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Pre-equilibrium and Equilibrium Energy Emission Spectrum of Nucleons and Light Nuclei Induce Nuclear Reactions on ^{63}Cu Nuclei

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Abstract

The differential cross sections of the pre - equilibrium stage are calculated at different energies using the Kalbach Systematic approach in Exciton model with Feshbach, Kerman and Koonin (**FKK**) statistical theory of Multistep Compound and direct reactions. In this work, the emission rate of light nuclei with emission energy in the centre of mass system in the isospin mixed case is considered in calculations to predict the cross-sections at the pre-equilibrium and equilibrium stages. The nucleons and light nuclei (^{2}D and ^{3}T) have been used as a projectile at the target ^{63}Cu nuclei and at different incident energies (4MeV, 14 MeV and 14.8MeV). The comparisons between the present calculated results with other, theoretical and experimental works, show an acceptable agreement for certain emission energies for the reactions ^{63}Cu (n, n)^{63}Cu , ^{63}Cu (p, n) ^{63}Zn, ^{63}Cu (p, D) ^{62}Cu , ^{63}Cu (p, p) ^{63}Cu and ^{63}Cu (p, ^{4}He)^{60}Ni.

Keywords: differential cross sections, pre - equilibrium stage, ^{63}Cu, FKK, Exciton model

طيف الانبعاث الطاقي لما قبل الاتزان والاتزان للنيوكليونات والنوى الخفيفة التي تؤدي الى التفاعلات النووية لنوى النحاس ^{63}Cu

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الخلاصة

تم حساب المقطع العرضي التفاضلي في مرحلة ما قبل الاتزان في طاقات مختلفة باستخدام تقريب منهج (Kalbach) لنموذج الاكسيتون مع النظرية الاحصائية لفيش باغ وكيرمن وكوننك(Feshbach, Kerman and Koonin (FKK)) للنوى المركبة متعددة الخطوات والتفاعلات المباشرة . في هذا العمل تم أعتماد معدل الانبعاث مع طاقة الانبعاث للنوى الخفيفة ، عند نظام مركز الكتله، في الحسابات لغرض تنبوء قيم المقاطع العرضية لمراحل ما قبل الاتزان والاتزان عند خليط الايزوسبن. أستخدم النيكليونات والنوى خفيفة ، مثل الديتريون والترتيون، كقذائف عل نوى النحاس ^{63}Cu وعند طاقات مختلفه (14.8MeV, 14 MeV,4MeV).

حيث بينت المقارنات بين حسابات النتائج الحاليه مع الاخرين، الاعمال النظرية والعملية، توافق مقبول عند طاقات انبعاث معينة للتفاعلات :

^{63}Cu (n, n) ^{63}Cu , ^{63}Cu (p, n) ^{63}Zn, ^{63}Cu (p, D) ^{62}Cu، ^{63}Cu (p, p) ^{63}Cu and ^{63}Cu (p, ^{4}He)^{60}Ni.

Introduction:

The mechanical of nuclear reaction, X (a, b) Y, is an important task for different fields in nuclear science and technology, where the measurements of the cross-sections are of great importance, due to the possibility of observation the most of a population, or a representative subset, at one specific point in time.

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At the beginning, the nuclear reaction caused by an incident particle of certain energy can be share the incident particle's energy with all nucleons of the nucleus target and reach to the final stage called the thermal Equilibrium State. In studies of light-ion induced nuclear reactions one can distinguish between three different mechanisms of the reaction: direct, compound and pre-equilibrium nuclear reactions.

The pre-equilibrium stage can be described extensively in the framework of Exciton model and assumed the excitation energy is shared between different particle-hole configurations, with the same exciton number (n) [1], and with the same probability. To keep track of the evolution of the scattering process, one merely traces the temporal development of the exciton number, which changes in time as a result of intra-nuclear two-body collisions.

