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HARD GAMMAS FROM LOW-ENERGY HEAVY-ION COLLISIONS[1]

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Single-particle radiative mechanism of γ emission embedded into the pre-equilibrium exciton model is used to calculate the γ emission from a decay of $^{160}\mathrm{Er}^*$ created in two different ways. The initial stage of a reaction is described using momentum-space overlaps of colliding nuclei. We can reproduce the main features of the observed γ energy spectra including the fact that the spectrum observed in more symmetric combination is slightly harder than in the other case.

1. Introduction

A significant progress in the study of γ emission in heavy-ion reactions can be marked within the last period, especially in collecting the experimental data and application of various bremsstrahlung mechanisms (see, e.g. [1, 2]). Other approaches, namely the quasideuteron model [3] suitable for intermediate energies, and the exciton model of the γ emission [4, 5], are less popular in heavy-ion physics. However, the pre-equilibrium exciton model has already firmly gained its ground in reactions induced by nucleons and light clusters at excitation energies of several tens of MeV, and it starts to expand its applications towards higher energies and especially heavier projectiles.

A great volume of available data on γ emission from heavy-ion reactions at γ energies above 30 or 40 MeV has been successfully analyzed in terms of bremsstrahlung. Emission of γ quanta below about 10 MeV (sometimes also at higher energies, occasionally even up to the switch-on of the bremsstrahlung regime) is usually attributed to the equilibrium mechanism. A relatively overlooked energy region from 10 to about 30 MeV is a potential source of emerging inadequacies in description of γ emission. Unfortunately, their manifestation is heavily masked by other effects, so that the needs of more precise description are thus suppressed. Practically, the *exclusive* γ spectra originated from a decay of the same nucleus created by two different projectile-target combinations, both leading to the same composite system at practically the same excitation energy and at very close angular momenta distributions, are the only known

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type of data sensitive to possible refined description of γ emission mechanism. Such measurements are unfortunately rather seldom.

In our earlier paper [6], we have been interested in the decay of ^{132}Nd* created once by ^{64}Zn + ^{68}Zn and by ^{20}Ne + ^{112}Sn in the other case. The *exclusive* γ spectra from these two reactions have been measured by Kamanin et al. [7] and they demonstrate slight differences in the γ energy region from 8 to 15 MeV. This has been explained by smaller number of degrees of freedom in the early stage of the reaction induced by lighter projectile, when compared to the other case.

This time, we have been intrigued by the case of ^{160}Er* decay; when the composite system originated from bombarding once by ^{16}O and the other time by ^{64}Ni, in both cases with the excitation energy $E = 53$ MeV. Though one would expect opposite, the observed *exclusive* γ spectra seem to be somewhat *harder* in the case of the Ni-induced reaction here [8].

2. Exciton model γ emission

We employ the pre-equilibrium exciton model in our study. Therein, the state of an excited nucleus is characterized by its exciton number n (particles above plus holes below the Fermi level) and the excitation energy E. The reaction proceeds from a relatively simple starting configuration, characterized by the initial exciton number n_0. In the course of a reaction, the nucleus develops via residual interactions towards an equilibrium distribution. In competition to the equilibration process, particle as well as γ emissions may occur.

For the energy region of 10 to 30 MeV, the single-particle mechanism of the pre-equilibrium γ emission dominates. Therein, just two processes responsible for the γ emission may occur, associated with the exciton number change $\Delta n = 0$ and $\Delta n = -2$ [4, 5]. The corresponding γ energy spectrum can be expressed as

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

with σ_R denoting the reaction cross section (that of a creation of a composite system) and τ_n being the total time spent by a nucleus in the n-exciton state. The γ emission rates can be written as [5]

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

where b's are the branching ratios for the two possible processes, ω's are the exciton level densities, and $\sigma_a(\epsilon_\gamma)$ is the photo-absorption cross section. Here, the experimental data are preferred, but the Lorentzian shape (or a sum of two Lorentzians for deformed nuclei) is frequently used, either with global parameters or refering to the existing tables of the GDR parameters with individual widths, energies and peak cross sections for various nuclei.

Obviously, one has to consider the successive γ's interspersed by nucleons as needed to get the total γ production. The significantly enlarged set of master equations of the exciton model, which includes the coupling of different nuclei and various excitation energies was employed to obtain τ_n's. The updated version of code PEQAG [9] has been used for the calculations.

3. Initial configuration

Till now we have introduced no specific features of the heavy-ion processes. Indeed (if we are within the frame of the pre-equilibrium exciton model), the main difference is contained in the proper initial configuration of the reaction. Commonly, one takes $n_0 = 1$ for nucleon- and $n_0 = 4$ for α-induced reactions. In the collisions of heavy ions, the same philosophy would lead to $n_0 = A_{proj}$, as was really used in the first calculations of that kind [10]. However, such a description has been found to be somewhat inadequate, and the initial exciton number has been a subject of separate studies.

As a first step, empirical systematics of n_0/A_{proj} have been reported [11, 12], which could serve as a rough guideline. Consequently, a model has been developed, which brings some insight into an understanding of the dependence of the initial exciton number on the energy, projectile mass and casually also the projectile-target combination [13, 14, 15]. The model is based on calculating the overlap of colliding partners in the momentum space. According to [14], the calculated results at energies well above the Coulomb barrier are grouped nearby line

$$\frac{E}{n_0} = 4.6 + 0.54 \cdot \frac{E_{cm} - V_C}{A_{proj}} \ , \tag{3}$$

whereas one should prefer

$$\frac{n_0}{A_{proj}} = 0.09 + \left(0.38 - 0.08 \cdot \frac{A_{targ} - A_{proj}}{A_{targ} + A_{proj}}\right) \cdot \sqrt{\frac{E_{cm} - V_C}{A_{proj}}} \tag{4}$$

as an approximate guide at smaller energies. In the above equations, E is the excitation energy of the composite system, E_{cm} the projectile c.m. energy, and V_C is the height of the Coulomb barrier.

