Initial exciton configuration in (p, n) pre-equilibrium emission reactions

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(Received 3 July 2007; revised manuscript received 5 March 2008; published 9 July 2008)

Possible configurations in which excitons can be excited are demonstrated and discussed. A pre-equilibrium model code was developed in the framework of exciton and hybrid models using specified exciton configurations. The calculations were restricted to proton induced reactions at energies below 100 MeV. Results support the suggestion that a hole exists just below the Fermi energy before the reaction is initiated. A reduction in the relative abundance of high energy particles in the emission spectra may arise from the existence of such a hole state in the initial reaction phase and a subsequent thermalization among excitons during the phase lifetime. All suggested particle configurations give similar final results; the distinction among them lies in how and when the emissions occur. A "memory" factor is given for the particle configurations to determine to what extent the configuration can "remember" the entrance channel.

DOI: 10.1103/PhysRevC.78.014601 PACS number(s): 21.10.Pc, 25.10.+s, 25.40.Kv

I. INTRODUCTION

In recent decades, many studies have appeared in literature concerning pre-equilibrium emission models of nuclear reactions, from the work of [1] to the developments of [2–14], and remarks prepared by [15,16]. The statistical semiclassical (SS) picture may be dated to 1948 by [17] as an internuclear cascade (INC) reaction, which is included in models of high energy nuclear collisions. Griffin [1] proposed his own SS picture focused on equilibration of the system as a whole in contrast to INC models which treat the equilibration as a sequence of quasifree emission processes.

Several formulas were proposed to describe SS particle emission [2–5,13,16,18–22]. In general, all these formulas treat the particle emission as a competition among excited particles undergoing an equilibration process. The exciton model (EM), as treated by [5], utilizes the average-state configuration lifetime instead of the single-particle lifetime viewed by Blann [2,13] in his hybrid model (HM). In addition, the EM treats the nucleon emission as well as nucleon cluster emission [23,24] and γ-emission [6,25,26]. Another modification was made for the HM by [13,14] to avoid the multi-exciton density that was criticized by [15].

Due to the nature of pre-equilibrium reactions as successive steps of phase transitions, the term "phase" will be used throughout the present work to denote the state of equilibration among excitons. In the present work, exciton configurations of the reaction phases are the subject of the investigation.

II. FORMULATION OF THE THEORY

In SS models, it is assumed that reactions take place in successive phases enumerated by index $i = 0, 1, 2, \ldots$. Each phase has its own configuration characterized by the number of particles, p_i, and holes, h_i in the system. The differential emission spectrum may be written as

$$\frac{d\sigma}{d\epsilon_p} = \sigma_R \sum_i^{i_{\max}} D_i \; W_{c,i}, \tag{1}$$

where

$$W_{c,i} = \rho_i(E, \epsilon_p, p_i, h_i) \frac{\lambda_{c,i}(\epsilon_p)}{\Lambda_{1,i} + \Lambda_{2,i}}. \tag{2}$$

Here, $W_{c,i}$ represents the conditional probability that a particle will be emitted to the continuum from the ith phase. The probability per unit time that a system in one of the time reversed phases will undergo a transition into *any one* of its time reversed compound nucleus states is the particle emission rate into the continuum, $\lambda_{c,i}(\epsilon_p)$,

$$\lambda_{c,i}(\epsilon_p) = \frac{(2s_p + 1)\mu_p}{\pi^2 \hbar^3 g} \epsilon_p \sigma_{inv}(p_i - 1, h_i, \epsilon_p, U). \tag{3}$$

On the other hand, the probability per unit time that an exciton belonged to the ith phase and with excitation energy ϵ undergoes a thermalization collision to form the next phase exciton(s) generation is denoted $\lambda_{+,i}(\epsilon_p)$; its value is derived from [27] formulas as

$$\lambda_{+,i}(\epsilon_p) = \frac{2\pi}{\hbar} |M|^2 \frac{g^3 \epsilon_p^2}{2(n_i + 1)}, \tag{4}$$

where $|M|^2$ is the square of the scattering matrix element. The term D_i is the statistical depletion factor that takes into account the nuclei that decayed in previous phases, and the fraction that remains subject to the next decay possibilities.