The Exciton model has been extended to include system properties and features with more details [2-5]. This is mostly based on the parameterization of experimental results and then reformulated the model to describe a wide variety of nuclear reactions. Also, many approach, in semi classical and quantum mechanics, frame of work and based on Griffin s idea, is distinguished between Multi-step compound (**MSC**) and Multi-step direct (**MSD**) processes, which are evaluated in the continue stage of reaction [6-8]. In energy scale, the MSC reaction can prevail at higher energy than those characteristic of compound nuclear decay, which provide the larger part of the pre-equilibrium nuclear reaction cross section [9].

The present work deals extensively with the calculated energy spectrum for different stages started from pre equilibrium to the direct and equilibrium reaction at different projectile energies (4,14,14.8 MeV) on ^{63}Cu target. The total cross- sections are compared with the available experimental data from EXFOR and theoretical data from TENDL-2014 [10].

The pre-equilibrium energy spectrum:

Different mechanisms have been used in calculating the energy spectrum of nucleons (n and p) and light nuclei (D and T) induced nuclear reactions with ^{63}Cu nuclei target, among that, the pre equilibrium mechanism, which described by two components Exciton model and included the primary and secondary nucleon emissions. Therefore, the particle emission rates of type (*b)* as a function of energy (ε) state particular class states in the [spin mixed case given by [10]:

$$W_b(p,p_\pi,E,\varepsilon)=\frac{2s_b+1}{\pi^2\hbar^3}\mu_b\varepsilon\sigma_b(\varepsilon) \times \sum_{T_B}\left|C_b(T,T_B)\right|^2\frac{w_{eff}\,(p_\pi-Z_b,h_\pi,p_\nu-N_b,h_\nu,U,T_B)}{w\,(p_\pi,h_\pi,p_\nu,h_\nu,E,T)} \qquad \textbf{(1)}$$

where the effective total residual state density is:

$$w_{eff}\,(p_\pi-Z_b,h_\pi,p_\nu-N_b,h_\nu,U)=\sum_{i=i_{\min}}^{h_\pi}\ \sum_{j=j_{\min}}^{h_\nu} w\,(p_\pi-Z_b,i,p_\nu-N_b,j,U)$$

The total residual state density takes into account more compound configurations when can be excited by stripping reaction [10, 11]. Where C_b (T, T_B) is the isospin coupling Clebsch-Gordan coefficient in the exit channel, T_B is the isospin quantum number in the residual nucleus, ε is the single particle energy, T is the isospin quantum number, Z_b is the emitted particle proton number, N_b is the emitted particle neutron number and μ_b is the reduced mass.

The effective of isospin in the residual nucleus, and residual excitation energy U=E-ε-B_b, where B_b is the binding energy of emitted particles.

The total energy spectrum in the center of mass system of the pre-equilibrium model for the emitted particles (b) at energy (ε) and spin dependent formulation is obtained by [10, 12, 13]:

$$\left[\frac{d\sigma_{a,b}(\varepsilon)}{d\varepsilon_a}\right]_{pre}=\sum_T\left[\frac{d\sigma_{a,b}(\varepsilon,T)}{d\varepsilon_a}\right]_{pre} = \sigma_a(\varepsilon_a)\sum_T\left|C_a(T,T_A)\right|^2\times\sum_p\sum_{p_\pi}S_{pre}(p,p_\pi,T)\;W_b(p,p_\pi,E,\varepsilon,T) \qquad \textbf{(2)}$$

Where $\sigma_{a,pre}$ is the cross section for modelling the complex nucleus that reduced by a cross section with direct reaction and S_{pre}(P, p_π, T) is the average amount of time spent in each class of configuration [11].

The result of the equation (2) is applied for each spin, *T*, and multiplied by the entrance channel isospin coupling Clebsch-Gordan coefficient. This can be applied when isospin is conserved. Since the pre-equilibrium stage a second emission of particles might be happening, therefore the emission will affect the energy spectra at high excitation energy [14].

The Nucleon transfer (NT) mechanism considered in the present calculations which includes the direct pickup or stripping up to three nucleons, if the projectile (a) and emitted particles (b) have different mass numbers. It also includes nucleon exchange reactions for inelastic scattering of all light projectiles and for the (t, ^{4}He) and (^{4}He,t) charge exchange reaction.

