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ENERGETIC PARTICLES AND GAMMAS FROM LOW-ENERGY NUCLEAR REACTIONS *

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We address pre-equilibrium model mechanisms for the cluster emission and compare them for reactions below 200 MeV. The conclusion about the proper mechanism is not unique yet, however. For the γ emission, the main attention is devoted to the nucleon radiative capture. The data suggest a shift of the effective position of GDR together with a new indication of its energy-dependent width.

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1. Introduction

The pre-equilibrium model [1, 2] is widely used to describe nuclear reactions in the energy range 10 to 200 MeV. So far the reactions involving only nucleons are quite reasonably understood, whereas those of cluster (complex particle) and γ emissions are still missing some of important facets of the problem. Nevertheless, reasonable progress can be reported also in these directions.

Pre-equilibrium emission of light clusters (d to α) is treated in several very distinctive ways. Already in the initial period of pre-equilibrium theories, two opposite mechanisms have been suggested. The concept of preformed α particles [3] stresses that the α particle is a very strongly coupled object, and assumes that it can be treated as a single (special) exciton. On

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the other hand, coalescence models initiated by Cline and Ribanský and Obložinský [4, 5] assume forming of a cluster in the course of a reaction from the excitons, or — at its later modification — also from already unexcited nucleons. The coalescence model is of more general nature that the pre-formed one and is currently applied to all types of complex particles. Nevertheless, problems survive and none of the mechanisms suggested for the cluster emission is free of shortcomings and the agreement to the data is of similar quality for different approaches.

Classically, the γ emission from nuclei excited to several MeV up to several tens of MeV has been rather often described in the terms of the Direct–semi-direct model (DSD) [6]. In late seventieths, the single-particle radiation mechanism of the pre-equilibrium γ emission (PEQ) [7] (the mechanism name itself is of later origin) has been developed to be applied to the same range of energies. At higher energies, however, other mechanisms of the γ emission are successfully applied.

2. Pre-equilibrium complex particle and γ emission

The pre-equilibrium model assumes the reaction to proceed via a sequence of relatively simple states characterized by their exciton number. The energy spectrum of the emitted particles and/or γ quanta in the spin-independent formulation of the model is

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

where $\lambda_x^c(n, E, \varepsilon_x)$ is the particle (γ) 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. In Eq. (1), τ_n is the time spent in an n-exciton state and σ_R is the cross section of creation of a composite system.

The nucleon emission rate (see, *e.g.*, [2]) is

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

where μ_x and s_x are the ejectile reduced mass and spin, respectively, and $U = E - B_x - \varepsilon_x$ is the energy of residual nucleus which is produced in an $(n-1)$-exciton state. The charge factor $R_x(p)$ takes into account the charge composition of the excitons with respect to the ejectile, and is not generally accepted [1].

In the most simple case, the cluster emission rate can be written formally in exactly the same way as it was for nucleons, just with replacing the

[1] A recent discussion of various forms of the charge factor is in [8].

exciton number of the residual nucleus $(p-1, h)$ by $(p-p_x, h)$ [4], where we assume that the cluster is formed by p_x of the total of p excited particles. Additionally, the emission rates can be multiplied by γ_x, the formation probability [5] of the coalescence models, or by the α pre-formation factor γ_α, if we assume their existence as special entities $(p_\alpha = 1)$ within the nucleus [3]. The original form of the coalescence model [4] has been soon improved by multiplying the emission rates by the number of configurations of those p_x excitons, namely $\omega(p_x, 0, \varepsilon_x + B_x)/g$ [5]. However, the presence of formation probabilities and/or other additional functions is not strictly justifiable from the detailed balance, and it is therefore rejected by some groups, even though it means worsening the quality of the agreement between theory and experiment.

The coalescence model has been modified as to allow the cluster to be formed not only of excitons, but also from so far unexcited nucleons below the Fermi level. This approach became popular as the Iwamoto-Harada model [9], even though it has been suggested and successfully applied five years earlier [10]. Mathematically, it means replacing of the density product $\omega(p-p_x, h, U) \times \omega(p_x, 0, \varepsilon_x + B_x)$ by [10]

$$\sum_{p^*=1}^{p_x} \int_{\varepsilon_x+B_x}^{E} \omega(p-p^*, h, E-\varepsilon_1)\omega(p^*, 0, \varepsilon_1)\omega(0, p_x-p^*, \varepsilon_2)\, \mathrm{d}\varepsilon_1 \;, \qquad (3)$$

where p^* is the number of excitons contributing to forming the cluster, and the remaining $(p_x - p^*)$ nucleons are picked up from the Fermi sea. Now, the cluster density is $g_x = g[g(\varepsilon_x + B_x + p_x E_F)]^{p_x-1}/[p_x!(p_x-1)!]\gamma_x$, making this approach to be parameterless for the cluster emission [10].

