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Iwamoto-Harada coalescence/pickup model for cluster emission: state density approach including angular momentum variables

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Abstract. For low-energy nuclear reactions well above the resonance region, but still below the pion threshold, statistical pre-equilibrium models (e.g., the exciton and the hybrid ones) are a frequent tool for analysis of energy spectra and the cross sections of cluster emission. For α's, two essentially distinct approaches are popular, namely the preformed one and the different versions of coalescence approaches, whereas only the latter group of models can be used for other types of cluster ejectiles. The original Iwamoto-Harada model of pre-equilibrium cluster emission was formulated using the overlap of the cluster and its constituent nucleons in momentum space. Transforming it into level or state densities is not a straigthforward task; however, physically the same model was presented at a conference on reaction models five years earlier. At that time, only the densities without spin were used. The introduction of spin variables into the exciton model enabled detailed calculation of the γ emission and its competition with nucleon channels, and – at the same time – it stimulated further developments of the model. However – to the best of our knowledge – no spin formulation has been presented for cluster emission till recently, when the first attempts have been reported, but restricted to the first emission only. We have updated this effort now and we are able to handle (using the same simplifications as in our previous work) pre-equilibrium cluster emission with spin including all nuclei in the reaction chain.

1 Introduction

The first attempt to include complex particle (light cluster) emission into pre-equilibrium models appeared already in 1970 [1]. Therein, the only change was decreasing the exciton number in a residual nucleus not by one, as is done for nucleons, but by the mass number of the emitted cluster. That approach yielded results deeply below the experimental data, and this disagreement grew with increasing mass number of the cluster. To remove this discrepancy, Cline suggested (without any physical argumentation) to multiply the emission rates by the factorial of the cluster mass [2], which brought the calculations closer to the data. The artificial multiplication by the factorial of cluster mass number was soon replaced by introducing a clusterization probability [4], which brought calculations closer

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to experimental data. In parallel to that, the Milan group [3] suggested the existence of preformed α-particles in nuclei. Unfortunately, this approach is practically impossible to generalize to other types of ejectiles, whereas the approach of Ribanský and Obložinský is of general nature. The preformed α-particle model yielded better agreement to data than the other one, but the consequent development of the clusterization model minimized this gap. Having in mind general applicability for wide range of ejectiles, we consider the Iwamoto-Harada (Iwamoto-Harada-Bisplinghoff) model (IHB model) [5, 6] to be a suitable starting point for interpretation of complex particle spectra and other quantities.

2 IHB model — Further Steps on the Coalescence Way

2.1 Coalescence cluster emission

The nucleon emission rate is proportional to the ratio of the density of states of the residual nucleus with energy U ($U = E - \varepsilon_x - B_x$) and of the composite system density of states, $\omega(p-1,h,U)/\omega(p,h,E)$, where E is the excitation energy of the composite system (the system generally is not in equilibrium !), p and h are the numbers of excited particles and holes, respectively, E is the excitation energy of the composite system, B_x the binding energy of the type of nucleon considered (neutrons or protons) and ε_x their energy in the continuum. The coalescence model simply decreases the number of particle excitons not by 1, but by the mass number of the emitted cluster [1, 2, 4]. Specifically, in the latest version of the "classical" coalescence model [9], the cluster emission rates of a cluster of type x are proportional to

$$\gamma_x \frac{\omega(p-p_x,h,U)}{\omega((p,h,E)} \frac{\omega(p_x,0,\varepsilon_x+B_x)}{g_x}, \tag{1}$$

where p_x and g_x are the number of nucleons composing the cluster and the single-cluster density, respectively, and γ_x is the probability to form the cluster from the given excitons. The last factor is merely the number of realizations of the cluster from the excited particles.

2.2 Density Approach to the Iwamoto-Harada Model

Later, the coalescence model has been made more sophisticated to allow the cluster to be formed not only of excitons, but also from unexcited nucleons below the Fermi level [5, 7], i.e. some form of a statistical description of pickup. This approach became known as the Iwamoto-Harada model.

We follow the notation of [7], which is fully consistent with the density-of-states concept inherent in the exciton model.