For the reaction ^{63}Cu (a, b) Y, the general formula for the NT energy differential cross section is given by [10]:

$$\frac{d\sigma_{a,b}^{NT}}{d\varepsilon}=\frac{2s_b+1}{2s_a+1}\frac{A_b}{A_a}\varepsilon\sigma_b(\varepsilon)K_{\alpha,p}\left(\frac{A_a}{E_a+V_a}\right)^{2n}\left(\frac{C_a}{A_B}\right)^{n}\times N_a\sum_{P_a}\left(\frac{2Z_A}{A_A}\right)^{2(Z_a+2)h_\pi+2p_\nu} \qquad \textbf{(3)}$$

$$\times\,\omega_{NT}(p_\pi,h_\pi,p_\upsilon,h_\upsilon,U)$$

where $\omega_{NT}(p_\pi,h_\pi,p_\upsilon,h_\upsilon,U)=\sum_{i=0}^{3}\sum_{j=0}^{3-i}(X_{NT})^{i+j}\omega\left(p_\pi+i,h_\pi+i,p_\upsilon+j,h_\upsilon+j,U\right)$

The factor X_{NT} is the probability of exciting each additional pair (particle, hole) and it is given by empirical formula given in [15, 16], E_a is the incident energy in the laboratory system, V_a is the average potential drop seen by the projectile between infinity and the Fermi level, C_a and N_a are the normalization constants [10,17,18], $K_{\alpha,p}$ is an enhancement factor for (α, N) and (N, α) reactions.

While in the FKK model the multi-step direct (**MSD**) or pre equilibrium or forward-peaked component includes the exciton model pre equilibrium components (both primary and secondary) as well as the cross sections from nucleon transfer, knockout and inelastic scattering (IN) involving cluster degrees of freedom, can be described by:

$$\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{msd}=\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{pre,1}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{pre,2}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{NT}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{IN} \qquad \textbf{(4)}$$

and for other reaction channel Knockout (KO) is,

$$\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{msd}=\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{pre,1}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{pre,2}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{NT}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{KO} \qquad \textbf{(5)}$$

where the **KO** is contribution occurs only for (N,α), (C,N) and (C,α) reactions, where N is a nucleon and C is a complex particle (d, t, ^{3}He or α-particle).

The corresponding equilibrium or symmetric component contains only the primary and secondary evaporation cross sections and is given by the Multi step compound spectrum,

$$\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{msc}=\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{eq.,1}+\left\lfloor d\sigma_{\varepsilon_b}\right\rfloor_{eq,2} \qquad \textbf{(6)}$$

Results and Discussions:

Since the Exciton model with FKK model , equations (4 and 5) of nuclear levels makes it possible to calculate the energy and angular distributions of the particles in the pre compound towards the continuum stage, therefore, the groups of particles corresponding to the discrete states clearly can be resolved and depends on the projectile's energy (E). At E=14.8 MeV incident neutrons with ^{63}Cu target different mechanisms, equations (4, 5, 6), have been used in calculating the energy spectrum at different particle and light nuclei emission energies, E_x, see Figure-1. From these figures one can distinguish the probability of the direct nucleon transfer contributions clearly dominant for the reactions (c, d and d) in Figure-1. As shown in Figure-2 the calculated energy spectrum as a function of particle and light particle emission energy, Ex, at 14.8 MeV incident neutron energy have been evaluated and compared with other theoretical results of [19] and the available experimental data from [18], for the reactions; ^{63}Cu (n, n)^{63}Cu, ^{63}Cu (n, T)^{61}Ni, ^{63}Cu (n, p)^{63}Ni, ^{63}Cu (n, D)^{62}Ni and ^{63}Cu (n, ^{4}He)^{60}Co respectively. The most inconsistency appears when the energy increases above ~3MeV for the reactions Figure-2b and 2d and above 4MeV for the reaction in Figure-2c, which indicates the necessity consideration of re-evaluate the reaction strengths using the two component non ESM Exciton model. However, when comparing the calculated energy differential cross-sections based on these spectra, better match with experimental and theoretical are found for the reaction ^{63}Cu (n, ^{4}He)^{60}Co, Figure-2e and all reactions shown in Figure-3a, b, c, d except Figures-4 and 5.