The denominator in Eq. (2) is the total emission rate of the ith phase due to possible particle emissions and transitions. In HM and its modification [13], it is assumed that the configuration mixing is absent (i.e., pure configurations) [15]. In such pure configurations, the probability for a particle to escape into the continuum is expressed as a branching ratio of single-particle emission rates $\lambda_{c,i}(\epsilon_p)$ and $\lambda_{+,i}(\epsilon_p)$ in the ith phase, i.e., $\Lambda_{1,i} = \lambda_{c,i}(\epsilon_p)$ and $\Lambda_{2,i} = \lambda_{+,i}(\epsilon_p)$. In the EM as formulated by [5], the configuration mixing exists and particle emission takes place from any configuration

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containing *such* particle. The emission competes with the decay from configurations of all excitons that are excited with all possible energies. That means that the denominator terms should be

$$\Lambda_{1,i} = \int_0^E \rho_i(E, \epsilon_p, p, h)(\lambda_{c,i}(\epsilon_p) + \lambda_{+,i}(\epsilon_p))d\epsilon_p$$

and

$$\Lambda_{2,i} = \int_0^E \rho_i(E, \epsilon_h, p, h)\ \lambda_{+,i}(\epsilon_h)d\epsilon_p.$$

The exciton distribution function $\rho_i(E, \epsilon_{p/h}, p_i, h_i)$ is the probability that one out of the total excitons, $n_{i,t} = p_i + h_i$, sharing the total excitation energy E is an exciton residing at a single-particle/hole energy ϵ_p/ϵ_h. The integration of exciton distribution function over all particle and hole energies yields the total number of excitons

$$\int \rho_i(E, \epsilon_p, p_i, h_i)d\epsilon_p + \int \rho_i(E, \epsilon_h, p_i, h_i)d\epsilon_h = n_{i,t}, \quad (5)$$

disregarding the model used.

The general form of the single-particle distribution function is

$$\rho_i(E, \epsilon_p, p_i, h_i) = g\frac{\omega(U, p_i - 1, h_i)}{\omega(E, p_i, h_i)} \quad (6)$$

and

$$\rho_i(E, \epsilon_h, p_i, h_i) = g\frac{\omega(U, p_i, h_i - 1)}{\omega(E, p_i, h_i)}\ , \quad (7)$$

where $U = E - B_p - \epsilon_{p/h}$ and B_p is the binding energy of the particle in the compound system. Several studies have focused on the exciton distribution function and particle state density $\omega(E, p_i, h_i)$ [28,29].

The number of excitons that are emitted and thermalized in each phase is given as

$$\int_0^E W_{c,i}(E, \epsilon_p, p_i, h_i) + W_{+,i}(E, \epsilon_p, p_i, h_i)d\epsilon_p + \int_0^E W_{+,i}(E, \epsilon_h, p_i, h_i)d\epsilon_h = n_{i,p}\ , \quad (8)$$

where, $n_{i,p}$ is partial number of excited particles generated in the ith phase, $n_{i,t} = n_{i,p} + n_{i-1,p} + \cdots + n_{0,p}$.

The value of Eq. (8) is one (taking into consideration that the number of particles generated during each phase is one) or p_{i-1} according to the particle configuration employed. In the context of original HM, this number is replaced by the number of excitons in the current phase, i.e., the total number of particles in each phase is twice the number of particles generated in the preceding phases (in addition to the generated holes). In the present calculations, the two values of $n_{i,t}$ are checked using both models. The value of $n_{i,p}$ was limited to unity using statistical weight illustrated in the following discussion of chains A and B in addition to the value involved Markov chain in which $n_{i,p} = 2n_{i-1,p}$.

