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Secondary Emission Effect on SomePre-Equilibrium Nuclear Reactions Spectra at Different Energies

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Abstract
The nuclear pre-equilibrium emission spectra have been studied and calculated using the exciton model with different reactions and incident energiesfor the target nuclei: ${}^{14}_{7}N$, ${}^{59}_{27}Co$, ${}^{90}_{40}Zr$ and ${}^{208}_{82}Pb$. The secondary emissioncomponent has been inserted to the final emission spectrum and its effectshave been studied for only reactions with primary nucleons emission because the restrictions introduced by primary clusters emission reactions. It revealed a big contributioninenhancing the calculated energy spectra atincident energies more than$\geq 15\ MeV$.

Keywords: Nuclear Reaction; Pre-equilibrium; Secondary Emission; and Exciton Model.

تأثير الأنبعاث الثانوي على بعض اطياف تفاعلات ما قبل التوازن النووية عند طاقات مختلفة

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الخلاصة
لقد تمت دراسة و حساب اطياف الأنبعاث لتفاعلات ما قبل التوازن النووية بأستخدام أنموذج الأيكسايتون عند طاقات مختلفة وللنوى الهدف: ${}^{208}_{82}Pb$ و${}^{90}_{40}Zr$ و${}^{59}_{27}Co$ و ${}^{14}_{7}N$. تمت اضافة مركبة الأنبعاث الثاني لطيف الأنبعاث النهائي ودُرست تأثيراتها لأنبعاثات النيوكليونات فقط لوجود مقيدات على انبعاث العناقيد. اضافة المركبة الثانية لطيف الأنبعاث النهائي عززت وبصورة كبيرة الأطياف النهائية وخاصة عند طاقات اكبر من 15 مليون الكترون فولط للجسيمات الساقطة.

Introduction

For more than forty years, pre-equilibrium nuclear reaction models still need spatial treatments because of the statistically nature of these models, which need many improvements on its components such as the partial level density and the matrix element. However, there are many attempts [1-6] were done to attend the good description of the emission spectra of the pre-equilibrium. The exciton model of Griffin [7, 8] represents the first and most successful and suitable modelover all other pre-equilibrium reactions models are based on, to describe the equilibration (the attainment of statistical equilibrium) of the composite nucleus. In this model, the states of a system are described by the number of excitons$n$that created as a result of the projectile-target interaction. These excitons are

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represented by the number of particles p and holes h produced from the residual, two-body and energy conserved intranuclear interactions that cause transitions between different states [9].
The pre-equilibrium reaction is assumed to be initiated by the formation of the composite nucleus with $n = p + h$ state, or $2p - 1h$ configuration. This state may decay by emitting $p$particles or makes an internal transition into another exciton state of$3p - 2h$ configuration.

The emission probability of a particle β with emission energy ε from n exciton state in a nucleus of excitation energy E is given by [9]:

$$W_\beta(n, E, \varepsilon) = \frac{2s_\beta+1}{\pi^2\hbar^3}\mu_\beta\varepsilon\sigma_\beta(\varepsilon)\frac{\omega(n-1,U)}{\omega(n,E)} \qquad \text{.................1}$$

wheres_β is β particle spin, and μ_β is the reduced mass. The quantity $\sigma_\beta(\varepsilon)$ is the total reaction cross section for the inverse of the exit channel process (i.e. absorption of a particle of type β on the residual nucleus), and U is the excitation energy in the residual nucleus. $\omega(n, E)$represents the state density of the excited state before emission. The $(n - 1)$exciton state produces residual excitation energy given by $U = E - \varepsilon - B_\beta$ where B_β is the binding energy of the emitted particle in the emitting nucleus.
In the two-component exciton model and by using the exciton state as$n = n_\pi + n_\nu = p_\pi + h_\pi + p_\nu + h_\nu$,then, $W_\beta(n, E, \varepsilon)$ can take the form:

$$W_\beta(p, p_\pi, E, \varepsilon) = \frac{2s_\beta+1}{\pi^2\hbar^3}\mu_\beta\varepsilon\sigma_\beta(\varepsilon)\frac{\omega(p_\pi-1,h_\pi,p_\nu-1,h_\nu,U)}{\omega(p,p_\pi,E)} \qquad \text{.........2}$$

where the label $(p, p_\pi, E, \varepsilon)$ is a shorthand for $(p_\pi, h_\pi, p_\nu, h_\nu, E, \varepsilon)$ and $p_\pi, h_\pi, p_\nu, h_\nu$ stands for proton particles, proton holes, neutron particles and neutron holes, respectively. The basic state density formula is given by Williams formula [10]:

$$\omega(p, p_\pi, E) = \frac{(g_{\pi0})^{n_\pi}(g_{\nu0})^{n_\nu}[E-A(p,p_\pi,E)]^{n-1}}{p_\pi!h_\pi!p_\nu!h_\nu!}. \qquad \text{................3}$$

$g_{\pi0}$and$g_{\nu0}$ are the proton and neutron single particle state densities respectively; $A(p, p_\pi, E)$ is the Pauli correction function.