The form of the emission spectra stems from different emission stages (different exciton numbers). However, at the high-energy edge of the spectrum, the contributions from complex later stages become negligible and the emission is determined by the initial (emitting) exciton configuration , so that $\mathrm{d}\sigma_x/\mathrm{d}\varepsilon_x \propto f(\varepsilon_x)U^{n_0-\Delta_n}$, where n_0, Δ_n and $f(\varepsilon_x)$ depend on the model assumptions of clusterization. The original form has been written for nucleons by Blann [11], later generalized to the cluster emission [12]. One must keep in mind that if the reaction starts from $n_0 = 1$, its whole strength is transferred (up to a tiny correction for the γ emission and possibly also another small one for the cluster emission in some models) to the $n = 3$ state, and the latter is the lowest emitting state considered by the above mentioned relation. Not clear understanding of this fact in the first decade implied misleading statement of $n_0 = 3$ for reactions induced by nucleons. Both Δ_n and $f(\varepsilon_x)$ are model and ejectile dependent; one has $\Delta_n = 2$ and $f(\varepsilon_x) = 1$ for nucleons and *e.g.* Δ_n =2 to 5 for α-particles.

The γ emission rate (in the non-spin case) is [7]

$$\lambda_\gamma(n, E, \varepsilon_\gamma) = \frac{\varepsilon_\gamma^2 \sigma_a(\varepsilon_\gamma)}{\pi^2 \hbar^3 c^2} \frac{\sum_{m=n,n-2} b(m, \varepsilon_\gamma)\omega(m, E - \varepsilon_\gamma)}{\omega(n, E)}, \tag{4}$$

where $\sigma_a(\varepsilon_\gamma)$ is the photoabsorption cross section (usually approximated by the GDR Lorentzian). The branching ratios are

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

and

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

Though the standard pre-equilibrium calculations of *nucleon* emission usually start from the 3-exciton state (see above), the presence of the $n = 1$ term is essential for the pre-equilibrium γ emission.

Generalization of the formalism as to include the spin and also different multipolarities is formally similar, but the branching ratios b's factorize. Their energy part is the same as in Eq. (4) and the spin coupling terms can be found in the original paper [13]. The influence of spin inclusion on the γ decay is pronounced in several cases [14], and its consideration is essential to trace the γ de-excitation completely and calculate the transitions to a given level.

3. Cluster emission

The α emission is the most frequently studied case of complex particles. High binding energy of nucleons in α justify to consider the latter alternatively as a single object [3, 15]. If we consider the complex particle emission as a whole, we have to take into account general mechanisms. The coalescence model in its pure form [4] obviously fails to reproduce the data. Two other competing models, namely the Ribanský-Obložinský coalescence model [5] and the Iwamoto–Harada one [9, 10] are good to describe some cases but failing elsewhere, with no simple rule about their applicability. There is still one model, rather successful at wide scale of reactions, namely the phenomenological one due to Kalbach [16] describing also pickup and stripping. Anyway, it contains many parameters without clear physical interpretation, just to fit the data. Therefore, it can be (and it is) applied to calculate cross sections and other quantities, but there is not much sense in discussing the underlying physics.

The coalescence model [5] often works well for deuteron emission, usually fails for α's, and there is a half-to-half chance of reasonable description for tritons and ^{3}He. The Iwamoto–Harada model does not contain any free parameter, as was the formation probability in the former case. The overall fit is of similar quality (though it may be significantly different for a specific reaction) than in the coalescence model, but one cannot find any drastic discrepancies with respect to the data here. In Fig. 1 we present a comparison of deuteron spectra from ^{120}Sn + p reaction at 62 MeV, with coalescence model [5] prediction as well as three (even four, in fact) different ones obtained within Iwamoto–Harada model. Very curiously, if the original calculation of Dobeš and Běták [10] is repeated with changed value of the intra nuclear transition matrix element, it practically coincides with the very sophisticated recent update of the same model by Basu and Ghosh [19].