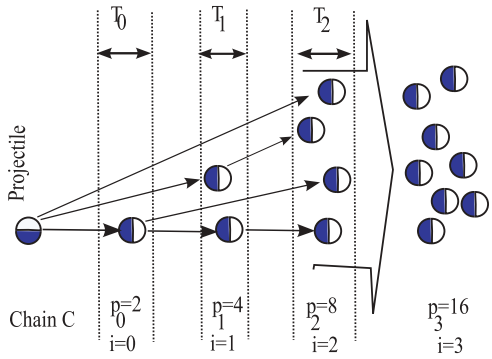

FIG. 1. (Color online) Markov-type configuration of particles excitation. The number of particles existing in each phase is the sum of the number of excited particles in the current phase and all previously excited particles plus the incident particle. The opaque and open part of the circle represent the possibility of neutron or proton excitation.

III. EXCITON CONFIGURATIONS

Considering phase lifetime τ_i to be the time taken by excitons to interact among each other, hence, the time between two successive phases, τ_i', leads us to the possible configurations that excitons can be generated at each step. Due to the distinction between neutron and proton mutual interaction cross sections [13], the population of the exciton state in each phase by protons or neutrons depends on how one describes the chain of excitation.

There are two limiting cases, one in which the phase lifetime is much less than inter-phases time, $\tau_i \ll \tau_i'$. In such case, it is possible for all excitons in the phase to generate additional p-h pairs, a Markov-type chain for excitation of particles is started, see Fig. 1. If hole interactions is taken into account, the Markov-type chain will be more complicated. The exciton number will increase as $n_{i,t} = 3n_{i-1,t}$. The Markov process is a discrete-time stochastic process with the Markov property. Having the Markov property means the next phase is solely dependent on the present phase and does not directly depend on the previous phases. The memory factors of Markov configuration in cases of incident protons will be $F_{M1} = 0.1181$, $F_{M2} = 0.023$, $F_{M3} = -0.0012$, $F_{M4} = -0.0073, \ldots$ etc. The minus sign indicates exceeding neutrons, see Sec. IV for the definition of memory factor.

The other limiting case occurs when the phase lifetime becomes comparable with the interphase time, $\tau_i \sim \tau_i'$. In the last situation, only one of the excited particles has the ability to induce the transition to the next phase. Consequently, the number of particles is increased by 1, see Fig. 2. In Fig. 2, chain A represents a configuration in which only one of the previously generated particles (statistically) has to create the next generation. The next phase will have only one additional particle whose type is determined by the statistical weight of previously excited particle interactions and types. The memory factors of this chain in cases of incident protons will be $F_{M1} = 0.1181$, $F_{M2} = 0.1182$, $F_{M3} = 0.07$, $F_{M4} = 0.061, \ldots$ etc.

Measurements cannot be performed nucleus by nucleus, but rather the collective emission of the sample is measured. Accordingly, it is not necessary for one nucleus to undergo

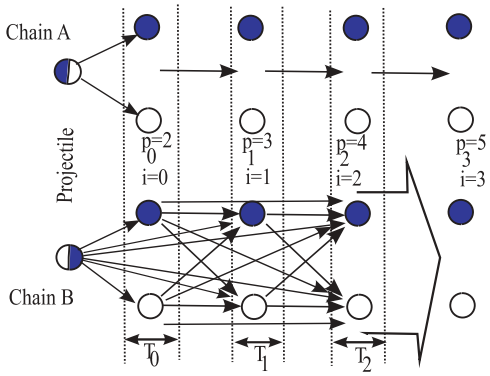

FIG. 2. (Color online) Exciton-type configurations of particle excitation. The number of particles that exist in each phase is the sum of all previously excited particles plus the incident particle and a particle excited in the current phase. The opaque and open circles represent the possibility of neutron or proton excitation.

all possible excitations but it is a matter of the weight of statistical ensemble of excited nuclei. Chain B represents the case in which the mutual nucleon-nucleon (NN) interactions determine the statistical weight for exciting a particle (proton or neutron) in all nuclei. The next phase will have one additional particle whose type is determined by the statistical weight of NN cross sections. The memory factors of this chain in cases of incident protons are $F_{M1} = 0.1181$, $F_{M2} = 0.054$, $F_{M3} = 0.03$, $F_{M4} = 0.019$, . . . etc.