Conclusions:

Different mechanisms have been used to calculate the total energy spectrum in terms of MSD and MSC models for the emission nucleons and light nuclei from reactions; ^{63}Cu(n,n)^{63}Cu , ^{63}Cu(n,p)^{63}Ni , ^{63}Cu(n,D)^{62}Ni, ^{63}Cu(n,T)^{61}Ni, ^{63}Cu(n, ^{4}He)^{60}Co, ^{63}Cu (p, n)^{63}Zn, ^{63}Cu (p, D)^{62}Cu , ^{63}Cu (p, p)^{63}Cu , ^{63}Cu (p, ^{4}He)^{60}Ni, ^{63}Cu(D, n)^{64}Zn, ^{63}Cu(D, p)^{64}Cu , ^{63}Cu(D,D)^{63}Cu, ^{63}Cu(D, ^{4}He)^{61}Ni, ^{63}Cu(T, n)^{65}Zn, ^{63}Cu(T, p)^{65}Cu, ^{63}Cu(T,D)^{64}Cu, ^{63}Cu(T, T)^{63}Cu and ^{63}Cu(T, ^{4}He)^{62}Ni, and at different incident energies 4 MeV,14 MeV and 14.8 MeV. Though the comparisons with others [17, 18], the present systemic calculations look an acceptable agreement for certain emission energies for the reactions ^{63}Cu (n, n) ^{63}Cu , ^{63}Cu (p, n) ^{63}Zn, ^{63}Cu (p, D) ^{62}Cu , ^{63}Cu (p, p) ^{63}Cu and ^{63}Cu (p, ^{4}He)^{60}Ni, and diverges at other emission energies for the rest of other reactions. The deviation of the present work with others for certain reactions reflects the need to consider secondary emissions in the equilibrium stage through the modified the evaporations component at low incident energies and consider the non-equidistant Exciton model for primary and secondary emissions in the pre-equilibrium stage with applicable corrections.

