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(n, d) – REACTIONS ON MEDIUM MASS NUCLEI

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Abstract

An analysis is made of the various mechanisms contributing to the (n, d) reaction on the ^{58}Ni, ^{63}Cu and ^{65}Cu nuclei at incident energies up to $15MeV$. It is shown that the main contribution is given by the pick-up process. The statistical contributions are small, especially for ^{65}Cu. A model of the (n, d) knock-out reaction in which restrictions on the available phase space for the proton and the neutron in the deuteron after the knock-out are imposed by a Pauli-blocking function is suggested and applied. The model is close to the quasi-deuteron photo- absorption one and the (n, α) knock-out model previously developed. It is shown that the knock-out contribution calculated within this model is generally small, but it leads to some improvement of the description of the existing data for the (n, d) reaction on the three nuclei considered in the energy interval $E_n = 8 - 9MeV$.

1 Introduction

The (n, d) reactions at neutron incident energies up to $20MeV$ have been relatively little investigated in comparison with many others neutron-induced nuclear reactions [1-12]. The emission of the deuterons in this process, as well as the sequential emission of two different nucleons in the $(n, n'p)$ and (n, pn) processes gives information about the nuclear structure and nuclear reaction mechanisms. They are also important for practical applications, namely concerning the radiation damage due to hydrogen and deuterium gas formation in the first wall materials of fusion reactors [9].

There are two main techniques used to measure the cross–sections of such reactions. The first is the activation technique which yields the sum of (n, d) , $(n, n'p)$ and (n, pn) cross–sections. Systematic radiochemical studies on medium and heavy nuclei have been performed mainly at $E_n = 14MeV$ (a review is given by Qaim [9]) and in several cases for a wider energy range of $E_n = 14 - 20MeV$ [3, 10]. The first systematic study of the energy dependence of the (n,d) cross-section for a medium mass target nucleus ^{58}Ni for lower energies ($E_n = 6.4$ to $9.5MeV$) has been carried out by Qaim and Wölfle [11]. The second technique consists in measuring the emitted charged particle spectra. These spectra yield the (n,d) cross-section unambiguously. For light nuclei ($A \leq 10$) the emitted deuteron spectra have been obtained at several incident neutron energies up to $E_n = 20MeV$ (e.g.[2, 3]). For medium and heavy mass nuclei ($A = 10 - 100$) the spectrum measurements have been carried out mainly at $E_n = 14MeV$ (e.g.[2, 3, 4, 5, 6, 7, 8]). It has been shown that these spectra are generally forward-peaked and show evidence of nonequilibrium contributions [6, 7, 8, 9, 11]. Indeed, the Hauser–Feshbach (HF) calculations of the (n,d) cross-sections on ^{27}Al, $^{46-49}Ti$, ^{51}V, $^{50,52}Cr$, ^{55}Mn, $^{54,56}Fe$, ^{58}Ni, ^{65}Cu and ^{93}Nb at $E_n = 14 - 15MeV$ by Qaim [9] show that the contributions of the statistical process to the (n,d) reaction cross-section are generally small. For instance, the calculations on the first-chance emission of a deuteron in the $^{58}Ni(n,d)^{57}Co$ reaction show that beyond $E_n = 11MeV$ the relative contribution of the statistical processes decreases and at about $15MeV$ it is less than 30% of the total (n,d) cross-section [11]. Now it is generally accepted that this process can be interpreted as a direct one and mainly as a proton pick-up process. This conclusion is in agreement with the known results for the (p,d) and (α,d) reactions that the deuteron emission is generally not a statistical process [9].

The aim of the present work is to analyze the contributions of various reaction mechanisms to the total (n,d) reaction for three medium mass nuclei, namely ^{58}Ni and $^{63,65}Cu$ for which experimental data are available. This includes the statistical contribution using HF calculations and the direct process contributions, consisting of the pick-up and knock-out mechanisms. The statistical and pick-up calculations are presented in Sections 2 and 3, respectively. In Section 4 a theoretical model for deuteron knock-out calculations is suggested. The discussion of the results and the conclusions of the work are given in Section 5.

2 The Hauser–Feshbach Statistical Model Calculations

The relatively small contribution of statistical emission to the (n,d)-reaction cross-sections is well-known [9]. However, it may still be appreciable especially for ^{58}Ni, and also for ^{63}Cu, due to the respective low values of the asymmetry parameter $(N - Z)/A$. HF model calculations have been carried out taking into account the neutron, proton, α-particle, deuteron and γ-ray emission to all allowed final states. The computer code STAPRE-H95 [13] was used, and the pre-equilibrium emission (PE) of nucleons and α-particles was included under general assumptions (e.g.[14, 15]) for the consistent description of all reaction channels.

