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Cluster-γ competition in the Iwamoto-Harada-Bisplinghoff model

Emil Běták[1,2,a]

[1] Institute of Physics SAS, 84511 Bratislava, Slovakia
[2] Fac. of Philos. and Sci., Silesian Univ., 74601 Opava, Czech Rep.

Abstract. The exciton model of pre-equilibrium decay was originally formulated for the emission of nucleons, and the other kinds of ejectiles have been introduced afterward. However, clusters and gammas have not been yet treated simultaneously in competition. In connection with series of experiments using the "Oslo method", we feel that such extension of calculations may be useful and we try to fill in this gap. To this aim, we employ the updated version of the Iwamoto-Harada-Bisplinghoff model.

1 Introduction

Pre-equilibrium model, formulated originally just for nucleon emission, has been extended to include also emission of light clusters (up to the α-particle) and γ quanta. We employ here the so-called Iwamoto-Harada mechanism for the cluster emission, where the cluster can be made of not only excitons, but also o-far unexcited nucleons, incorporating thus also pick-up [1,2]. This approach is — as for the cluster emission — parameterless. For the specific case of α-particles, Bisplinghoff pointed out the importance of the binding energy of nucleons inside the cluster [3]. Consequently, his approach was extended to other kinds of clusters and also knock-out was incorporated [4, 5].

The pre-equilibrium continuous γ emission [6,7] turns our interest to other facet. It has been studied independently, essentially in the reactions of nucleon radiative capture. Therein, the γ-to-nucleon competition is of a great importance. To the best of our knowledge, no attempt to combine both ingredients, i.e. the γ emission and the Iwamoto-Harada model simultaneously and consistently as competing mechanisms over the whole course of a nuclear reaction has been reported.

The recent set of experiments done by the Oslo group (see, e.g., [8,9]), where both the cluster (α or ^{3}He) emission and γ spectra were measured, raised question *"How much of γ's are emitted prior the cluster goes out?"*. Intuitively, one expected that just equilibrium γ's are important here, and all interpretation was done under that assumption, but it was just an assumption. Here, we try to answer it.

[a] e-mail: betak@savba.sk

2 Basic ideas

2.1 Iwamoto-Harada-Bisplinghoff model for cluster emission

The spin-dependent formulation if the Iwamoto-Harada-Bisplinghoff model (IHB) is still to be developed, and we limit ourselves to the more simple version today, namely to the spin-independent one. Therein, the energy spectrum of the emitted particles is

$$\frac{d\sigma}{d\varepsilon_x} = \sigma_R \sum_n \tau_n \lambda_x^c(n, E, \varepsilon_x), \qquad (1)$$

where $\lambda_x^c(n, E, \varepsilon_x)$ is the particle emission rate from an n-exciton state ($n = p + h$) of excitation energy E to continuum, the energy of the ejectile of type x is ε_x, and τ_n and σ_R are the time spent in an n-exciton state and the cross section of creation of the composite system, respectively.

The nucleon (x stands for proton π or neutron ν) emission rate (see, e.g. [10]) is

$$\lambda_x^c(n, E, \varepsilon_x) = \frac{2s_x + 1}{\pi^2\hbar^3}\mu_x\varepsilon_x\sigma^*_{\rm INV}(\varepsilon_x)\frac{\omega(p-1, h, U)}{\omega(p, h, E)}R_x(p)\,, \qquad (2)$$

where μ_x and s_x are the ejectile reduced mass and spin, respectively, $\sigma_{\rm INV}$ is the inverse cross section, which is, in fact, replaced by the cross section of the capture of a projectile x by the nucleus in its ground state, and U is the energy of residual nucleus which is produced in an $(n-1)$-exciton state. The factor $R_x(p)$ takes into account the charge composition, but is not generally accepted (see also [10]). Introducing coalescence of excitons to form a cluster means replacing the exciton number of the residual nucleus $(p-1, h)$ by $(p-p_x, h)$ [11,12], where we assume that the cluster x is formed by p_x of the total of p excited particles and finally introducing $\gamma_x \times \omega(p_x, 0, \varepsilon_x + B_x)/g_x$, which has straightforward physical interpretation: its second part is the number of configurations of the p_x excitons, and γ_x is the formation probability [13]