In the Iwamoto-Harada model, the density product $\omega(p-p_x,h,U)\omega(p_x,0,\varepsilon_x+B_x)$ is replaced by the folding expression

$$\sum_{p^*=1}^{p_x} \int_{\varepsilon_x+B_x} \omega(p-p^*,h,E-\varepsilon_1)\omega(p^*,0,\varepsilon_1) \omega(0,p_x-p^*,\varepsilon_2)\mathrm{d}\varepsilon_1, \tag{2}$$

where p^* is the number of excitons contributing to the formation of the cluster, and the remaining $(p_x - p^*)$ nucleons are picked up from the Fermi sea. The cluster density $g_x \propto \gamma_x$ [7] makes the formulation of the problem — as far as complex particles (clusters) concerns — parameterless [1].

[1]Obviously, the parameters which are common to the exciton model, like the state density parameters and optical model transmission coefficients (or corresponding cross sections) are also included in our calculations

2.3 Extensions of the IH (Pickup) Model

Bisplinghoff pointed out that not all nucleons are available for cluster formation, but only those close to the Fermi energy, and that the energy width of the "band of availability" is determined by the binding energy of nucleons within the cluster [6] [2].

As already sketched (without considering spin variables) in [11], we have extended some ideas behind those of the original pure IHB model:

It is natural to generalize the idea to arbitrary combination of excited and unexcited nucleons, and to all types of clusters. As the binding energy of nucleons in a deuteron is small, the pickup possibility of nucleon coalescence to form a deuteron is of minor effect. Thus, strongly bound entities, like α's, have a large energy space available for pickup (which makes the approach close to the original ideas [5, 7]), whereas loosely coupled objects (e.g. deuterons) get rather close to the standard coalescence model (see [8]).

It is necessary to keep the consistency with the compound nucleus theory (equilibrium one!) when one deals with pre-equilibrium models. One of the basic requirements is the principle of microscopic reversibility applied to the emission rates and to the particle capture, and the other one is the necessity of reaching the compound nucleus theory as the limiting (equilibrium) case of pre-equilibrium emission when one goes to sufficiently long times. Both of these can be dealt with relatively easily in the case of nucleon emission [9] and, with some additional approximations, also for cluster coalescence model in its pure version [10], where the Weisskopf-Ewing formula can be reached within the model by summation over all exciton states (up to a possible charge factor).

Therefore, we assume that the pickup is effective only when the number of excited particles is insufficient to form the cluster of the required type. When the exciton number is large enough, the excitons do not show any need to pickup their partner(s) from the Fermi sea. This suggestion does not influence the high-energy part of the spectrum, but is able to yield the proper equilibrium limit.

Further on, we have included some "energy blurring" to simulate the thermal movement of nucleons in an excited nucleus.

The last of the modifications stems from the Heisenberg uncertainty relation: the most simple exciton states created at the very initial stage of a reaction live very shortly, which can be interpreted as an uncertainty in the exciton energy available for the cluster emission.

There are no free parameters specific to cluster emission; other parameters have been kept at their overall (default) values.

2.4 Knockout Admixtures in the α Emission

The Iwamoto-Harada model introduced pickup reactions into the statistical formulation of the pre-equilibrium model. However, at least for the most compact ejectiles, like α particles, the possibility of knockout seems to be reasonable to be added as well.

Expressed in the statistical language of the exciton model, the (N,α) knockout yields the corresponding final density [8, 11]

$$\int_0^E \omega(0,4,U-\varepsilon)\omega(1,0,\varepsilon)\mathrm{d}\varepsilon. \tag{3}$$

It is rather complicated to say something *a priori* about the fraction of knockout reactions in the pre-equilibrium process and we take it here as a free parameter to be determined from the fit to the data.

[2]The Iwamoto-Harada model with Bisplinghoff's improvement is denoted as the Iwamoto-Harada-Bisplinghoff (IHB) model.

