutron angular distributions in deuteron-induced reactions on ^{27}Al, ^{56}Fe, ^{63,65}Cu, and ^{89}Y target nuclei, around B, are compared with the results of an unitary analysis of every reaction mechanism. The latter values have been supported by the previously established agreement with all available deuteron data for ^{27}Al, $^{54,56-58,\mathrm{nat}}$Fe, $^{63,65,\mathrm{nat}}$Cu, and ^{93}Nb.
Results: There is a significant difference between the larger CN contributions obtained from measured neutron angular distributions and calculated results of an unitary analysis of every deuteron-interaction mechanism. The decrease of the latter values is mainly due to the BU component.
Conclusions: The above-mentioned differences underline the key role of the breakup and direct reactions that should be considered explicitly in the case of deuteron-induced reactions.

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Motivation. Recent studies [1,2] of deuteron-induced reactions around the Coulomb barrier B pointed out that numerical calculations for deuteron-induced reactions are beyond current capabilities although their case might contain interesting physics [2]. The statistical Hauser-Feshbach model has been used within these studies, as the main tool to calculate reaction cross sections at low incident energies. The compound-nucleus (CN) mechanism has been considered to be responsible for at least 90% of the total-reaction cross section in this energy range [1]. However, specific noncompound processes should be considered for the deuteron-induced reactions, making them different from reactions with other incident particles. Thus, the deuteron breakup (BU) was proved long ago to be quite important (e.g., Refs. [3–5] and references therein) since it is also followed by various reactions induced by the BU nucleons.

The assumption of lower noncompound components of the neutron spectra measured at backward angles with 5- to 7-MeV deuterons on ^{63,65}Cu and ^{89}Y [1,2] thereby led to contradictory results: (i) finding that more than 70% of the total-reaction cross sections σ_R are determined by the CN mechanism, in agreement with previous results for similar reactions on ^{27}Al and ^{56}Fe target nuclei [6], and (ii) failure to describe the proton-emission cross sections. Statistical model calculations alone have also been shown [7] to not be able to reproduce recent surrogate deuteron-induced reaction data.

Broader approach. By contrast, we compare here the CN fractions from the above-mentioned studies [1,2,6] with the results obtained previously through a broader, unitary, and consistent analysis of the available data for deuterons incident on ^{27}Al [8,9], $^{54,56-58,\mathrm{nat}}$Fe [10], $^{63,65,\mathrm{nat}}$Cu [11], and ^{93}Nb [12]. Since Refs. [8–12] include detailed descriptions of the involved model assumptions and consistent parameters sets that were either established or validated using various independent data, we briefly mention here only the main lines of these analyses.

First, the available measured elastic-scattering angular distributions for the above-mentioned target nuclei were used in a deuteron optical model potential (OMP) analysis. Then, the same deuteron OMP parameters were used within various reaction mechanism models concerned with the description of all available deuteron data for the same nuclei.

Second, appropriate but still quite different treatments concerned the direct interaction (DI) processes. Thus, the BU cross sections have been obtained from an empirical parametrization [8] of both the elastic breakup (EB), in which the target nucleus stays in its ground state and both of the deuteron constituents fly apart [4], and the total BU, including also the inelastic breakup or breakup fusion (BF), where one of these deuteron constituents interacts nonelastically with the target nucleus [3]. On the other hand, the contributions of the (d,p) and (d,n) stripping and (d,t) and (d,α) pickup direct reactions (DR) were calculated using the distorted-wave Born approximation (DWBA) method within the highly developed coupled-reaction channels (CRC) formalism and the advanced code FRESCO [13]. The corresponding transferred nucleon and deuteron bound-state parameters as well as spectroscopic factors have been taken from DWBA analyses carried out for each specific DR process, with details given elsewhere [8–12].

Third, the deuteron OMP total-reaction cross section was corrected by subtraction of the BU+DR cross sections, and then used in the assessment of the statistical emission at

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pre-equilibrium (PE) or from the fully equilibrated CN. An updated version of the code STAPRE-H [14] was used in this respect as well as local consistent parameters that were obtained or checked through the analysis of various independent experimental data, in advance of the deuteron cross-sectional analysis. The default predictions of the well-known TALYS code [15] were also used within a useful comparison of the local and global approaches [9,11,12]. The BU processes are taken into account in TALYS through the addition to the usual PE exciton model results (Ref. [16] and references therein) of the Kalbach's parametrization of the total BU cross section [17]. We may add, for the sake of completeness, that the PE geometry-dependent hybrid model (Ref. [18] and references therein) has been used within the STAPRE-H code for nucleon and α-particle PE emission including angular-momentum conservation and advanced partial level densities [19].