Iwamoto-Harada model adds the possibility to include not only excitons, but also unexcited nucleons, and it mathematically means to replace the density product

$$\omega(p - p_x, h, U)\omega(p_x, 0, \varepsilon_x + B_x) \quad (3)$$

by

$$\sum_{p^*=1}^{p_x} \int_{\varepsilon_x+B_x}^{E} \omega(p-p^*, h, E-\varepsilon_1)\omega(p^*, 0, \varepsilon_1)\omega(0, p_x-p^*, \varepsilon_2)\, \mathrm{d}\varepsilon_1, \quad (4)$$

where p^* is the number of excitons contributing to forming the cluster, while the remaining $(p_x - p^*)$ nucleons are picked up from the Fermi sea. The cluster density is $g_x = g\gamma_x[g(\varepsilon_x + B_x + p_x E_F)]^{p_x-1}/p_x!(p_x - 1)!$, making this approach parameterless for cluster emission [2].

Bisplinghoff suggested that not all nucleons be available for the cluster formation within the model, but only those close to the Fermi energy, and the energy width of the "band of availability" is determined by the binding energy of nucleons inside the cluster [3]. It is natural to generalize the idea to arbitrary combinations of excited and unexcited nucleons, and to all types of clusters. As the binding energy of nucleons in the deuteron is small, the pick-up possibility is hardly likely to be observed in practice. Thus, strongly bound entities, like α's, have large energy space available for their creation (which makes the approach close to the original [1,2] ideas, and loosely coupled objects (e.g. deuterons) practically get close to the standard coalescence model [4,5]).

It is necessary to keep the consistence with the compound nucleus theory when one deals with pre-equilibrium models. One of the principal 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 limit (equilibrium) case of the pre-equilibrium emission when one goes to sufficiently long times. Both of them can be dealt relatively easily in the case of nucleon emission and with some additional approximation also for cluster coalescence model in its pure version, where the Weisskopf-Ewing formulae within the model by summation over all exciton states can be reached (see [5] for more details). It is much more difficult to reach the proper equilibrium limit for cluster emission with some allowance for pickup and possibly other processes.

In our model, 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 the 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.

Two other suggestions are used: First, we have included some "energy blurring" to simulate the thermal movement of nucleons in excited nucleus. Second, we have incorporated the Heisenberg principle approximately in the very first stage. Therein, the nucleus lives *very* shortly, and due to the uncertainty relation it is possible with a rather small, but nonzero amplitude, that the exciton can "borrow" energy to pickup nucleons from the sea also much deeper than allowed by the cluster binding energy.

However, at least for compact ejectiles, like α particles, a 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 gives [4,5] $\int_0^E \omega(0,4,U-\varepsilon)\omega(1,0,\varepsilon)\mathrm{d}\varepsilon$. It is rather complicated to say something *a priori* about the fraction of the knockout reactions f_{KO} in the pre-equilibrium process, and we take it as a free parameter to be determined from the fit to the data.

2.2 Gamma emission

The pre-equilibrium model (see, e.g., [10]) is in its nature a statistical approach to the problem. Significant improvement was the incorporation of spin into the formalism of the pre-equilibrium exciton model [14,15], which enabled also pre-equilibrium calculations leading to discrete states. However, we shall restrict our present calculations to the spin-independent description only.

The model is based on the pre-equilibrium single-particle radiative mechanism [6,7], which proved to be very successful at the incident energies below about 30 MeV. On the other hand, it gives also a good and reliable description at energies as low as about 5 MeV [16,17]. The γ emission rates can be expressed as [6,7]

$$\lambda_\gamma(n, E, \varepsilon_\gamma) = \frac{\varepsilon_\gamma^2 \sigma_{\mathrm{GDR}}(\varepsilon_\gamma)}{\pi^2\hbar^3c^2} \frac{\sum_{m=n,n-2} b(m, \varepsilon_\gamma)\omega(m, E - \varepsilon_\gamma)}{\omega(n, E)}, \quad (5)$$

where $\sigma_{\mathrm{GDR}}(\varepsilon)$ is the photoabsorption cross section, b's the corresponding branching ratios (see [6,7]) and ω's the corresponding state densities with specified energy and the number of excitons. The branching ratios are

$$b(n-2, \varepsilon_\gamma) = \frac{\omega(2, \varepsilon_\gamma)}{g(n-2) + \omega(2, \varepsilon_\gamma)}$$
$$b(n, \varepsilon_\gamma) = \frac{gn}{gn + \omega(2, \varepsilon_\gamma)}. \quad (6)$$

With the inclusion of spin, however, the branching ratios become much more complicated, but — fortunately — they factorize, and their energy-dependent parts are identical to those of the spin-independent ones.