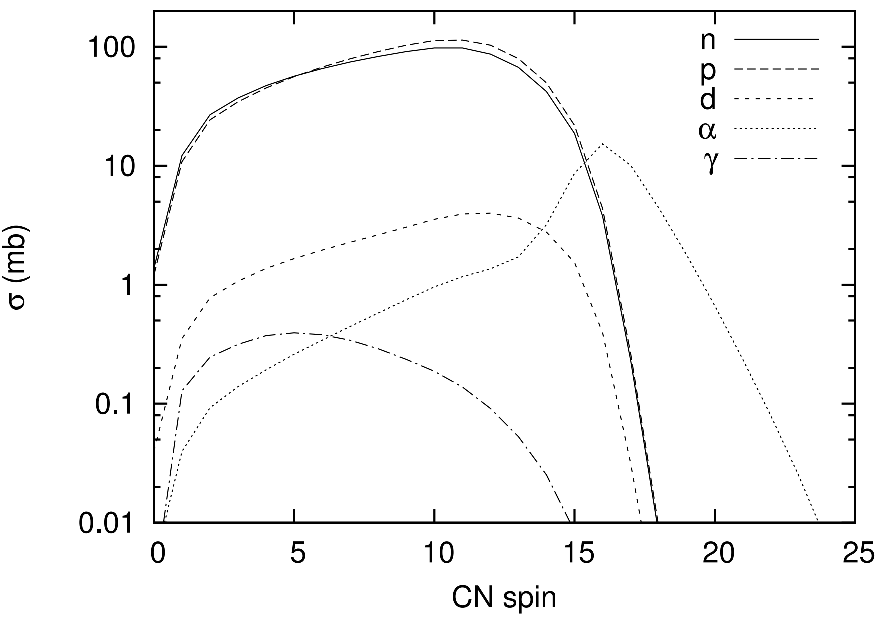

Figure 1. Particle and γ emission (from the primary nucleus only) frordifferent spins of the composite system (^{197}Au+p at 62 MeV). The α-emission is calculated with an enhanced knockout contribution to better see its influence on the emission.

2.5 Angular Momentum

Current pre-equilibrium models often ignore the influence of angular momentum. The difference between calculations with and without angular momentum is easily shown to be rather small for nucleon emission, but it is larger for clusters, because *i)* cluster emission is usually enhanced at higher angular momenta, which means an increased role of the nuclear surface and consequent effective lowering of the Coulomb barrier, especially in the case of deformed nuclei; *ii)* many of the quantities entering pre-equilibrium reactions are both spin- and energy-dependent and their simple contraction to one variable necessarily affects the results. The consistent incorporation of angular momentum is more complicated. Some steps have been undertaken in [12], but the full formulation of the spin-dependent intranuclear transition and emission rates has been made possible only by the work of Obložinský and Chadwick [13]. It has been developed for the equilibration process, nucleon- and γ emission. Obviously, if we calculate the time spent in the n-exciton state by solving the set of master equations [14], this set becomes much larger (from tens of thousands coupled equations up).

It is not a trivial task to apply angular momenta coupling rigorously to the case of cluster emission. For a first view, a similar (but more complicated) set of formulae than in the nucleon or γ emission case should be derived and consequently used in a computer code. However, one can — at least as a starting approximation — use the fact that the formation probability γ_x contains all the dynamics of the process, i.e. it contains also the spin couplings. We should emphasize that such a happy coincidence of cancellation of the cluster couplings is possible for the IHB model formulated in the exciton-energy space and it cannot be straightforwardly applied to cases where the final expression for the cluster emission still contains the formation probability or some similar quantity. This essentially simplifies the task here and makes it feasible to be applied to calculations of nuclear reactions. We have adopted this approach and illustrated the influence of angular momentum couplings below.

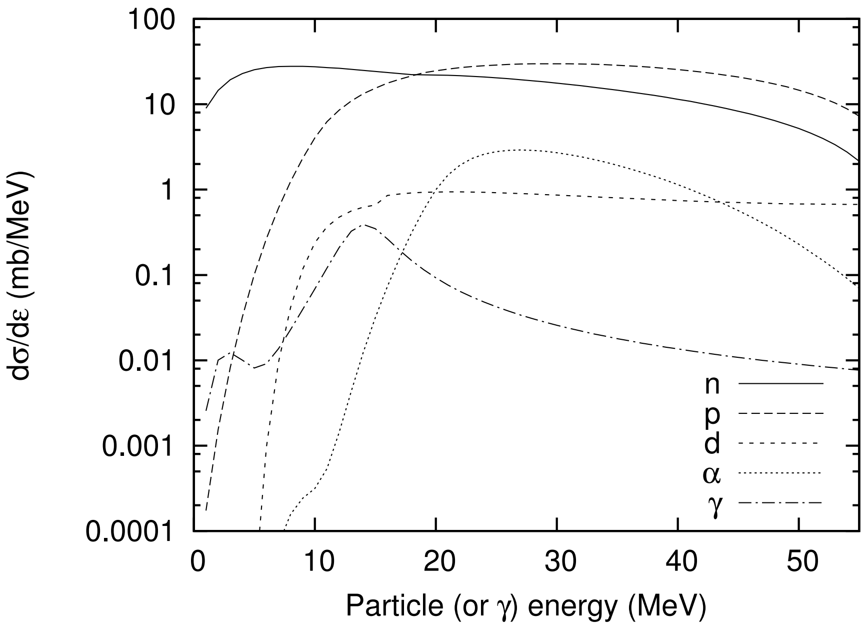

Figure 2. The same reaction as in Fig. 1: spin-dependent emission spectra. Only the emission from the primary nucleus is depicted for nucleons and clusters; whereas the γ spectrum also includes the γ cascade deexcitation.