4. Results and discussion

In our case (86.3 MeV ^{16}O ions and 236.6 MeV ^{64}Ni beams), direct use of formula (4) yields $n_0 = 6$ for O-induced and $n_0 = 11$ for Ni-induced reactions. However, as we are very close to the Coulomb barrier in the case of ^{64}Ni beams, the influence of small additive term on the r.h.s. of eq. (4), which has been extracted with relatively large uncertainty, becomes significant. Therefore a straightforward use of (4) is not recommended and we have to apply the full overlap calculations as described in [13]. This procedure yields $n_0 = 7$ for the reaction induced by ^{16}O, but only $n_0 = 5$ for that by ^{64}Ni.

The typical energy of the emitted particles at the early stage of the reaction is $\epsilon_{part} \approx E/n$, and that of γ's $\epsilon_\gamma \propto E/n$, so that the lower exciton number implies higher mean energy of ejectiles, and — consequently — harder spectra. We came to the conclusion that the full account of the initial stage of the reaction leads to *lower*

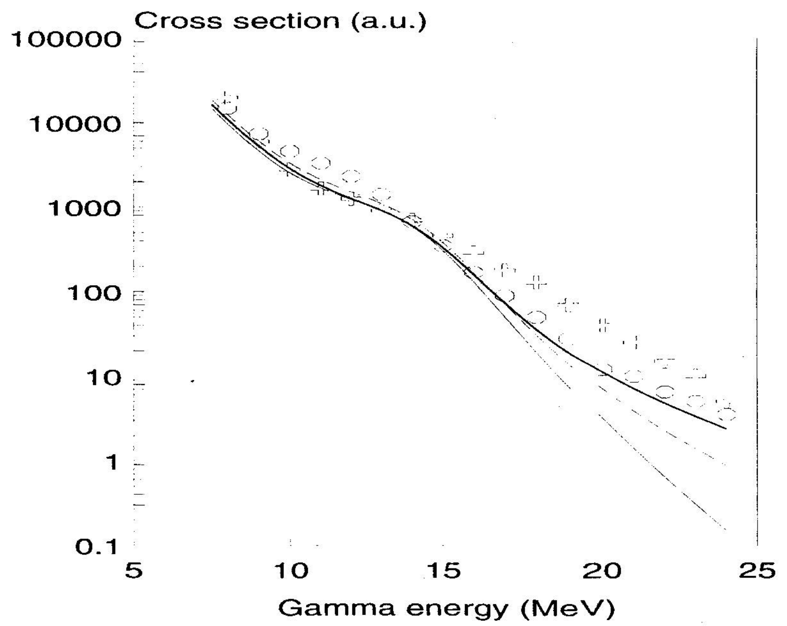

Fig. 1. Measured and calculated γ energy spectra from the decay of ^{160}Er* created in two different ways. Circles are the experimental data of ^{16}O + ^{144}Nd and crosses that of ^{64}Ni + ^{96}Zr [8]; calculated spectra are drawn as lines: dashed (^{16}O), thin (^{64}Ni with n_0 from eq. (4)) and thick one (^{64}Ni with properly calculated n_0).

initial exciton number for *more massive projectile* in our case, just the opposite than one would expect! The experimental data of exclusive γ energy spectra have slopes close for the two diffrent combinations, but the spectrum from Ni-induced reaction is somewhat harder. Fig. 1 brings the comparison of experimental and calculated γ spectra. Unfortunately, the available experimental data do not extend above 25 MeV. Rather fine differences at gamma energies 15 to 25 MeV do not enable to extract more than conditional conclusions from a comparison to their theoretical prediction. The calculated spectra are relatively close to the measured ones, and the γ spectrum from Ni-induced reaction calculated with proper tracing the initial stage of the reaction in the overlaps of the colliding nuclei is harder than that from O-induced case, just in accord with the data. In neither of the cases the pre-equilibrium description fully reproduces the data, and some minor differences between the calculations and the experiment remain in both projectile-target combinations considered; e.g., the calculated spectra are somewhat below the experimental ones at energies exceeding 16 MeV. The main and striking feature of the data, namely that the γ's from more symmetric combination are harder than in the asymmetric case, is caught and reproduced in our calculations; whereas other approaches fail to reproduce this specific feature of the data.

5. Conclusions

We are aware of the fact that we have not arrived to a sufficient and satisfactory agreement of the calculations to the data. The pre-equilibrium exciton model including all its ingredients (level densities, initial exciton number, transition matrix element, etc.) is very schematic and rough, and one cannot expect a complete fit here. Our calculations have been performed just with global parameters both for the model and for the γ emission itself, so that they lead to an *a priori* result.

By sophisticated adjustment of the parameters, one will be able to improve the quality of the fit, but such a calculation will not bring more physical information than the present one due to the underlying shortcomings of the model.

Finally, we conclude that we are able to catch the main features of the observed γ spectra below 25 MeV, namely their slope and its possible variation with changing projectile-target combination for heavy-ion collisions at moderate energies within a simple use of the single-particle radiation mechanism in connection with the pre-equilibrium exciton model. This includes also the experimental aspects which are not reproducible by other approaches.

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