3 Calculations and results

We benefit from the set of master equations for the pre-equilibrium exciton model, written with couplings among all participating nuclei and their possible γ de-excitations [18]. This approach naturally contains competitions among all possible emission at each stage of the reaction and it also includes — as its equilibrium limit — the compound nucleus emission. Thus, it is free from possible inconsistencies (even though they are probably rather small) arising

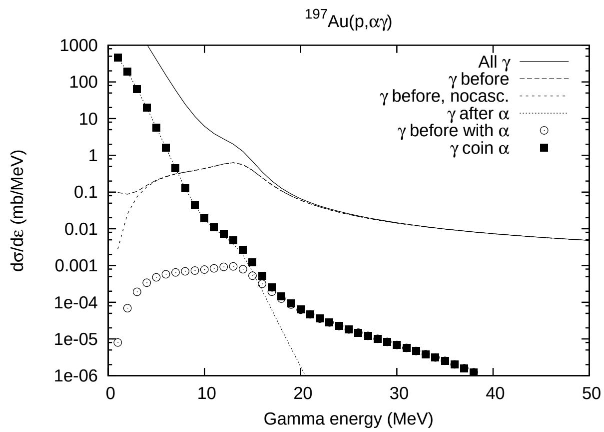

Fig. 1. Gamma spectra from ^{197}Au+p at 62 MeV. The full line depicts the total γ spectra including cascades. The portion which comes out from the initial composite system, i.e. prior to any particle emission, is drawn as a dashed line. If one does not allow for γ cascades before the particle emission, the low-energy side is decreased (dotted line). The part of γ's, which is emitted in coincidence with α's, is drawn by black squares and it consists essentially of the emission from the original (highly excited) composite system before α emission (open circles) plus γ de-excitation immediately following the α emission (densely dotted line).

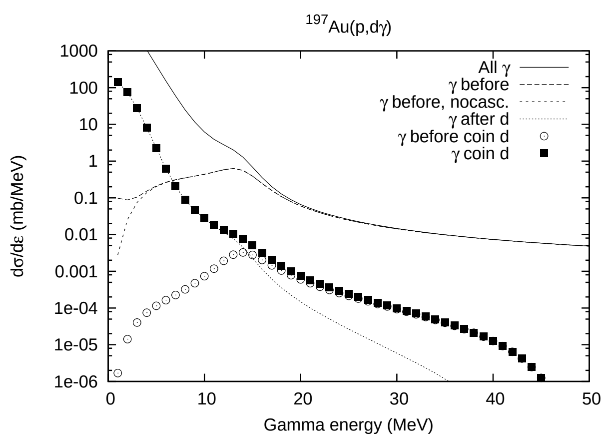

Fig. 2. As in Fig. 1, but for the deuteron emission.

from "gluing" of different approaches. Moreover, all bookkeeping is naturally contained therein, so that the calculation of exclusive processes is envisaged.

We start illustration of the cluster-γ competition using the system created by 62 MeV protons on ^{197}Au. This is one of those, where the generalization of IHB has been presented five years ago [5].

Fig. 1 shows the calculated γ spectra originated from 62 MeV protons impacting on ^{197}Au. The full γ spectrum is shown here together with its portion before any particle is emitted, i.e. from originally created composite system (^{198}Hg). There are practically no γ's above 20 MeV after the emission of particles (of any kind, not only α's). For curiosity, also the corresponding γ spectrum without γ cascades in the original composite system is shown.