Fourth, we also took into account the decay of the compound nuclei formed in the interactions with the same target nucleus of the nucleons that follow the BF process. Additional contributions are thus brought to the population of various reaction channels of the above-mentioned deuteron-induced reactions. However, the reactions induced by the BF nucleons are related to the deuteron BU process since they are just subsequent to this one, and lead to different compound nuclei than the incident deuterons do. The partition of the BF cross section among various residual nuclei is triggered by the energy spectra of the BF nucleons and the excitation functions of the CN reactions induced by these nucleons on the target nuclei [10–12,20]. Last but not least, the excitation energies of the CNs which are formed by the incident deuterons and the BF nucleons, respectively, are quite different. The latter could be lower than the former by even a factor of ~ 2 for the deuteron energies of Refs. [1,2,6]. Therefore, the emitted particles following the decay of the CN from the reactions induced by either the incident deuterons or the BF nucleons, which interact with the target nuclei, populate different residual nuclei and have also quite different energy spectra which should be distinctly considered.

The comparison of all available deuteron data and the sum of calculated contributions of the BU, DR, PE, and CN components of the deuteron interaction with the above-mentioned ^{27}Al, $^{54,56-58,\mathrm{nat}}$Fe, $^{63,65,\mathrm{nat}}$Cu, and ^{93}Nb targets is shown as detailed as possible in Refs. [8–12].

Comparison of CN fractions. The accuracy of the unitary and consistent consideration of the BU, DR, PE, and CN processes has been proved by the agreement of the calculated and all available reaction data of deuterons incident on ^{27}Al, $^{54,56-58,\mathrm{nat}}$Fe, $^{63,65,\mathrm{nat}}$Cu, and ^{93}Nb targets [8–12]. Therefore, in the following we compare only the corresponding ratios of the CN cross sections to σ_R and the similar values obtained by analysis of measured neutron angular distributions [1,2,6]. These ratios are shown by the solid curves and symbols, respectively, in Figs. 1(a), 1(c), 2(a), 2(c), and 3(a). The similar ratios but for the DI and PE components are also included in these figures in order to point out the need to take them into account. Moreover, the corresponding cross sections for each DI process are shown in Figs. 1(b), 1(d), 2(b), 2(d), and 3(b), for a better understanding of the various contributions to the DI component of σ_R.

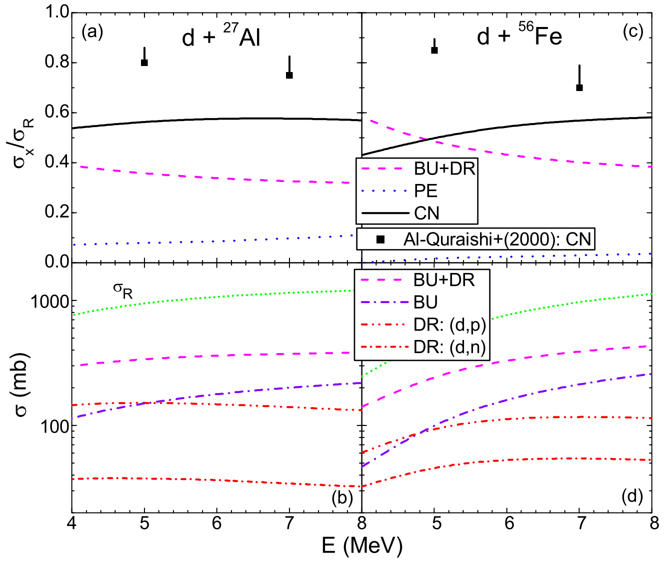

FIG. 1. (Color online) (a,c) Comparison of the CN fraction of the total-reaction cross section σ_R, obtained by analysis of measured neutron angular distributions in deuteron-induced reactions on (a) ^{27}Al and (c) ^{56}Fe target nuclei [6] around the Coulomb barrier, and the calculated values [9,10] of this fraction (solid curves) as well as for the BU+DR (dashed curves) and PE (dotted curves) processes. (b,d) The corresponding calculated cross sections [9,10] of either the BU+DR components sum (dashed curves) or the distinct BU (dash-dotted curves), where (d,p) and (d,n) are stripping direct reactions (dash-dot-dotted and short dash-dotted curves, respectively), while σ_R values are also shown (short-dotted curves).