The energy spectra of the emitted particles depend on excitonstates because different exciton states give different energy distributions. Thus, the energy spectra (differential pre-equilibrium cross sections) is given by:

$$I_\beta(\varepsilon, t)d\varepsilon = \frac{d\sigma}{d\varepsilon} = \sum_n P(n, t)W_\beta(n, \varepsilon)d\varepsilon \qquad \text{........4}$$

$P(n, t)$is the occupation probability that represents the time weighting factor. It is the probability of a system to occupy a state specified by the exciton number n and excitation energy E at time t. $P(n, t)$isrelated to the *transition rates* or *interaction rates*λthat resulted from the two-body interactions which specifies the density of the final accessible states. $\lambda$is calculated from the*Time-dependent Perturbation Theory* and given by awellknownrelation *"Fermi's Golden Rule"* [7,8,11]:

$$\lambda = \frac{2\pi}{\hbar}|M|^2\omega_f \qquad \text{.........5}$$

where $|M|^2$ is the mean square matrix element of initial and final states of a specific interaction and it is evaluated empirically by making a global fit with experimental data [12]; and ω_f is the density of final accessible states.

Since the state density, Eq. (3), depends on the number of excited particles p, then there would be a possibility for the nucleus to emit more than one particle if there is sufficient energy.
If the composite nucleus is at a state given by $n = 3$or $n = 5$, the primary particle emission will leave the nucleus with $p - 1, h$ configuration at residual excitation energy $U(= E - B_\beta - \varepsilon)$ [13]. After that, the emission of a second particle may occur from the same exciton stateor from higher states as a result of another intranuclear transitions caused by the residual two-body interactions.

At incident energies approach 200 MeV, the pre-equilibrium emission calculations must involve the multiple emission process [14]. The early work of Blann [15] showed that the secondary pre-equilibrium emission is possible and more probable from the same exciton state at high excitation energies. Thus, the secondary pre-equilibrium reactions importance manifested at $n > n_0$ states.

Fortunately, the physical addition of this process is straightforward in the exciton model [14]; since the change is carried out on the binding energy of the residual nucleons. If the primary emitted nucleon was a neutron, then the binding energies become $B_n(Z, N - 1)$and $B_p(Z, N - 1)$; and if it was a proton then they become $B_n(Z - 1, N)$ and $B_p(Z - 1, N)$. This directly change the energy of the residual nucleus U, therefore we can use the same equations and parameters of the primary nucleon emission.

Results and Discussion

The calculations ofthetotal reaction spectra (Eq. 4) for various reactions at different energies,for $^{14}_{7}N$, $^{59}_{27}Co$, $^{90}_{40}Zr$ and $^{208}_{82}Pb$ targets taken with $(p,p),(n,n),(p,n)$ and (α,p) reactions at 18 MeV, 25 MeV,62.9 MeV and96 MeV, were performedusing PRECO-2006 code [12].PRECO-2006 is a two-component exciton model code for the calculation of double differential cross sections of light particle nuclear reactions. The code, written in FORTRAN-77, runs on a PC and calculates the emission of particles up to mass four, including separate subroutines for nucleon transfer processes, knockout and inelastic scattering involving complex particles, and collective state excitation (both discrete and giant resonance states).The results were compared with experimental data taken from EXFOR online library [16] to investigate the effects of secondary emissionon the total reaction spectrum.

The comparisons showed that secondary emissions give a significant contribution to the energy spectrum. It was found that the probability of secondary particle emission increases with increasing the projectile’s incident energy (or excitation energy$E$). This behavior can be showed as follow; as the energy increased the number of excitons also increased and there will be sufficient energy to more than one particle to be emitted during pre-equilibrium stage.

The calculations of the present work were divided into two parts to investigate the effects of secondary emission on energy spectra; one of them took the secondary emission into account and the other did not. For taken into account secondary emission calculations, the total energy spectra were closer to that of experimental as the excitation energy increased and there was no difference and/or no significant difference at relatively low energies, e.g. 18 MeV. The calculated spectra illustrate that secondary emission decreases as the emission energy ε increases, i.e. its probability to occur at first stages of emission is higher than that at later stages since the energies taken in earlier stages are small compared with those of later.This gives the opportunity to the emission of a second particle.