In this work local optical model potential (OMP) parameter sets for neutrons established through the SPRT method (i.e. by simultaneous fit of the resonance data and the neutron total cross-section within the whole energy range, supplemented by scattering analysis) have been used rather than global potentials. The optical potentials of Chiba et al. [16] and Duke University [17] were used for the target nuclei ^{58}Ni and $^{63,65}Cu$, respectively. The proton OMP parameter set obtained by Arthur and Young

[18] for the mass region $A = 50 - 60$, and the α-particle global OMP of ref.[19] have been also used. Unfortunately, only the global OMP-parameter sets of Lohr and Haeberli [20] and Perey and Perey [21] were available for the description of the deuteron emission. The former has been used since it was obtained by the analysis of both elastic differential cross-sections and polarization data in the incident-energy region of 8 to $13MeV$. However, using the latter OMP has only the effect of decreasing the (n,d) cross-section by around 10%.

In the calculations the nuclear level density formula given by the back-shifted Fermi-gas (BSFG) model [22] has been used and appropriate values of the BSFG model parameters a and Δ_{BSFG} were derived [23] by fitting the recent experimental low-lying discrete levels and the s-wave nucleon resonance spacing. The a-parameter starting values, which were not varied for the nuclei without resonance data, have been obtained by using the smooth-curve method [24] applied to the parameters of Dilg et al.[22] and Holmes et al.[25].

The sequential decay of the residual nuclei has been described by using the γ-ray transmission coefficients based on the γ-ray strength functions. The strength function of the dominant electric dipole transition was calculated within the giant dipole resonance model with a modified energy-dependent Breit-Wigner line-shape in agreement with the experimental data [26]. The atomic masses and the Q-values used in the calculations were taken from ref.[27].

The results of the HF calculations are given in Figs.1-3 by solid lines with dots. As expected, the statistical contribution to the excitation functions of the three reactions are quite small. The result for the case of $^{58}Ni(n,d)^{57}Co$ reaction obtained in this work is in general agreement with the HF calculations performed in [11]. The experimental data presented in the Figures have been taken from [12].

3 The Pick-up Reaction Mechanism

The differential cross-sections of the $^{58}Ni(n,d)^{57}Co$ reaction to the ground state and to the $1.38MeV$ excited state in ^{57}Co have been calculated with the Distorted-Wave Born Approximation (DWBA) in the zero-range local approximation using the program code DWUCK4. The values of the optical model parameters were taken for neutrons and deuterons from [28] and [20], respectively. The spectroscopic factors of the transitions have been obtained by comparing the calculated differential cross-sections with the experimental data for the $^{58}Ni(n,d)$ reaction initiated by $14MeV$ neutrons [29] taking into account the compound nucleus and knock-out cross-sections calculated in Sections 2 and 4. The spectroscopic factors for the ground state $7/2^-$ and the excited state $(3/2^-, E_x = 1.38MeV)$ are 6.47 and 0.96, respectively. The excitation of the $3/2^-$ state and the value of the spectroscopic factor imply that the ^{58}Ni ground state has a significant $2p2h$ component. If we assume that the absent pick-up strength is spread over higher excited states in the continuum we can take them into account by normalizing the sum of the spectroscopic factors $Sp_{7/2^-}$ and $Sp_{3/2^-}$ to 8. We note that the spectroscopic factors which are obtained by fitting the experimental data at $E_n = 14MeV$ are physically reasonable, so one could have used the simple shell-model values without much affecting the results. In addition, the calculations give the energy variation of the pick-up cross-section in good agreement with the data. The $^{63}Cu(n,d)$ and $^{65}Cu(n,d)$-reactions are treated in a similar way. The transitions to the ground states of the Ni isotopes and to

