PRE-EQUILIBRIUM CLUSTER EMISSION: SOME EXAMPLES*

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Several co-existing models of pre-equilibrium cluster (complex particle) emission are currently in use. They are quite different in their physical assumptions, but in some cases they yield rather close results. We apply current pre-equilibrium models to the isotopic effect of (n,α) reactions and illustrate some possible future modifications of the existing models for the complex particle emission.

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1. Introduction

Various statistical models of cluster (complex particle) emission are used to analyze nuclear reactions at few tens of MeV (see, *e.g.*, [1]). The broadest range of model assumptions has been developed for α-particles, the most frequent cluster ejectiles. The concept of pre-formed α particles [2] stresses that the α particle is a very strongly coupled object, and assumes that it can be treated as a single (special) exciton. On the other hand, coalescence models initiated by Cline and Ribanský and Obložinský [3, 4] assume forming a cluster (not necessarily the α-particle) in the course of a reaction from 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. Apart of these

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two groups of models with straightforward physical background, also phenomenological descriptions are popular [5]. In fact, their predictive power is higher than of the former groups, though they are handicapped by more parameters.

2. Pre-equilibrium complex particle emission

The energy spectrum of the emitted particles and/or γ quanta in the spin-independent formulation of the model is

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon} = \sigma_{\mathrm{R}} \sum_n \tau_n \lambda_x^c(n, E, \varepsilon) \ , \tag{1}$$

where $\lambda_x^c(n, E, \varepsilon)$ is the particle (or 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. In Eq. (1), τ_n is the time spent in an n-exciton state and σ_{R} is the reaction cross section.

The particle emission rate (see, *e.g.*, [1,6]) is

$$\lambda_x^c(n, E, \varepsilon) = \frac{2s_x + 1}{\pi^2 \hbar^3} \mu \varepsilon \sigma^*_{\mathrm{INV}}(\varepsilon) \frac{\omega(p - p_x, h, U)}{\omega(p, h, E)} R_x(p) \gamma_x \frac{\omega(p_x, 0, \varepsilon + B)}{g} \ , \tag{2}$$

where μ and s_x are the ejectile reduced mass and spin, respectively, and $U = E - B - \varepsilon$ 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 Eq. (2), we assume that the cluster is formed by p_x of the total of p excited particles, γ_x is the formation probability [4] of the coalescence models, or the α pre-formation factor γ_α, if we assume their existence as special entities within the nucleus [2][2]. The last term, $\omega(...)/g$, appears only in the coalescence model [4], and it is the number of configurations of those p_x excitons. It should be noted, however, that 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 [8], even though it has been suggested and successfully applied five

[1] A recent discussion of various forms of the charge factor is in [7].
[2] Obviously, one has $\gamma_p = \gamma_n = 1$ for the nucleon emission.

years earlier [9]. Mathematically, it means replacing of the density product $\omega(p-p_x,h,U)\times\omega(p_x,0,\varepsilon+B)$ by the folding of three densities expressing the excitons taking part in forming the cluster, the nucleons picked up from the Fermi sea, and the spectator excitons [9].

3. Isotopic effect

Reactions induced by 14 MeV neutrons represent bulk amount of experimental data of various kind. Due to their large amount, many different trends have been observed and/or discovered just for these reactions. One of them is the isotopic effect in the (activation) cross sections corresponding to the emission of charged particles (most commonly protons and α's), *i.e.* the exponential decrease of the cross section with increasing $(N-Z)$. The experimental status has been reviewed by Gul [10]; the recent need for (mainly medical) applications stimulated further studies (see, *e.g.*, [11]). Theoretical study of the effect in (n,p) reactions within pre-equilibrium formalism was given by Čaplar [12].

Using some simplifying assumptions, the full expression derived within the compound nucleus (*i.e.* equilibrium) theory is [10, 13]

$$\sigma_{n\alpha}=\sigma_{\mathrm{R}}\exp\left[a_1+a_2\frac{Z-1.5}{TA^{1/3}}+a_3\frac{N-Z+0.5}{TA}+a_4\frac{Z-2}{E_{\mathrm{inc}}A^{1/3}}\right]. \quad (3)$$

Neglecting differences in temperature, essentially just the $(N-Z)$ dependence remains.

Semi-empirical formulae can be found in literature, *e.g.* [14]

$$\sigma_{n\alpha}=C\pi(R+\lambda\!\!\!^{-})^2\exp\left[-K\frac{N-Z}{A}\right], \quad (4)$$

where C and K are energy-dependent fitting parameters. More frequently, $(R+\lambda\!\!\!^{-})$ is replaced by $(A^{1/3}+1)$ with corresponding change of the parameter C [15].