The overall obtained results and comparisons with experimental data are illustrated in Figures-(1**,** 2**,** and 3). They give the difference between spectra with secondary emission and spectra without it. In all figures, the agreement between the calculated spectra means that there is no secondary emission at these emission energies and the deviation refer to the presence of secondary emission. In Figure-1there is very small difference between calculated spectra at first emission stagesdue to the relatively low incident energy (18 MeV). The differences become more obvious for higher incident energies and extend to more emissionenergies as shown in Figures-(2, 3) at 25 MeV,62.9MeV and96 MeV. At 25 MeV, Figure-2, the calculation with secondary emission are closer to the experimental than the calculation without it at first emission energies. However, the differences between the emission spectra with and without secondary emission became obviousat incident energy more than 15MeV, and this can be attributed to the increasing in the sharing energy of the constituents of the excited nucleus that give more chance to emit a secondary particle. This behavior is clearly showed in Figures-(2, 3).
In addition, the obtained results strongly suggested that there are no effects of the types of the incident and emitted particles on the increasing the probability of secondary emission. Finally, increasing in the mass number of the target and the incident particle don’t showed cleareffects.

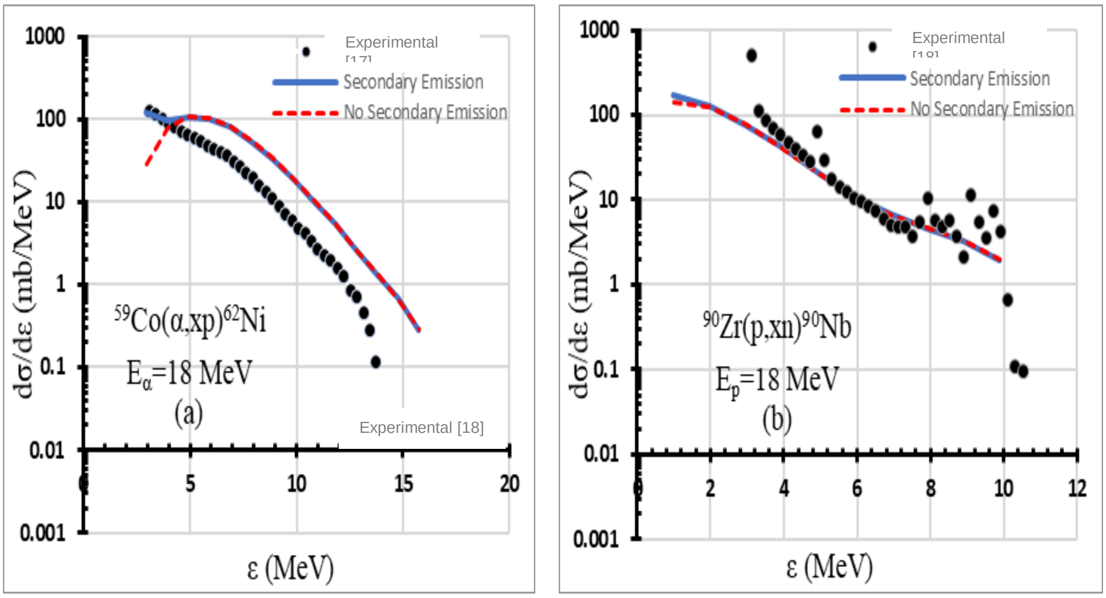

Figure 1-A comparison between the calculated spectra, with and without secondary emission (blue line and red dashed line), and experimental spectrum (black circles) for the reactions: (a) $^{59}Co(\alpha,p)^{62}Ni$ at $E_\alpha = 18\ MeV$ [17] and (b) $^{90}Zr(p,n)^{90}Nb$, at $E_p = 18\ MeV$ [18].