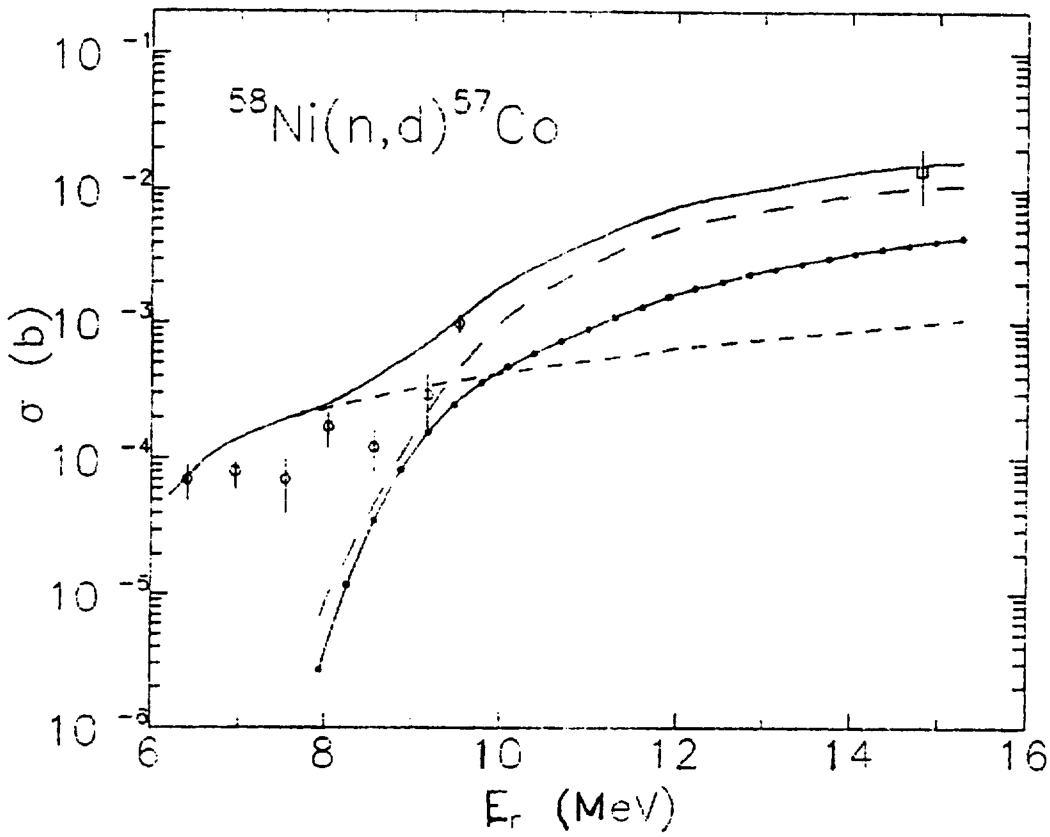

Fig.1. The total cross-section of the $^{58}Ni(n,d)^{57}Co$ reaction. Solid line with dots: $\sigma^d_{compound}$, short-dashed line: $\sigma^d_{knock-out}$, long-dashed line: $\sigma^d_{pick-up}$, solid line: $\sigma^d_{total} = \sigma^d_{compound} + \sigma^d_{knock-out} + \sigma^d_{pick-up}$. The experimental data are taken from [12].