If just one of the excited nucleons has to create the next generation, chain A, the system continues to remember the entrance channel for a longer time than the case in which the probability of exciting next generation particles results from the contribution of all existing particles, chain B. In the second case the system quickly forgets the entrance channel.

It is assumed that a hole cannot interact with a particle and a particle cannot interact with a hole according to [5]; holes just appear upon particle excitation and take its energy as a result of conservation of momentum. The original HM and EM assume that particles and holes are capable of producing additional pairs in any subsequent phase. However, hole interaction with a particle is still questionable. The author of [5] restricted the exciton-exciton interaction to p-p and h-h interactions. Since the hole is the act of the whole nucleus but one, the last suggestion may be true for the first approximation because of the low mobility of holes at low excitation energy <100 MeV.

The configurations of hole generation are restricted in the present work into two types, one in which the hole is created as a consequence of a particle excitation and another which is similar to the first one excluding the initial phase configuration in which the hole is absent.

IV. THE NUMERIC COMPUTATIONS

The present calculations are based on the general formula (1). The fusion reaction cross section is calculated using the well-known formula [30]. Transmission coefficients, on the other hand, are calculated using the complex phase shift caused by the optical model potential. The fundamental constants used in the calculation were taken from [31]. The optical model parameter used in the following calculations are those recommended by [32] for the global optical model potential. The calculations also involve the computation of the Coulomb wave function using the procedure mentioned in Refs. [33,34]. The transition rate, $\lambda_{+,i}$, is calculated using [35] matrix element formula

$$|M|^2 = A^{-3} \frac{8.1 \times 10^5}{(E/n_i + 14.4)^3}. \tag{9}$$

In order to find the collision partners of NN interaction in each phase, formulas presented in [13] are used. It is assumed that proton-neutron (π-ν) cross section is three times the ν-ν or π-π cross sections. An additional factor is used in the present work; it is the "memory" of the configuration. Here, one could define the memory factor as $F_{Mi} = [p_i^{\text{inc.}}/(p_i^{\pi} + p_i^{\nu}) - 0.5]$, where $p_i^{\pi/\nu}$ is the number of protons/neutrons in the ith phase and $p_i^{\text{inc.}}$ is the number of incident-like particles in the ith phase. The value of F_{Mi} is between -0.5 and 0.5.

V. RESULTS AND DISCUSSIONS

Neutron energy-differential cross sections are calculated for reactions presented in Table I. The following subsections are the discussions of the role of hole configuration, particle configuration, and models selection.

TABLE I. List of investigated reactions associated with its incident particle energy (in Lab.) and citation.

Target	Reaction	Energy (MeV)	Ref.
^{50}Cr	(p, xn)	25	[36]
^{52}Cr	(p, xn)	25	[36]
^{53}Cr	(p, xn)	25	[36]
^{54}Fe	(p, xn)	25	[36]
^{54}Fe	(p, xp')	28.8	[37]
^{56}Fe	(p, xn)	25	[36]
^{58}Fe	(p, xn)	25	[36]
^{59}Co	(p, xn)	25	[36]
^{60}Ni	(p, xn)	25	[36]
^{90}Zr	(p, xn)	25	[36]
^{92}Zr	(p, xn)	25	[36]
^{92}Zr	(p, xp')	30.3	[38]
^{92}Mo	(p, xn)	25.6	[39]
^{92}Mo	(p, xp')	30.3	[38]
^{94}Zr	(p, xn)	25	[36]
^{94}Mo	(p, xn)	25.6	[39]
^{96}Mo	(p, xn)	25.6	[39]
^{100}Mo	(p, xn)	25.6	[39]
^{104}Pd	(p, xn)	21.6	[40]
^{105}Pd	(p, xn)	21.6	[40]
^{106}Pd	(p, xn)	21.6	[40]
^{108}Pd	(p, xn)	21.6	[40]
^{159}Tb	(p, xn)	25	[36]
^{208}Pb	(p, xn)	25	[21]
^{208}Pb	(p, xn)	35	[21]
^{208}Pb	(p, xn)	45	[21]
^{208}Pb	(p, xn)	62.9	[41]