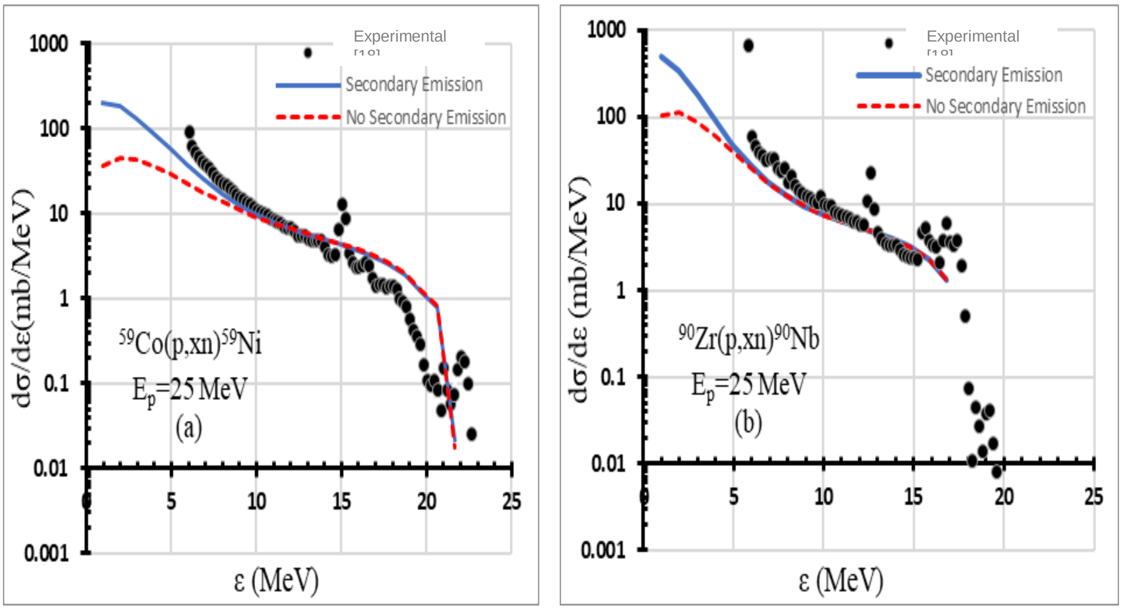

Figure 2-A comparison between the calculated spectra, with and without secondary emission (blue line and red dashed line), and experimental spectrum (black circles) for the reactions: (a) $^{59}Co(p,n)^{59}Ni$ and (b) $^{90}Zr(p,n)^{90}Nb$, at $E_p = 25\ MeV$ [18].

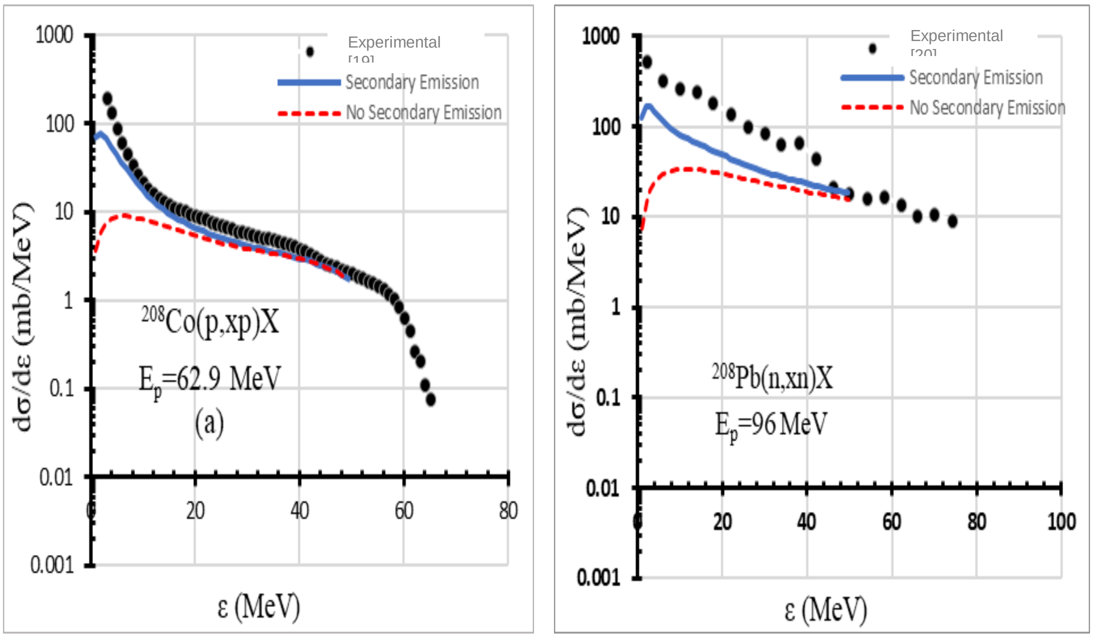

Figure 3-A comparison between the calculated spectra, with and without secondary emission (blue line and red dashed line), and experimental spectrum (black circles) for the reactions: (a) $^{59}Co(p,xn)X$ at $E_p = 62.9\ MeV$ [19] and (b) $^{208}Pb(n,xn)X$ at $E_n = 96\ MeV$ [20].

Conclusion

In this work, the effect of adding the secondary emission to the emission spectra of pre-equilibrium nuclear reaction using exciton model was studied and compared with available experimental data. From the obtained results, one can conclude that the emission spectra have been improved by adding secondary emission, especially at incident energy more than 15 *MeV*. Furthermore, the mass numbers of the target and projectile, and the types of the projectile and emitted particle don't affect the increasing of the probability of secondary emission.

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