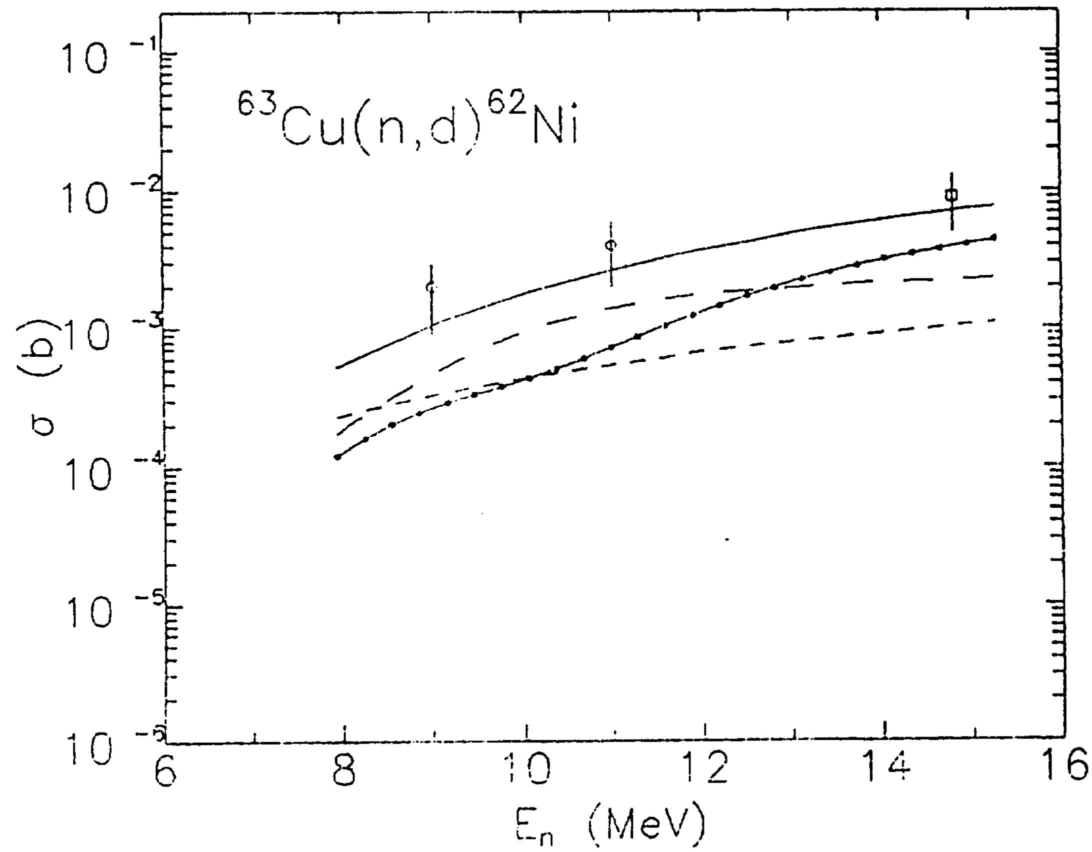

Fig.2. The same as in Fig.1 for the $^{63}Cu(n,d)^{62}Ni$ reaction.

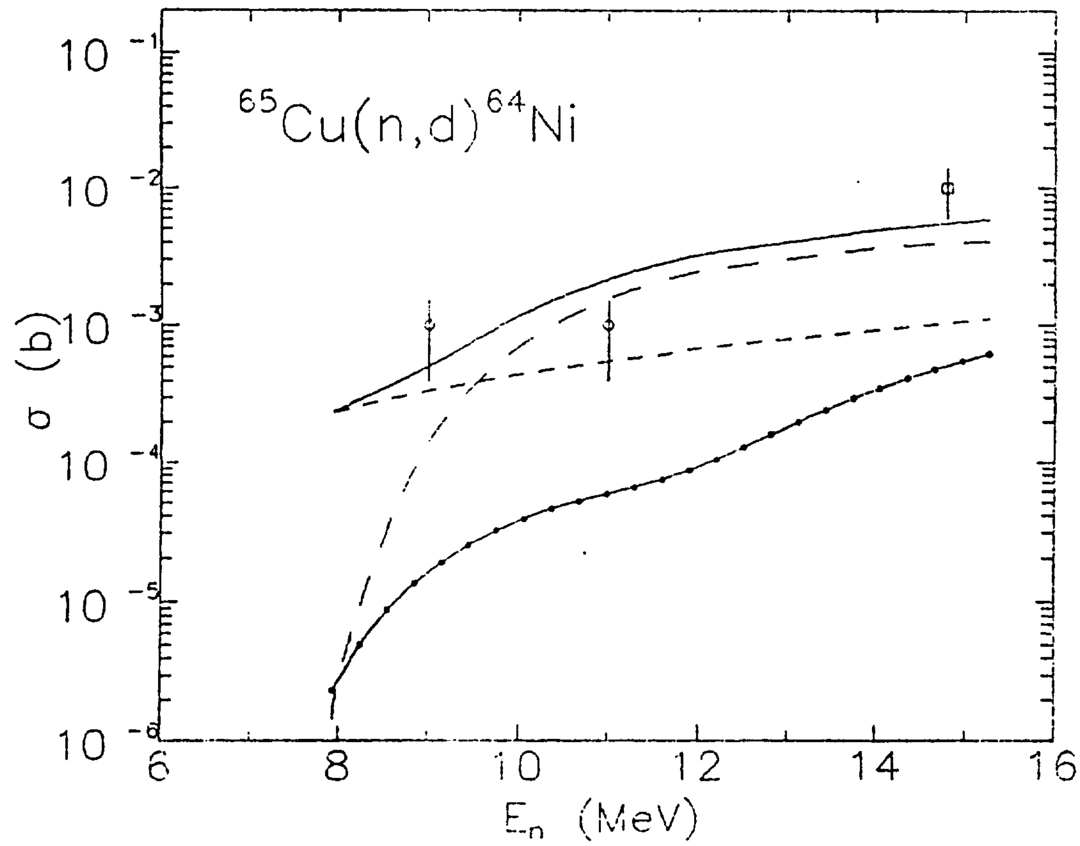

Fig.3. The same as in Fig.1 for the $^{65}Cu(n,d)^{64}Ni$ reaction.