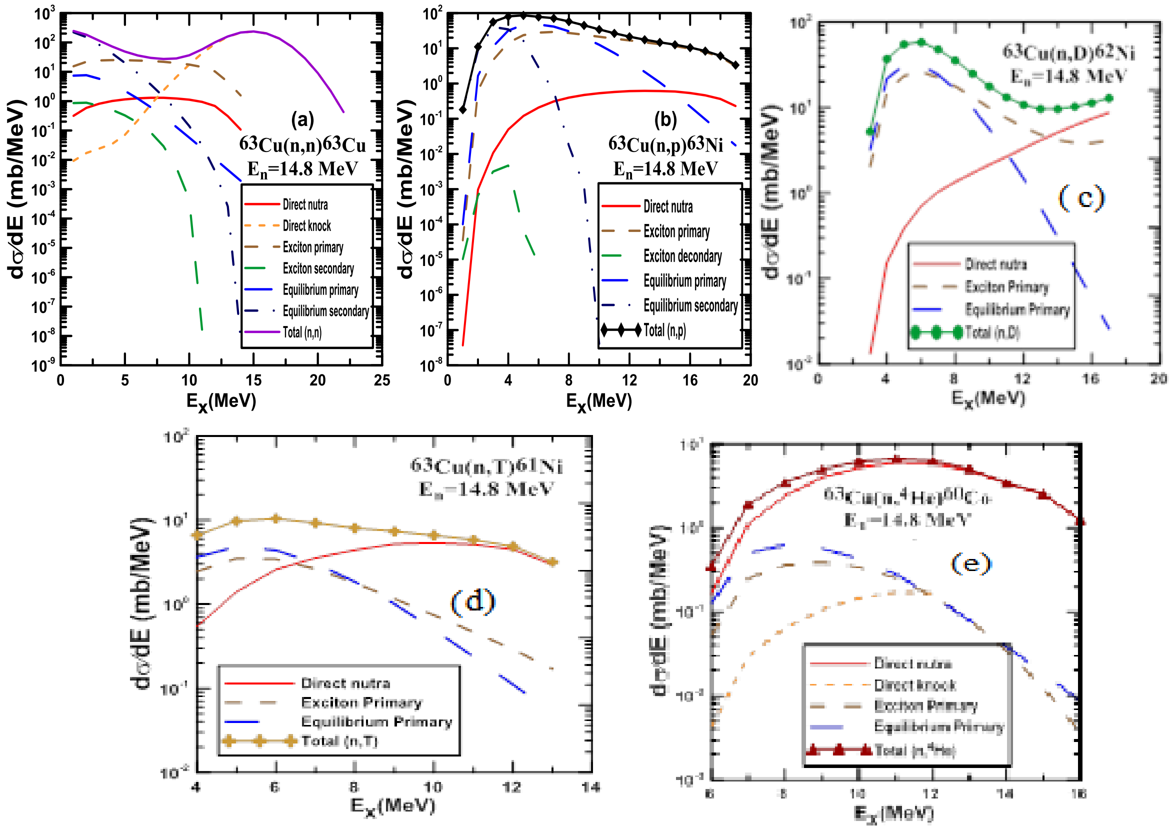

Figure 1- The energy spectrum of different mechanisms as a function of the particle emission energy, E_x, in cm-system for emission nucleons (n and p) and light nuclei (D, T and ^{4}He), in different reactions at incident energy 14.8MeV, (a) ^{63}Cu (n, n) ^{63}Cu (b) ^{63}Cu (n, p) ^{63}Ni (c) ^{63}Cu (n, D) ^{62}Ni (d) ^{63}Cu (n, T) ^{61}Ni and (e) ^{63}Cu (n, ^{4}He)^{60}Co.

