Exciton model for the description of pre-equilibrium emission in heavy-ion reactions

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INTRODUCTION

Series of experiments were performed in order to study the pre-equilibrium emission of Light Charged Particles (LCP) in fusion-evaporation reactions with different mass-asymmetry in the entrance channel [1-4] using the GARFIELD apparatus [5]. The LCP were measured in coincidence with evaporation residues to exclude contributions from other processes than fusion, including, for example, deep-inelastic reactions.

In this work we present a first attempt to describe experimental data with the exciton model based on the early work of J. J. Griffin [6].

EXCITON MODEL

In this model the state of the nuclear system is determined by the exciton number \( n = p + h \) and excitation energy \( E^* \). Here \( p \) is the number of particles above the Fermi energy level and \( h \) is the number of holes under the Fermi energy level. To analyze the probability \( P \) of finding the system in the \( n \)-exciton state at the time \( t \) the generalized kinetic master equation is used:

\[
\frac{dP(n,t)}{dt} = P(n-2,t)\lambda_+(n-2,E^*) + P(n+2,t)\lambda_-(n+2,E^*) - P(n,t)\left[\lambda_+(n,E^*) + \lambda_-(n,E^*) + W(n,E^*)\right]
\]

with the initial condition

\[
P(n,0) = \delta_{n,p_0} \delta_{h,h_0},
\]

where

\[
W(n,E^*) = \sum_b W_b(n,E^*) = \sum_b \int \lambda_b(n,\varepsilon_b) d\varepsilon_b
\]

is the emission probability of the particle \( b \) into a continuum, \( B_b \) is the binding energy and the transition rate of the particle emission into continuum. The transition rates \( \lambda_+ \) (in case when a particle-hole pair is created and a particle is scattered) and \( \lambda_- \) (in case when the single exciton scattering occurs with an increase of energy due to annihilation of a pair) [7] are defined as:

\[
\lambda_\pm = \frac{2\pi}{\hbar} \langle |M|^2 \rangle \omega^\pm (E^*),
\]

where \( \omega^\pm \) are appropriate particle-hole state densities and \( \langle |M|^2 \rangle \) is the transition matrix element. For more detailed description of the formalism we refer to section 4.1 of the reference [8].

Among the free parameters of the model we vary the parameter \( k \) of the transition matrix element \( \langle |M|^2 \rangle \), the initial exciton configuration \((p_0,h_0)\), and the parameter \( g \) of the particle-hole state densities \( \omega^\pm \). The single particle level density \( g \) around the Fermi surface is related with the level density parameter \( a \) as \( g = 6a / \pi^2 \). The value \( a \) is taken from the traditional Fermi-gas model or the phenomenological model of nuclear level density [9]. The parameter \( k \) defines the transition rates between the exciton configurations and time of the relaxation to the equilibrium state of the nuclear system. As a result, it affects the particle emission probability with the energy \( \varepsilon_b \). This parameter \( k \) is varied in the wide range from 100 to 800 MeV³.

COMPARISON WITH EXPERIMENTAL DATA

The experimental alpha-particle and proton spectra were measured for the mass-symmetric channel reactions 300, 400, 500 MeV \(^{64}\text{Ni} + ^{68}\text{Zn}\) and the mass-asymmetric channel reactions 130, 250 MeV \(^{16}\text{O} + ^{116}\text{Sn}\). In case of
complete fusion they would all lead to the Compound
Nucleus (CN) \(^{132}\text{Ce}^*\), with the excitation energies of 100,
150, 200 MeV in the case of the Ni induced reactions and
100, 200 MeV for the O induced reactions, respectively.

We performed the calculations for all reactions listed
above considering two thermal sources. The first source is
associated with the statistical particle distribution and we
will refer to it as “evaporative source”. The second source
represents the pre-equilibrium emission and will be
referred as “pre-equilibrium source”. Calculations of the
pre-equilibrium spectra were performed using the initial
exciton configurations \(n_0 = (32p,1h)\) and \(n_0 = (16p,0h)\) for
the \(^{64}\text{Ni} + ^{68}\text{Zn}\) and \(^{16}\text{O} + ^{116}\text{Sn}\) reactions, respectively and
the parameter of the transition matrix element \(k = 800\)
MeV\(^3\). Typical results of the exciton model calculations
are shown in Fig. 1 for the 250 MeV \(^{16}\text{O} + ^{116}\text{Sn}\) reaction at
\(\theta_{\text{lab}} = 35^\circ\). The results of the calculations are shown with
circles for the evaporative source, with triangles – for the
pre-equilibrium source and as a wide line for the sum of
the two sources, while experimental data are shown with
the crosses. As one can see there is an overall agreement
between the experimental data and calculations. A small
non-described extra yield is present in the alpha-particle
spectrum. This extra yield presumably could be due to an
additional fast source due to the projectile break-up.

**OUTLOOK**

Present calculations are performed in the simplified
exciton model, where the angular distribution of the pre-
equilibrium particles is assumed to be uniform in the
center-of-mass system. Therefore, as the next step of our
studies of the equilibration process, we plan to investigate
the angular distribution anisotropy of the emitted particles.
In this connection we plan to introduce the angular
dependence using the hybrid exciton model [10]. This
approach, regarding the angular distributions of the
particles, will allow us to analyze the proton and alpha-
particle spectra in the \(^{64}\text{Ni} + ^{68}\text{Zn}\) and \(^{16}\text{O} + ^{116}\text{Sn}\) reactions measured at a wide range of angles. This allows us to fix
the mentioned above free parameters of the exciton model
and use them for the calculations of the LCP pre-
equilibrium spectra.

Another important aspect is the calculation of the pre-
equilibrium neutron spectra since the average kinetic
energy of pre-equilibrium neutrons and pre-equilibrium
neutron multiplicity are necessary parameters in the total
CN energy loss determination. The results of the total
energy losses for the studied reactions will be presented in
detail in a forthcoming paper [3].

We expect that these calculations combined with the
measured spectra of LCP will shed more light on the
understanding of the pre-equilibrium emission mechanism.

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Workshop on Multifragmentation and Related Topics, Catania,
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references therein.