3 Calculations

For the calculations, we have chosen the ^{197}Au(p,α) reaction, already calculated in the spin-independent case [11]. The spin-dependent calculations have been performed using the PEGAS code [14] (modified) with default values of level density parameters, intranuclear transition rates *etc.*. Those without spin variables used the more simple code PEQAG [15]. In both cases, the calculations presented here have been done without any aim to fit the parameters in order to achieve better agreement with the data.

Fig. 1 shows which angular momenta of the composite system are responsible for the emission of different types of ejectiles (n, p, d, α and γ) in the ^{197}Au(p,α) reaction at 62 MeV. Similarly, Fig. 2 depicts the energy emission spectra from the primary composite system, i.e. prior to any particle emission (the γ emission calculation includes cascades — they are responsible for the peak close to $\varepsilon_\gamma \approx 2$ MeV).

Finally, Fig. 3 (from [16]) brings the α spectra from the same system, but now with inclusion of all possible reaction chains due to consequent emission of nucleons and α's.

In general, if we allow any depth of the nuclear potential to be available for pickup, we exceed the experimental data, and the restriction to the deuteron binding energy suggested by the IHB model

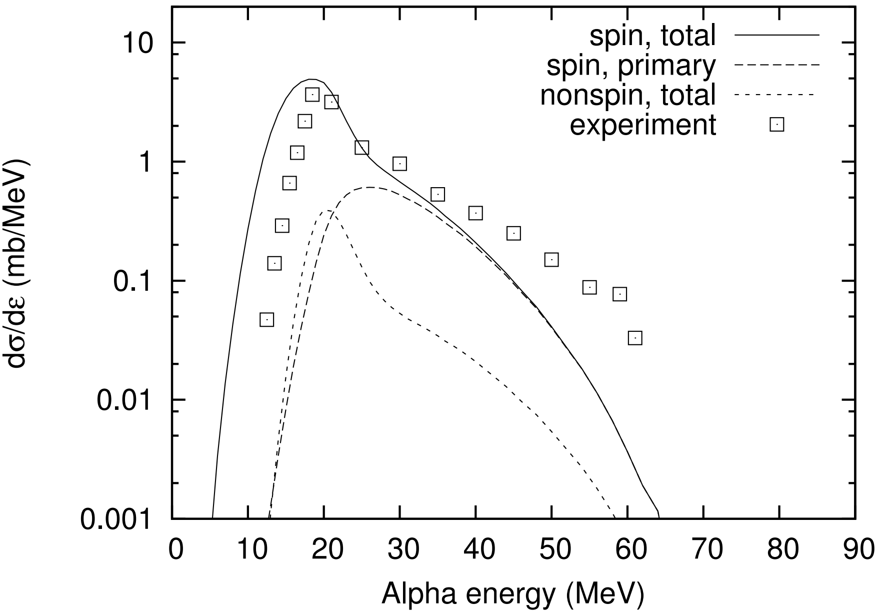

Figure 3. The reaction ^{197}Au(p,α) at 62 MeV: spin and spin-independent (nonspin) α energy spectra. For the case with angular momentum variables, the spectrum from the primary nucleus (i.e. prior to other particle emission) is shown separately, in addition to the total energy spectrum (from [16]).

draws the spectra down. For loosely bound ejectiles like deuterons, the energy spectra are practically indistinguishable from those of pure coalescence calculations.

In all cases, the introduction of angular momentum increases the cluster spectra significantly and — on the average — it decreases other (competing) emissions, as expected.

4 Conclusions

We have developed a simple model to include spin variables into the Iwamoto-Harada-Bisplinghoff model of pre-equilibrium cluster emission. Due to the happy fact that the spin couplings responsible for the creation of clusters within a reaction are implicitly contained in the formation probabilities (or can at least in the very first approximation be considered as such), which in the IHB model cancel in the final stage, the approach is free from parameters specific to their formation and emission, and only the global parameters of the exciton model remain. The spectra with angular momentum couplings describe the data better than those of the spin-independent case.

The IHB model describes coalescence and pickup. We have partially included knockout, but its importance should be still studied, as well as the possible inclusion of other types of direct reactions into the statistical model.

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