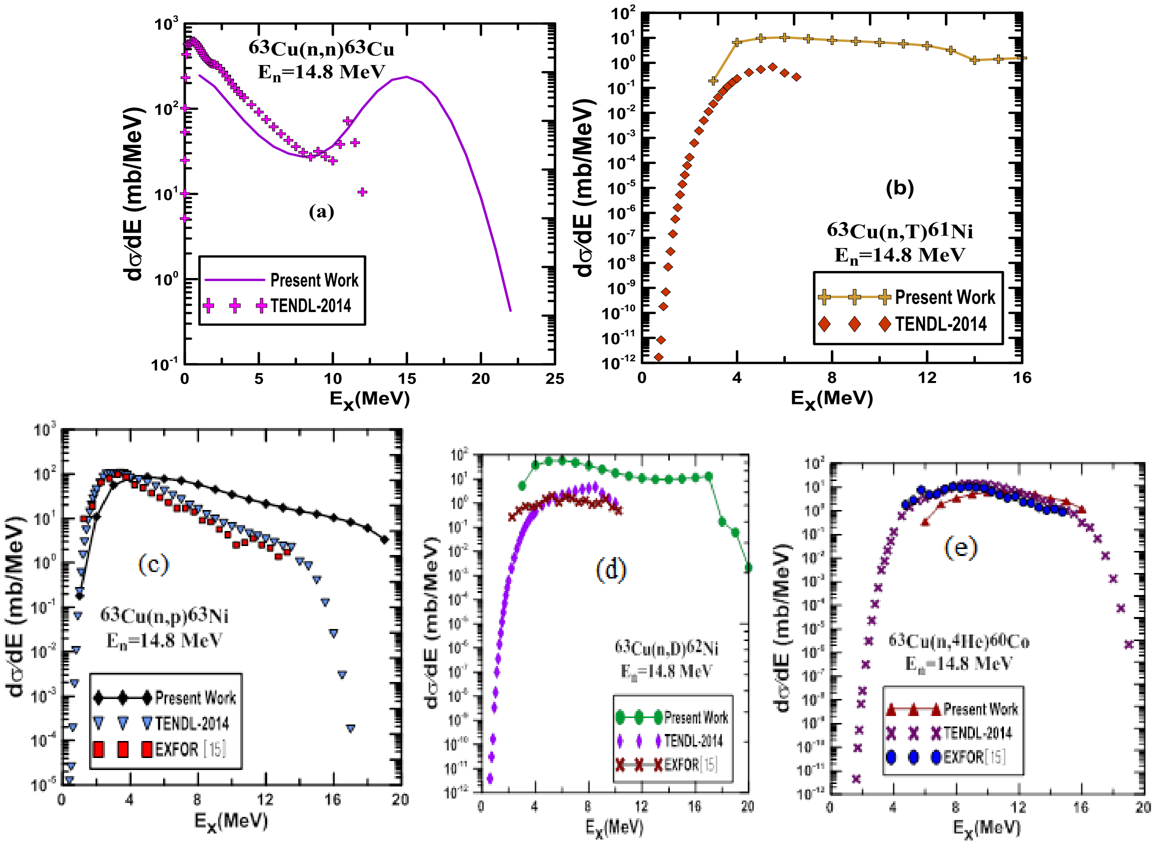

Figure 2- A comparison between the calculated energy spectrum with refs [19, 20], as a function of particle emission energy, Ex, in cm-system and 14.8 MeV incident neutron for the reactions (a) ^{63}Cu (n, n) ^{63}Cu. (b) ^{63}Cu (n, T)^{61}Ni (c) ^{63}Cu (n, p)^{63}Ni. (d) ^{63}Cu (n, D)^{62}Ni (c) ^{63}Cu (n, ^{4}He)^{60}Co.

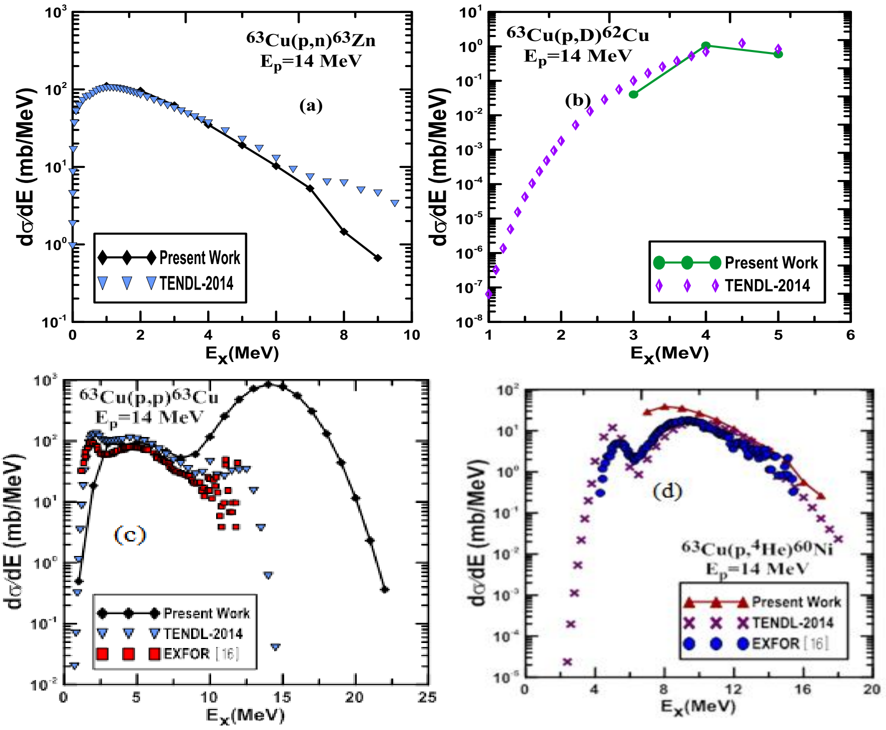

Figure 3- A comparison between the calculated energy spectrum with refs [19, 20], as a function of particle emission energy, Ex, in cm-system and 14MeV incident proton for the reactions (a) ^{63}Cu (p, n)^{63}Zn. (b) ^{63}Cu (p, D)^{62}Cu (c) ^{63}Cu (p, p)^{63}Cu (e) ^{63}Cu (p, ^{4}He)^{60}Ni.