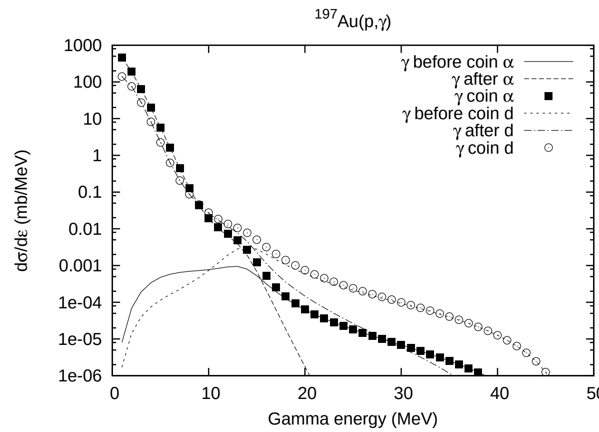

Fig. 3. Gamma spectra from ^{197}Au+p at 62 MeV in coincidence with α's (black squares) and with deuterons (open circles) together with their components.

The spectra of γ's in coincidence with α's much lower. They are decomposed into the part prior to particle emission [1] and that with γ's emitted after α. We have not considered the emission of more particles together with α and γ in coincidence. These reactions are much below two main contributions because of too low phase space.

Fig. 2 presents the γ spectra in coincidence with deuteron emission. The deuteron is not only loosely bound entity than strongly bound α, but one should consider also that deuteron is composed only of two nucleons (and not four as α), what implies that the "classical" coincidence (without participance of so-far unexcited nucleons) starts at earlier stage of equilibration process than it was in the previous case.

In order to compare the γ spectra in coincidence with deuterons and with α's, both resulting spectra of the previous case are brought together in Fig. 3. It is worth to note that the form of γ spectra in coincidence with α's differs from that in coincidence with d's.

Finally, we come to a reaction selected from those which motivated the present study, namely ^{160}Dy(^{3}He,α) at 45 MeV [8]. As above, the total γ coincidence spectrum is decomposed into the portion emitted prior and after the α emission. Generally, at energies below 10 or 12 MeV, practically all γ's are emitted after α from already sufficiently equilibrated nucleus, what justifies implicit assumptions done at analyses.

4 Conclusions

The emission of γ's in coincidence with clusters has been studied using the Iwamoto-Harada-Bisplinghoff model for clusters and single-radiative pre-equilibrium mechanism for

[1] For simplicity, we skipped the possibility of cascading γ before any particle emission, as that influences only the lowest portion of this part of γ spectrum, which itself is — in this energy region — by more than 5 orders of magnitude below the total resulting spectra.

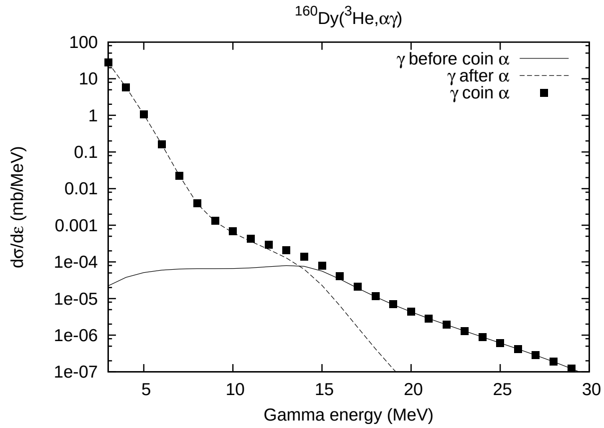

Fig. 4. Gamma spectra from ^{160}Dy+^{3}He at 45 MeV in coincidence with α's together with their components.

the γ emission. They both have been embedded into a huge set of master equations, enabling thus not only coupling and book-keeping of all stages of the reaction, but also to see the reaction course in an unifying matter.

At excitation energies of several tens of MeV — as was so far expected — practically all emission of γ at lower energies (say, below 10 MeV or so) comes after the α emission and it is practically from equilibrated compound nucleus.

In some future, however, experimental data may become measurable at energies above 15–16 MeV (the present experiments of the Oslo group usually end at about 7–8 MeV due to very low cross sections). Then the pre-equilibrium contribution to the γ emission prior to α's has not only to be taken into account, but it plays the essential role.

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