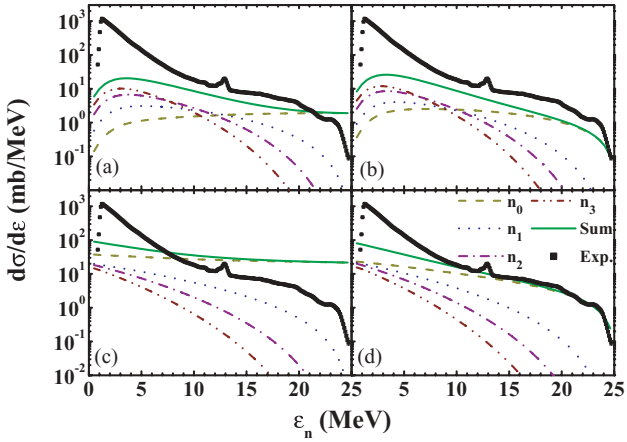

FIG. 3. (Color online) Energy-differential cross sections calculated with different hole configurations for ^{100}Mo(p, xn) reaction. Calculations were done with $n_0 = 2$ [(a) and (c)] and $n_0 = 3$ [(b) and (d)] in the framework of the exciton model [(a) and (b)] and hybrid model [(c) and (d)] assuming the configuration presented in chain A of particle generation.

A. Role of hole configuration

Neutron energy-differential cross sections are calculated for ^{100}Mo(p, xn) reaction with the two limiting hole cases. One in which a hole state exists in the initial phase ($n_{0,t} = 3$) and another in which the hole is absent ($n_{0,t} = 2$). Figure 3 shows the emission spectra of neutron treated by EM and HM considering particle configuration shown in Fig. 2A. Results showed that whatever the reaction model used, the existence of a hole state in the initial configuration is a necessity to accomplish the best fit to experimental measurement.

The high energy tail of the emission spectra for $n_{0,t} = 2$ is much higher than the experimental data in agreement with the results given by [3]. A hole state has to exist in the calculations. Such issue may be thought as a consequence of the existence of a hole just below the Fermi energy before the reaction is initiated [42]. The smallest interphase time is suitable to describe the pre-equilibrium nuclear reaction which is mainly a direct reaction. However, the reduction in the relative abundance of high energy particles upon the existence of a hole state in the initial phase configuration suggests that thermalization occurs within the phase lifetime, τ_0. Henceforth, the calculation will be performed with configurations involving a hole state in the initial phase.

B. Role of particle configuration

It is mentioned in textbooks that a compound-nuclear reaction does not have a "memory". In pre-equilibrium nuclear reactions the nucleus remembers the entrance channel for a period of time as indicated in Sec. III. The calculations are performed for the ^{100}Mo(p, xn) reaction with the three mentioned particle excitation configurations to distinguish to what extent the nucleus continues to remember the entrance channel. Figure 4 illustrates the calculated neutron spectra calculated for the presented particle configurations using HM and EM in comparison with experimental data.

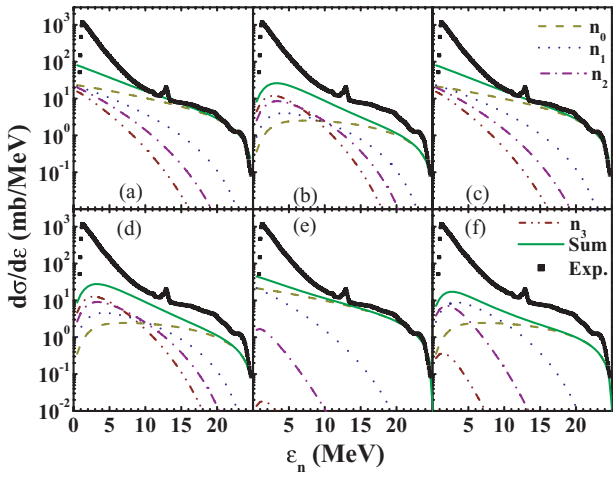

FIG. 4. (Color online) Energy-differential cross section calculated with the three mentioned particle configurations for the ^{100}Mo(p, xn) reaction. (a) and (b) represent calculations for chain A for both HM and EM, respectively. (c) and (d) show calculations for chain B for both HM and EM, respectively. (e) and (f) show calculations for the Markov chain for both HM and EM, respectively.