the first excited states ($E_x = 1.13 MeV$ for the second case, respectively) are included. The experimental data for the differential cross-sections of the transitions for ^{63}Cu are taken from [29] and for ^{65}Cu from [30]. The reactions to the two lowest excited states account for most of the pick-up cross-section, as the strengths of the transitions to the other final states are small [30]. The cross-sections of the reactions to these two states may therefore be summed to give the total pick-up contribution to the total (n,d)-reaction cross-section for the ^{58}Ni and $^{63,65}Cu$ nuclei in the region $E_n = 8 - 15 MeV$ and these are shown by the long-dashed lines in Figs.1-3.

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4 The Deuteron Knock-out Model

In this Section we will consider another also possible direct mechanism, namely the knock-out process. We introduce a (n,d)-reaction model in which restrictions on the available phase space for the two nucleons of the deuteron after the knock-out are imposed by a Pauli-blocking function. A similar model of (n,α) knock-out reactions has been suggested and applied successfully in [31] to analyze excitation functions of (n,α) reactions on medium mass nuclei. It was shown that the Pauli-blocking effects are important for describing the (n,α) processes. Our model is closely related to that of Chadwick et al. [32] who studied Pauli-blocking effects in the quasi-deuteron photoabsorption reaction.

We treat the deuteron knock-out process by assuming that the incident neutron collides with a preformed deuteron in the target nucleus and ejects it, leaving the neutron in a single-particle state along with some hole excitations. The emitted deuteron-like cluster can have a range of energies and the residual nucleus is, in general, excited. We compare the calculated cross-sections with the available (n,d) activation data, thus including only deuteron-emission reactions in which no other particles are emitted, apart from γ-rays. We consider neutron incident energies such that the dominant decay mechanism of the excited residual nucleus is by γ-ray emission to its ground state. In support of the use of a preformed deuteron we should mention the observations of deuterons emitted from reactions of very energetic protons on nuclei.

In this work the Pauli-blocking effects on the (n,d) reaction are included using a model of deuteron knock-out in which the cross-section is related to the free (n,d) cross-section. In the latter case the nuclear medium is not present, while in the nuclear case the occupied states in the rest of the nucleus restrict the number of states accessible for the neutron and the deuteron after the interaction. It is assumed in the model that if the available phase space for the two nucleons after the knock-out is reduced by the Pauli blocking, the (n,d) cross-section is also reduced by the same amount. It is required that the proton and the neutron of the preformed deuteron in the nucleus after leaving it have momenta greater than the Fermi momentum k_F.

The total cross-section of the knock-out process can be written in the form

$$\sigma_k^d = \Phi_d \sigma_{(n,d)}^{free}(\varepsilon_{inc}) f(\varepsilon_{inc}) \ , \tag{1}$$

where Φ_d is the deuteron preformation factor, $\sigma^{free}_{(n,d)}$ is the free neutron–deuteron cross-section and $f(\varepsilon_{inc})$ is the Pauli-blocking function. Eq.(1) is similar to the Levinger's expression for the nuclear photoabsorption cross-section [32]. Two simplifying approximations have been used for the Pauli-blocking function in (1): i) the free (n,d) cross-section is not folded in and ii) the Fermi-gas momentum distribution has been used for the deuterons. We assume the Fermi-gas state density for the deuterons

$$\rho_d(\varepsilon_d) = \frac{3}{2\varepsilon_F^d}\left(\frac{\varepsilon_d}{\varepsilon_F^d}\right)^{1/2} , \tag{2}$$

normalized to unity:

$$\int_0^{\varepsilon_F^d} \rho_d(\varepsilon_d) d\varepsilon_d = 1 . \tag{3}$$

The quantity ε_F^d in (2) and (3) is the effective Fermi energy of the deuteron and ε_d is the energy of the preformed deuteron relative to the bottom of the nuclear well. The Pauli-blocking function has the form (similar to that for the (n,α) knock-out case [31]):

$$f(\varepsilon_{inc}) = \int_0^{\varepsilon_F^d} \rho_d(\varepsilon_d) F(\varepsilon_d + \varepsilon_{inc}) T(\varepsilon_d + \varepsilon_{inc}) d\varepsilon_d . \tag{4}$$