Though the general form of exponential decrease of $\sigma_{n\alpha}$ can be easily derived in compound nucleus theory, it is not the case of the absolute value. The latter one can be explained only assuming the presence of non-equilibrium processes.

Let us consider only the isotopic chains of even–even nuclei, in order to reduce the possible influence of even-odd effects in the reaction. An example of the experimental data and the calculated dependences can be seen in Fig. 1. The calculations have been performed using codes GNASH [17], CLUEX [18] and CLUDEG [19][3]. The code CLUEX uses the coalescence model [4] with $\gamma_\alpha = 0.0025$ and the dashed line is GNASH calculation [17] based on the phenomenological pickup-stripping model [5] with standard parameters. Both the calculations describe the cross section decrease at higher A and yield reasonable absolute value. At lower A, however, some discrepancy remains. The purely statistical approach used by CLUEX reflects high Q value of the (n, α) reaction on ^{94}Mo by cross section clearly over predicting the measured one; whereas the semi phenomenological approach built in GNASH copes better with this anomaly.

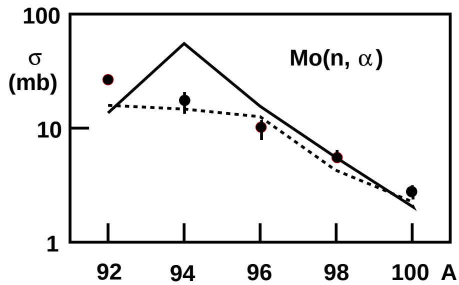

Fig. 1. Isotopic effect of (n, α) reactions at 14 MeV on the chain of even–even isotopes of molybdenum. The data are from Refs [16]; the full curve is the calculation using the code PEQAG [18] and the dashed line is that of GNASH [17].

4. Development of models for cluster emission

The α emission is the most frequently studied case of complex particles. High binding energy of nucleons in α justifies considering the latter alternatively as a single object [2]. If we consider the complex particle emission as a whole, we have to take into account general mechanisms.

The coalescence model [4] 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 [8, 20] does not contain any free parameter, as was the formation probability in the former case. As already seen in Fig. 1, rather different models of the α-particle reaction mechanisms yield very close results.

Some years ago, Bisplinghoff [21] 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

[3] The code CLUDEG [19] is a spin-dependent exciton model one, very similar to spin-independent CLUEX. The inclusion of spin variables emphasizes the α emission, or — in other words — the formation probability obtained from the fit is lower. The final results practically coincide with those obtained by CLUEX [18].

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.

To illustrate this influence, we present in Fig. 2 the initial-stage α spectra from the reaction ^{120}Sn+p at 62 MeV. The variation of the width of the available energy band changes significantly both the shape and the absolute value of the energy spectrum. Though the basic idea was formulated and implemented for α-particles already by Bisplinghoff some years ago [21], its general formulation and study of related effects is still to be done.

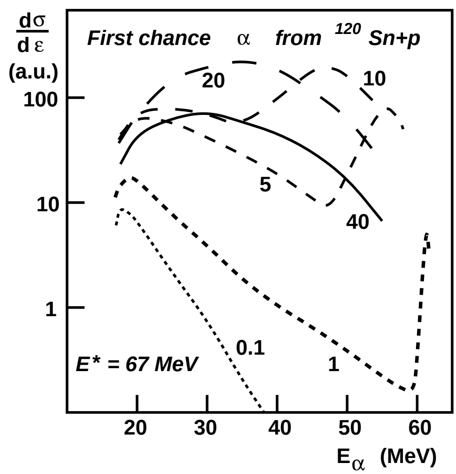

Fig. 2. Influence of restricted region of the Fermi sea contributing to the cluster formation within the Iwamoto–Harada model, as demonstrated on the very initial stage of α emission from ^{120}Sn+p at 62 MeV. The numbers at each curve indicate the effective potential depth (in MeV) considered for creation process of the cluster.

5. Conclusions and outlook

The isotopic *trends* in (n, α) reactions can be explained already within the frame of the compound nucleus theory. However, it completely fails to reproduce the *absolute values*, for which the presence of the pre-equilibrium emission is essential. The differences among various models of pre-equilibrium cluster emission are of minor importance for these data.

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 and is promising for future model developments.

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