It is apparent from the results shown in Fig. 4 that all indicated particle configurations give, approximately, the same final results. The dissimilarity comes from the fraction of particles emitted in each phase. Most of the high energy particles emerge during the initial phase. Considering chains A and B, lower energy particle emission proceed with competition among different phases if the rules of EM are employed, while emission may take place in competition between emission and transition in each phase if the bases of HM are applied. In the case of Markov configuration, the contributions of the high-index phases are very small compared with the initial phase even for lower energy particle emission. Such difference may be explained in the framework of fast equilibration among excitons in each phase. In the Markov configuration, the energy is shared among a greater number of excitons, consequently, the statistical weight of particle emission from higher-index phases is smaller than emission from the other proceeding phases.

C. Models

The results plotted in Figs. 3 and 4 show differences between the bases of EM and HM calculations. The statistical probability of the particle emission sequence and its energy at that time explain the difference between EM and HM calculations. In the case of HM, a portion of the lower energy particle will be emitted also within the initial phase in addition to a comparable contribution of the higher-index phases. On the contrary, the greater portion of the lower energy particle will be emitted from higher-index phases by employing EM rules. This conclusion is acceptable if the deductions attained in the previous section become true, the thermalization occurs within the phase lifetime. However, it is difficult to judge the validity of one model or another from the present experimental

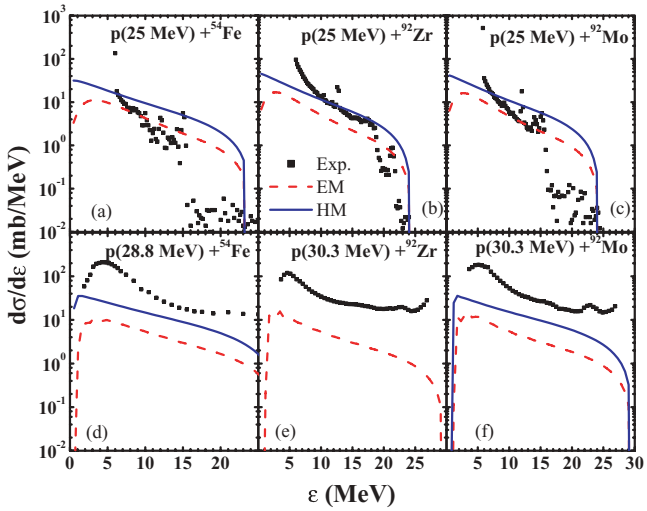

FIG. 5. (Color online) Emission spectra for neutrons (a)–(c) and protons (d)–(f) from different proton induced reactions.

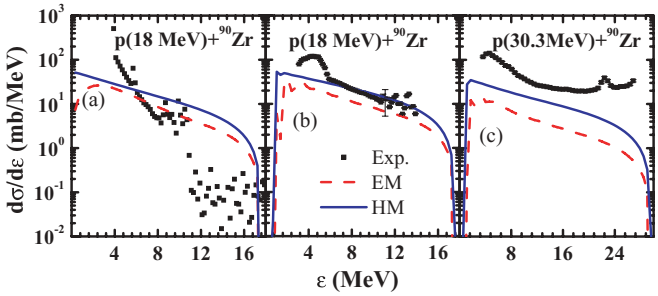

FIG. 6. (Color online) Emission spectra for neutrons (a) and protons [(b) and (c)] from a proton reaction with ^{90}Zr.

data; a time resolved differential cross section is needed but is impracticable.