The quantity

$$F(E) = \frac{\rho^P(2p,E)}{\rho(2p,E)} \tag{5}$$

is the Pauli-blocking factor, which is defined by the ratio of the two-particle state densities in which the Pauli-blocking is taken into account $(\rho^P(2p,E))$ and ignored $(\rho(2p,E))$. Following [32] they have the form:

$$\rho^P(2p,E) = \frac{9NZ\theta(E-2\varepsilon_F)}{4\varepsilon_F^3}\left[\frac{1}{2}(E-2\varepsilon_F)(E\varepsilon_F - \varepsilon_F^2)^{1/2} + \frac{1}{4}E^2 sin^{-1}\left(\frac{E-2\varepsilon_F}{E}\right)\right] , \tag{6}$$

$$\rho(2p,E) = \frac{9\pi NZ}{32\varepsilon_F^3}E^2 , \tag{7}$$

where Z and N are the proton and neutron numbers in the target nucleus, respectively, and ε_F is the nucleon Fermi energy. Using (6), the Pauli-blocking factor (5) can be written as

$$F(E) = \theta(E - 2\varepsilon_F)F'(E) . \tag{8}$$

In (8) the quantity $2\varepsilon_F$ enters the argument of the unit step function and plays the role, in some sense, of the "effective Fermi energy" of the gas of deuterons. This is so because the Pauli-blocking factor is equal to zero below this limit and is finite in the region above the limit of $2\varepsilon_F$, where the deuteron-like cluster is assumed to be after the collision with the incident neutron. We note that the appearance of the quantity $2\varepsilon_F$ as an "effective Fermi energy" follows naturally from the Fermi-gas model for the nucleons which form the deuteron. This can serve as a justification of the concept of "the deuteron-cluster Fermi-gas model".

In (4) T is the transmission coefficient related to the interaction of the deuteron with the residual nucleus. It can be calculated from the optical model potentials for the deuteron plus residual interaction (see Sect.2). In the Fermi-gas model we measure the energies of the particles from the bottom of the potential well, so the transmission coefficient in (4) contains a step function which enables it to "start" at an energy $2\varepsilon_F + B_d$ ($B_d = 2.225MeV$ being the deuteron binding energy):

$$T(E) = \theta[E - (2\varepsilon_F + B_d)]T'(E) . \tag{9}$$

In this work we use transmission coefficients averaged over a range of values of the angular momentum. In (4) and (9) we have approximately

$$T'(E) = \frac{\sum_{L=0}^{L_{max}} (2L+1) T_L(E)}{\sum_{L=0}^{L_{max}} (2L+1)} \ . \tag{10}$$

Finally, using Eqs.(2), (8) and (9) and after the substitution $\varepsilon = \varepsilon_d + \varepsilon_{inc}$ in (4), the Pauli–blocking function takes the form:

$$f(\varepsilon_{inc}) = \frac{3}{2(\varepsilon_F^d)^{1/2}} \int_{\varepsilon_F^d}^{\varepsilon_F^d + \varepsilon_{inc}} (\varepsilon - \varepsilon_{inc})^{1/2} F'(\varepsilon) T'(\varepsilon) d\varepsilon \ . \tag{11}$$

where

$$\varepsilon_F^d = 2\varepsilon_F + B_d \ . \tag{12}$$

Thus we can calculate the knock–out cross–section σ_k^d (1) using the free (n,d) cross–section $\sigma_{(n,d)}^{free}(\varepsilon_{inc})$ and two model parameters, namely the nucleon Fermi energy ε_F have been taken from [33, 34]. For the preformation factor Φ_d we have used the value $\Phi_d = 0.40$. Comparing it with same theoretical predictions of Sato et al. [35] we consider this value as a reasonable one. For the nucleon Fermi energy we have used $\varepsilon_F = 38MeV$ which corresponds in the local density approximation to the equilibrium density in the central part of the nucleus. By investigating the L–dependence of the transmission coefficients, we determined that it is sufficient to include coefficients up to $Lmax = 18$ in (10) for the energies considered in this work. The values of σ_k^d are given in Figs.1-3 by the short–dashed line.