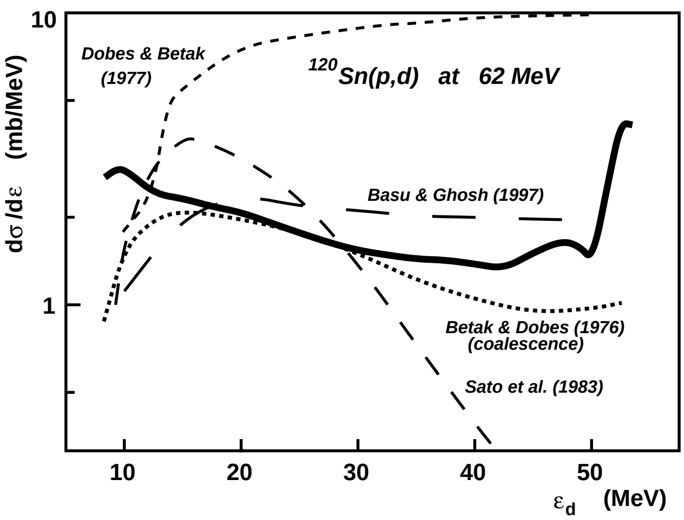

Fig. 1. Deuteron spectra from ^{120}Sn+p at 62 MeV. The experiment [17] is drawn as a heavy full line. Dotted line is the coalescence model [5] calculation with $\gamma_d = 0.022$ [18]; the other lines are within the so-called Iwamoto–Harada model [9, 10]: medium-dashed line the original calculations of Sato *et al.* [9], long-dashed line the refined one of Basu and Ghosh [19], and the short-dashed one the original calculation by Dobeš and Běták of 1977 [10] with the matrix element constant $K = 190$ MeV^3. After renormalizing the matrix element constant to 950 MeV^3, this calculation coincides above 15 MeV with that of Basu and Ghosh.

Some years ago, Bisplinghoff [15] suggested that not all nucleons be available for the cluster formation within the Iwamoto–Harada 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. This idea brings the model very close to the coalescence one, both in their model assumptions and in their predictions.

4. Gamma emission

There are two models for γ emission, DSD and PEQ. They are complementary in their assumptions, but they cannot be combined together. The main PEQ contribution comes from the $n = 1$ state, and it therefore corresponds to the direct term of DSD. The Consistent DSD [20] yields an

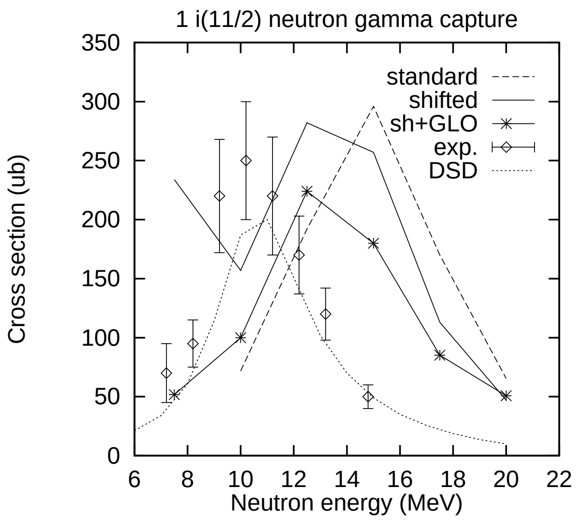

Fig. 2. Direct transitions to the first excited ($1i_{11/2}$) state in the radiative capture ^{208}Pb+n. Data (points) are those of Ref. [30]. The DSD calculation is shown for comparison as a dotted line. Three sets of PEQ calculations performed by code DEGAS [29] are given, one for the standard (unshifted) E_{GDR}, and two calculations for E_{GDR} lowered by 1.5 MeV, using the standard GDR width as well as the energy-dependent one in conjunction with generalized Lorentzian. (From [22])

effective lowering of the GDR energy to be used in statistical calculations as a result of interference of real and imaginary parts of the interaction. This idea works rather successfully also in the case of pre-equilibrium γ emission [21, 22]. continuum directly to the discrete bound state. As we are free of side effects arising from averaging (or integrating) over the states, we dared simultaneously to test another hypothesis, namely the change of the GDR width with energy. For low energies, this has been suggested by Joly *et al.* [23] [2] and in a more sophisticated manner in [25, 26]. Now, we apply this philosophy to transitions leading directly to a discrete state and *simultaneously* with the suggested shift of the GDR energy. Also in present

[2] It is interesting to note that possibility of the GDR width increasing with energy appeared already in the classical work of Brink [24].

case, such an idea significantly helps to improve the quality of the fit [22], see Fig. 2 [3].

The maximum of the excitation curve of the $1i_{11/2}$ state in the neutron radiative capture on ^{208}Pb calculated using the standard GDR parameters is shifted in the energy by about 1.5–2 MeV with respect to the data.

5. Conclusions and outlook

Cluster emission can be expressed in several different ways, each of them having their pros and cons. Possible restriction of the Iwamoto–Harada model to the nucleons near the Fermi level makes it close to the original coalescence one.

PEQ calculations of nucleon radiative capture support the idea justifiable within DSD that the *effective* GDR energy should be shifted to the lower values. The fit to the data needs this displacement to be 1.5 to 2 MeV. Simultaneously with this, we obtained a further support for possible change of the GDR shape (changing its width) with energy.

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