From the results shown in Figs. 3 and 4, one realizes that HM gives a good approximation to the emission spectra, EM gives lower estimates. In order to make an acceptable comparison, five pre-equilibrium proton emission (p, p') in addition to four neutron emission reactions are calculated using EM and HM rules and compared with some of the available experimental data for neutron and proton emission from the same nuclei, Figs. 5 and 6. The measured spectra for the outgoing energies higher than 14 MeV show that pronounced structures correspond to the excitation of collective levels, such as the lowest 2^+ and 3^- levels of even-even zirconium nuclei. Such structures may restrain a proper comparison with model calculations. In general, predictions of the HM surpass EM predictions because the HM is based on the competition between emission and transition to the next phase only while bases of EM assume configuration mixing.

The emission competition among all particles that exists in prior and former phases may be statistically acceptable if all nuclei are in the same statistical ensemble. This idea is not practically acceptable because nuclei are isolated systems. Each nucleus undergoes a specific phase and the emission takes place from that phase regardless of what the other nuclei possess. The competition of emission takes place among particles within single phase, the other emission chances take place from other isolated nuclei determined by the depilation factor D_i. That is why the bases of HM are more practical than that of EM. Figures 7–9 show the HM predictions of neutron emission from proton induced reactions on the nuclei tabulated in Table I using the three mentioned particle configurations. In general, the Markov configuration has lower estimates than chains A and B. This is a result of the competition among a

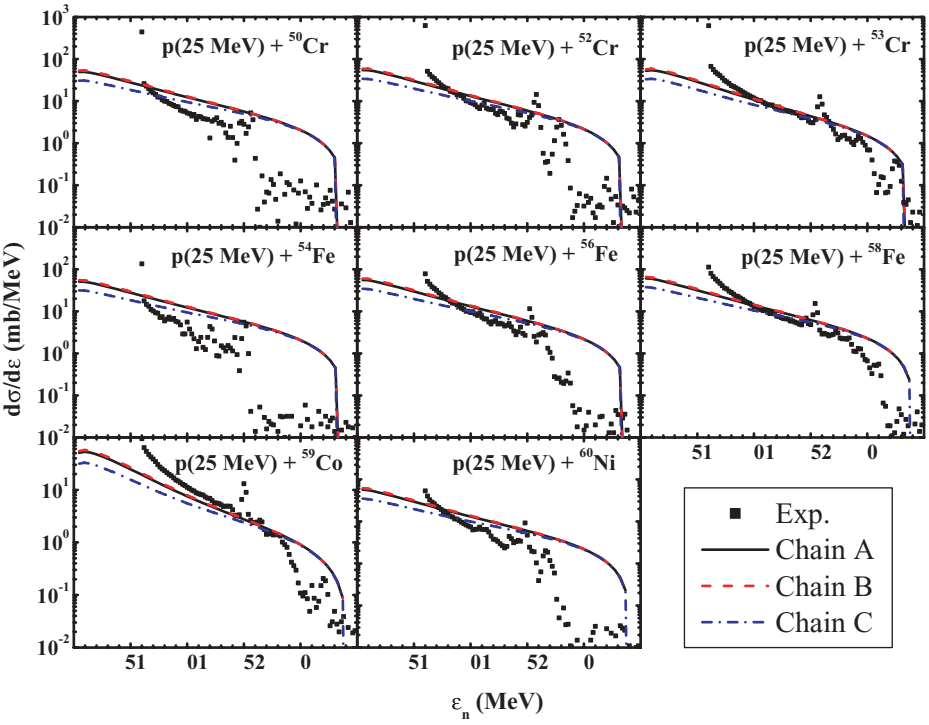

FIG. 7. (Color online) Neutron emission spectra from proton reaction with nuclei extended from ^{50}Cr to ^{60}Ni.