We should note that our model is close to the quasi–free scattering (QFS) pre–equilibrium model developed by Mignerey et al. [36, 37] and based on the Harp–Miller–Berne approach [38, 39]. As in the case of the (n,α) knock–out model suggested in [31], the main differences are in the treatment of the Pauli–blocking effects and the use of transmission coefficients, rather than inverse cross–sections, with detailed balance to account for the barrier penetration by the deuteron. In this sense, the main relations of our model (Eqs.(1), (4) and (11)) can be considered as the first term of a scattering series suggested in the QFS model [36, 37].

5 Discussion and Conclusions

The statistical, pick–up and knock–out contributions to the total cross–sections of the (n,d) reaction on ^{58}Ni, ^{63}Cu and ^{65}Cu at incident energies up to $15M$eV are considered in this work. The results are presented in Figs.1-3 and are compared with the available experimental data.

As can be seen from the Figures, the main contribution to the (n,d) cross–sections on the nuclei considered is given by the pick–up mechanism.The statistical contributions are small, especially for the case of the ^{65}Cu nucleus. This is in agreement with the results from [9, 11] where it has been shown that the contributions of statistical processes to the total (n,d) cross–section are generally small, a result similar to that deduced from angular distribution measurements on (n,d) reactions, and also with the known results from (p,d) and (α,d) reactions. The knock–out contribution calculated by the model suggested in this work is generally small, but as can be seen from the figures, it makes it possible to describe better the data for the three cases in the low energy interval. Commenting the latter, we should mention Ref.[11] where it has been shown that the first four values of the $^{58}Ni(n,d)^{57}Co$ cross–section at low energy give the pure (n,d) reaction data and the next three values (between 8.5 and $9.5MeV$) also give primarily (n,d) data. On the other hand, the statistical [11] and precompound calculations [10] fail to explain the low energy cross–sections. In our opinion, the proposed model (in this first step of its development) could shed some light on a possible mechanism for description of the (n,d) reaction in the low energy region.

Considering the comparison with the experimental data given in the figures, we should note that the data include activation cross–sections only in the case of the ^{58}Ni target nucleus for the energy range $6.41-9.52MeV$. In this case one should consider also the contribution of the $(n,n'p)$ and (n,pn)processes. However, due to the energy threshold for these channels which lies at $8.31MeV$ and the additional Coulomb barrier effect for the emitted protons, the contribution of $(n,n'p)$ reaction is present only in the case of the cross–section value at the incident energy of $9.52MeV$.

Detailed model calculations of the particle-emission spectra and excitation functions of the (n,n') direct processes, pre–equilibrium emission and compound–nucleus mechanism, carried out for experimentally–known reaction channels for fast neutrons on the stable isotopes of Ni [22] have given cross–section values of $0.96mb$ and $0.25mb$ for the $(n,n'p)$ and (n,d) reactions, respectively, around the incident energy of $9.5MeV$. The corresponding ratio is opposite to that cited in [11], but it should be noted that the respective calculation within the first energetic bin above the threshold is the most uncertain one when a constant energy mesh is used in statistical model calculations. Therefore, the cross–section value at $9.52MeV$ should be taken into account with caution.

In the case of the $^{58}Ni(n,d)^{57}Co$ reaction (Fig.1) we give the knock–out contribution and the total cross–section results for lower neutron energy as well. We should note that the threshold of this reaction is $6.15MeV$ while the effective threshold of the OMP transmission coefficients for deuterons is in between $2-2.5MeV$. Therefore, the effective thresholds of around $8MeV$ and $9.5MeV$ for the (n,d) and $(n,n'p)$ reactions are specific also for the statistical model calculated cross–sections.

We should like to note that the detailed analysis of various reaction mechanisms would require also consideration of particle emission spectra and angular distributions. There are such spectral measurements only at $E_n = 14.8MeV$ [7]. Emission spectra can be calculated by statistical model and should be included after summing them with the direct contribution. The angular distributions are not particularly calculated, but also have to be added to the direct contribution in order to compare the total calculated value with the experimental cross–section. We should admit a deficiency of our analysis not including such considerations. We limit ourselves now only by comments that concerning the statistical model results, the angular distributions are not significant because they are isotropic. On the other hand, the emission spectra can be calculated and used to get the total emission spectra. As can be expected, the low energy end of the deuteron spectra (up to around $4MeV$) [7] are quite well reproduced except the structure present in the case of the ^{65}Cu target nucleus. The more energetic particles should originate from the direct processes.

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