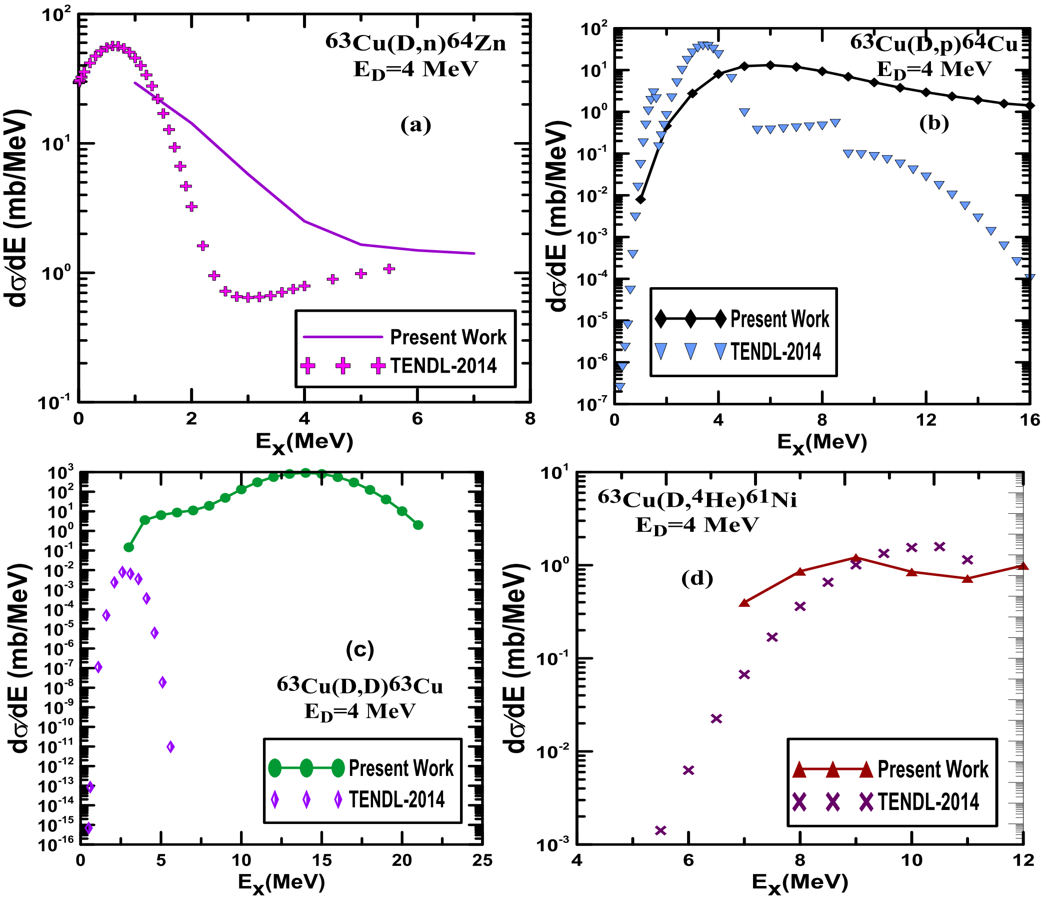

Figure 4- A comparison between the calculated energy spectrum with ref [19], as a function of particle emission energy, Ex, in cm-system and 4 MeV incident deuteron for the reactions:
(a) ^{63}Cu (D, n)^{64}Zn (b) ^{63}Cu(D, p)^{64}Cu (c) ^{63}Cu(D,D)^{63}Cu (d) ^{63}Cu(D, ^{4}He)^{61}Ni.