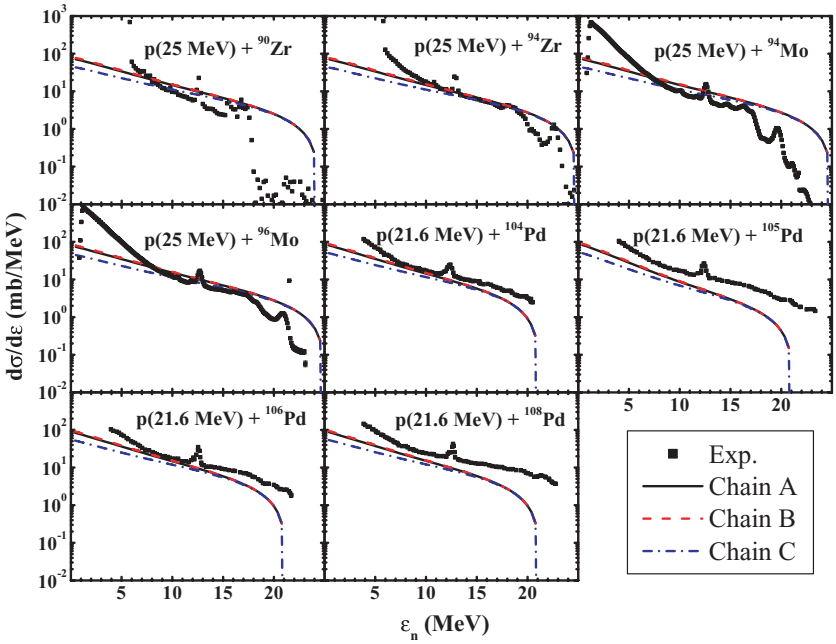

FIG. 8. (Color online) Neutron emission spectra from proton reaction with nuclei extended from ^{90}Zr to ^{108}Pd.

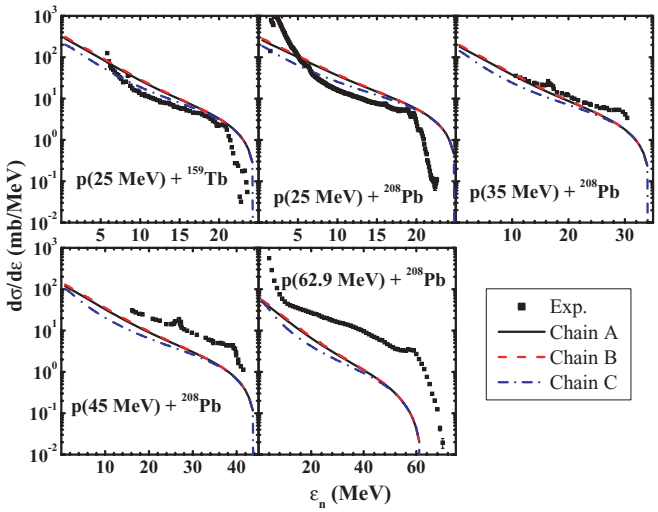

FIG. 9. (Color online) Neutron emission spectra from proton reaction with ^{159}Tb and ^{208}Pb.

greater number of excitons in that configuration. Remembering that the pre-equilibrium model is intended for a calculation of the high energy tail of the emission spectra, these three particle configurations are acceptable unless additional experimental measurements define the validity of one.

In Figs. 7–9, the HM calculations coincide with most of the emission spectra. Some deviation happened at high atomic weight and/or high energies in consequence of the usage of extrapolated global optical model parameters and/or level densities. Another reason is the existence of structural behavior near the high energy tail.

VI. CONCLUSION

In pre-equilibrium nuclear reactions, exciton configuration is an effective factor for emission spectra calculations. The possible exciton configurations are illustrated on the bases of EM and HM models. A hole has to exist in the initial configuration to realize the experimental behavior. The reduction in the relative abundance of a high energy particle upon the existence of a hole state in the initial phase configuration suggests that full thermalization occurs within the phase lifetime. Three particle configurations are checked. All particle configurations give, approximately, the same final results with both HM and EM models. The Markov configuration quickly forgets the entrance channel while other particle configurations have some longer "memory". Results show that model calculations may depend on the exciton configuration and each model has to have its own time emission pattern.

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