The comparison shown in Figs. 1–3 points out altogether a significant difference between the larger CN contributions obtained by analysis of measured neutron angular distributions

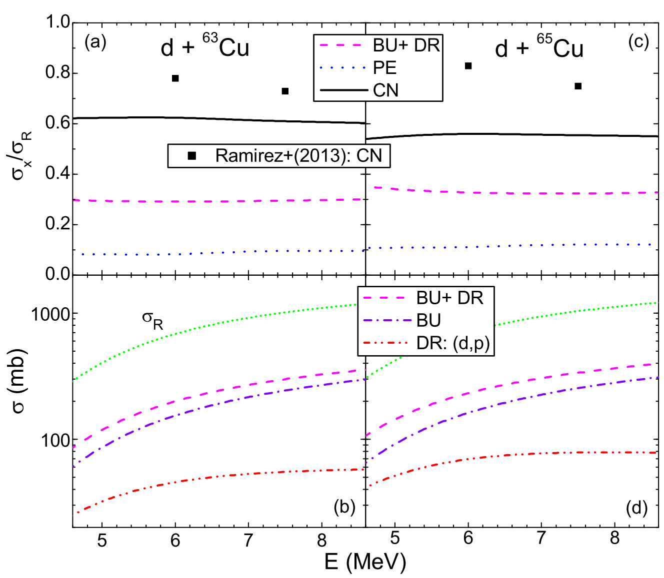

FIG. 2. (Color online) Same as Fig. 1 but for the target nuclei ^{63,65}Cu, with the measured neutron angular distributions of Ref. [1], and calculations of Ref. [11].

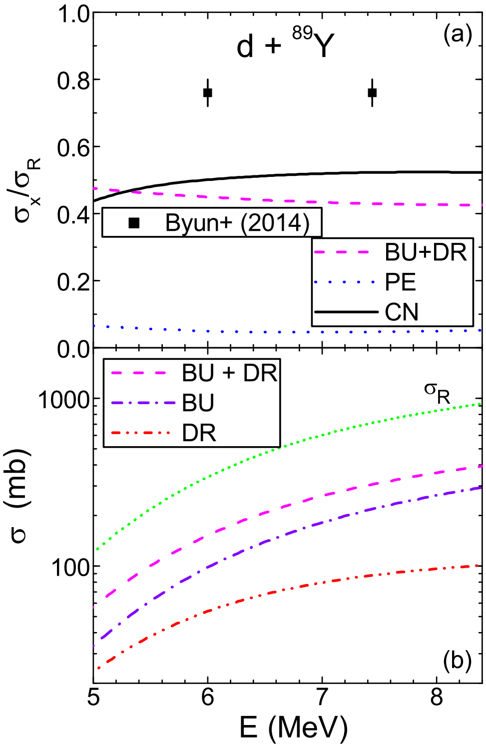

FIG. 3. (Color online) Same as Fig. 1 but for ^{89}Y nucleus, with measured neutron angular distributions of Ref. [2], and DR calculations [12] for the similar odd-even neighboring nucleus ^{93}Nb.

[1,2,6], and the calculated values following the unitary analysis of every deuteron-interaction mechanism. The lower values are due to the significant BU component, which has been not taken into account by the analyses performed within Refs. [1,2,6].

A particular note should concern the prevention of the BU double counting in the case of the deuteron data analysis for the iron isotopes [10] that was carried out by using only the code TALYS for the account of the PE+CN contributions. It was carried out by overruling the use of the BU parametrization of Kalbach [17] and involving the above-mentioned parametrization [8] in a way similar to the case of using the code STAPRE-H. Most recently [21] the latter parametrization was added as an option in TALYS, that was used to obtain the present results for deuterons incident on ^{89}Y.