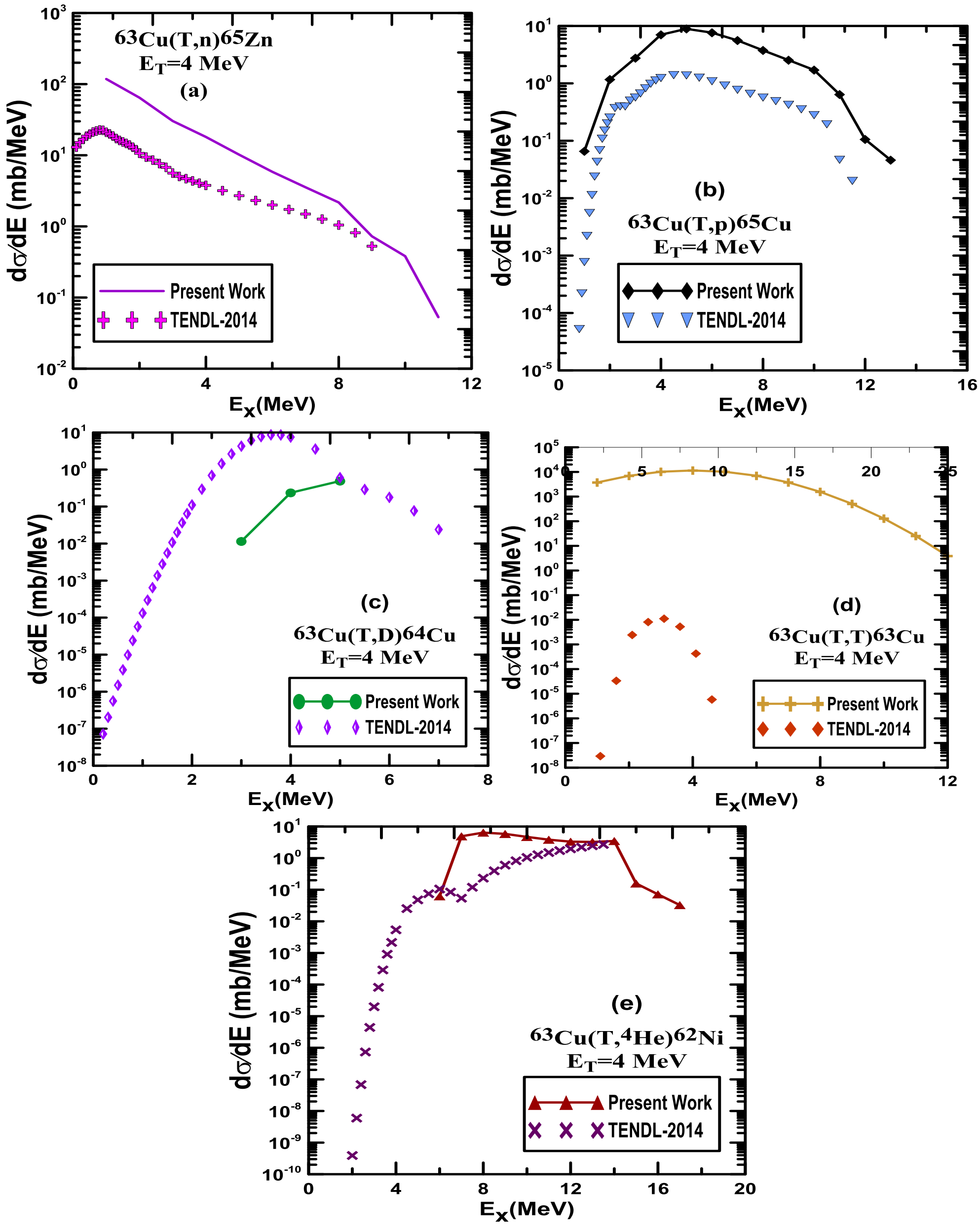

Figure 5- A comparison between the calculated energy spectrum with ref [19], as a function of particle emission energy, Ex, in cm-system and 4 MeV incident triton for the reactions (a) ^{63}Cu(T, n)^{65}Zn (b) ^{63}Cu(T, p)^{65}Cu (c) ^{63}Cu(T,D)^{64}Cu (d) ^{63}Cu(T, T)^{63}Cu (e) ^{63}Cu(T, ^{4}He)^{62}Ni at 4 MeV.

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