In the particular case of the CN contribution for the target nucleus ^{89}Y, shown in Fig. 3, the following details should be included. The deuteron σ_R values have been obtained using the optical potential of Daehnick *et al.* [22]. The DR fraction of σ_R which was obtained through the detailed analysis of all available data for deuterons incident at the same incident energies on the similar odd-even neighboring nucleus ^{93}Nb [12] has also been considered here. Since the main contribution to the BU+DR cross-section sum is brought by the BU term, the eventual effect of this DR approximation has been assumed to be minor. The similar values obtained for the DR contribution in the cases of ^{56}Fe and ^{63,65}Cu target nuclei (Figs. 1 and 2) have supported this assumption as well.

Deuteron BU role. Essentially, the authors of Refs. [1,2] claimed that their results were obtained by using the phenomenological Kalbach formula for the continuum angular distribution in nucleon- and α-particle-induced reactions [5]. However, neither Eqs. (3) nor (10) of this reference work nor the corresponding parameters were involved in Refs. [1,2]. Instead, simplified forms of the Kalbach's Eqs. (1) and (2) [5] were introduced in Refs. [1,2] as well as different slope parameters of the forward-peaked and symmetric components of the angular distributions. Actually, the use of their own parameters obtained by fit of the measured neutron angular distributions could be able to increase the accuracy of the final results of Refs. [1,2]. However, it was not taken into account that Kalbach did not include the deuteron-induced reactions in her valuable systematics just because of the expected significant contributions from the projectile BU processes [5]. Thus, Kalbach noted that the only aim with reference to deuteron-induced reactions was to see how well her parametrization can do for these reactions, and her results "perhaps surprisingly, ... account quite well for the 25 MeV data, except, of course, for the breakup cross section in the proton channel."

On the other hand, a similar analysis but for ^{27}Al and ^{56}Fe target nuclei [6] did properly consider the so-called one-step reaction which results in the dissociation of the deuteron without CN forming. Thus, by taking into account the peaks in the neutron and proton spectrum which sum to the incident energy minus the deuteron-binding energy of ~ 2.2 MeV, a corresponding cross section of about 15 mb was found for each target at each energy. However, this process corresponds actually only to the elastic BU, which is by far smaller than the inelastic BU (e.g., Refs. [3,8]). The role of the BF processes was particularly underlined even by Kalbach's remark that PE reactions induced by one of the BU nucleons would be "a possible mechanism to explain significant forward angle cross sections" [5].

It should be also pointed out that the deuteron DR effects are moderate at the deuteron energy of 25 MeV, where Kalbach systematics's check made use of the available data. Actually, these BU+DR effects are well enlarged just around B, i.e., within the energy range of the data of Refs. [1,2,6]. Therefore, the Kalbach's warning about these effects should receive an even increased consideration at the energies where the present comparison is carried out. On the other hand, we strengthen the conclusion of Byun *et al.* [2] that similar theoretical investigations of residual-nuclei level densities should be continued for reactions induced by projectiles other than deuterons.

The energy dependence of CN contribution. Contrary to the expectation of Ramirez *et al.* [1] for a decreasing CN contribution with the deuteron-energy increase, this contribution is slightly increasing with energy since both the major BU and especially the DR component have a slower increase with energy than σ_R. Most significant in this respect are the maxima of the (d,p) and (d,n) stripping excitation functions around 6–8 MeV. This energy dependence of the CN fraction around B is obvious for ^{56}Fe and ^{89}Y target nuclei (Figs. 1 and 3), while otherwise a rather constant value is closer to a former ~50% estimation of the same authors for medium-mass nuclei [23].

In summary, there are key differences between the CN components established by analysis of measured neutron angular distributions, in deuteron-induced reactions around the Coulomb barrier [1,2,6], and the results of an unitary analysis of every deuteron-interaction mechanism [8–12,24]. Actually, these differences may account for the failure to describe the neutron spectra from 7.5-MeV deuteron interaction with ^{63,65}Cu [1], or proton spectra corresponding to 6-MeV deuterons on ^{89}Y [2]. It seems that use of the Hauser-Feshbach formalism alone within deuteron-induced reactions cannot be as successful as, e.g., Kleinfeller *et al.* [3] proved to be the unitary BU+DR+PE+CN analysis of the whole double differential cross sections. Nevertheless, the use of the more realistic CN cross sections following the deuteron-interaction unitary and consistent analysis could improve the nuclear level densities which result from statistical neutron evaporation spectra [1,2,6] as well as the results of the surrogate-reaction method [7].

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