COMPLEX-PARTICLE EMISSION IN THE HYBRID MODEL[1]

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The pre-equilibrium emission of particles of a higher complexity than nucleons was almost exclusively studied within the Griffin exciton model [1], where two different approaches were developed. The first of them, restricted to α-particles, is based on the assumption that the α-particle is preformed in a target nucleus and potentially represents one exciton [2]. The analysis of many α-spectra from reactions induced by 14 MeV neutrons gave good results here. The second approach assumes that a complex particle, represented by the number of excitons equal to its mass number [3], is formed from the excited nucleons of a composite nucleus [4]. The advantage of the latter conception is especially its universality, which has been demonstrated [3, 4, 5] on the spectra of d, t, τ and α-particles.

So far the only attempt to extend also Blann's hybrid model [6] to complex-particle emission has been due to Hollinger [7]; following the first conception, it has been limited to α-particles, with good results. Our contribution represents an attempt to extend the hybrid model in the sense of the second approach.

In the simple variant of the hybrid model, the probability of emitting a nucleon of a type x in the channel energy range ε to $\varepsilon + d\varepsilon$ is given as

$$P_x(\varepsilon)\,d\varepsilon = \sum_{\substack{n=n_0\\ \Delta n=+2}}^{\bar{n}} \left[\frac{p_x}{p}\,\frac{\omega_{p-1,h}(E-B_x-\varepsilon)}{\omega_{p,h}(E)}\,\omega_{1,0}(B_x+\varepsilon)\,d\varepsilon\right]\left[\frac{\lambda_c^x(\varepsilon)}{\lambda_c^x(\varepsilon)+\lambda_+^x(\varepsilon)}\right]D_n\,. \qquad (1)$$

The first set of square brackets represents the probability to find a nucleon of the required type and energy in a p-particle-h-hole state. Here, B_x is the binding energy of the nucleon, E means the excitation energy of a composite nucleus and p_x denotes the number of nucleons of the type x in a state with $n = p + h$ excitons. The intermediate state densities ω used in this work are those of the equidistant spacing type. The second set of brackets of (1) contains the probability that the excited particle of interest will decay into the continuum at the rate λ_c^x before it interacts internally at the rate λ_+^x to give an $(n+2)$-exciton state. For the latter quantity we have used the simple expression [6]

$$\lambda_+^x(\varepsilon) = (1.4\times 10^{21}(\varepsilon + B_x) - 6.0\times 10^{18}(\varepsilon + B_x)^2)/k, \qquad (2)$$

where k is the adjustable parameter. Finally, D_n is the depletion factor which represents the fraction of the initial population surviving the deexcitation by the particle emission

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prior to the n-exciton state under consideration. The summation in (1) goes from the initial exciton number n_0 up to its equilibrium value $\bar{n}$.

The probability of emitting a complex particle β, formed from p_β excited nucleons of the suitable type, can be written analogically to Eq. (1) as

$$P_\beta(\varepsilon)d\varepsilon = \sum_{\substack{n=n_0\\ \Delta n=+2}}^{\bar{n}} \left[R_\beta(p)\,\frac{\omega_{p-p_\beta,h}(E-B_\beta-\varepsilon)}{\omega_{p,h}(E)}\,\omega_{p_\beta,0}(B_\beta+\varepsilon)\,d\varepsilon\right] \times \left[\frac{\gamma_\beta\lambda_c^\beta(\varepsilon)}{\gamma_\beta\lambda_c^\beta(\varepsilon)+\gamma_\beta\lambda_+^\beta(\varepsilon)+(1-\gamma_\beta)\overline{(\lambda_c^x(\varepsilon)+\lambda_+^x(\varepsilon))}}\right]D_n\,. \qquad (3)$$

The expression in the first set of square brackets represents the probability to find p_β particles of the required type having a total energy $\varepsilon + B_\beta$ in an n-exciton state. The quantity $R_\beta(p)$, responsible for the right combination of neutrons and protons to form the outgoing particle [3], ensures the use of one-component state densities rather than two-component ones. The second set of square brackets of (3) represents the probability that the complex particle will be emitted before its intranuclear scattering occurs or before the configuration of p_β nucleons is destroyed by emission and the scattering of some of them. We assume that the probability of the complex particle being formed is γ_β or, expressed in other words, the given configuration of p_β nucleons can be treated as the cluster β only γ_β-fraction of the life-time of this configuration. Therefore the emission and scattering rates of the complex particle as well as the competition of individual nucleons have to be appropriately weighted. For the nucleon competition we used the average value

$$\overline{\lambda_c^x(\varepsilon)+\lambda_+^x(\varepsilon)} = \sum_{x=\nu,\pi}\int_0^{\varepsilon+B_\beta} (\lambda_c^x(\varepsilon')+\lambda_+^x(\varepsilon'))\,\frac{\beta p_x}{p_\beta}\cdot\frac{\omega_{p_\beta-1,0}(\varepsilon+B_\beta-\varepsilon')}{\omega p_\beta,(\varepsilon+B_\beta)}\,g\,d\varepsilon', \qquad (4)$$

where the averaging is done through all possible partitions of the total energy $\varepsilon + B_\beta$ among p_β nucleons, ν and π being a neutron and a proton, respectively. The emission rate of a complex particle can be derived from the principle of detailed balance as

$$\lambda_c^\beta(\varepsilon) = (2s_\beta + 1)\,\frac{m_\beta\varepsilon\sigma_{inv}}{\pi^2\,\hbar^3 g}\,, \qquad (5)$$

where s_β and m_β are the spin and the reduced mass of the particle β, σ_{inv} being the inverse cross-section. Since the complex particle is formed from nucleons having the single-particle state density g, the cluster β necessarily occupies energy states in the intervals $1/g$. Therefore the initial state density of the cluster was taken as g in Eq. (5). The quantities λ_c^β and, as can be supposed, λ_+^β (for α-particles see Ref. [7]) do not differ too much from λ_c^x and λ_+^x, respectively. Thus for $\gamma_\beta \ll 1$ one can neglect the first two terms in the denominator of the second set of square brackets of (3).

It can be seen that Eq. (3) for the case of the nucleon emission, i.e. $p_\beta = 1$ and $\gamma_\beta = 1$, is identical with Eq. (1). This feature indicates a consistency of the extended hybrid model with the original one.

Comparison with the experimental spectra was done first of all for d, t, τ and α-particles from the reaction $^{120}Sn + p$ at $E_p = 62$ MeV measured by Bertrand and Peelle [8]. The intranuclear scattering parameter was obtained from the fit to the proton spectrum as $k = 3$. The only parameter for the complex-particle emission was thus γ_β. Corresponding spectra with adopted forming probabilities are shown in Figs. 1 and 2. Our values of γ_β are on principle in accordance with those obtained by the extended Griffin model [4, 5]. Fig. 3, the last figure, shows spectra of α-particles from the reaction ^{93}Nb + + n at 14.2 MeV. This reaction was successfully analyzed in Ref. [2], from where we took over the experimental results. Since the pre-equilibrium decay of the discussed system represents only several percents, the essential contribution to the spectrum should

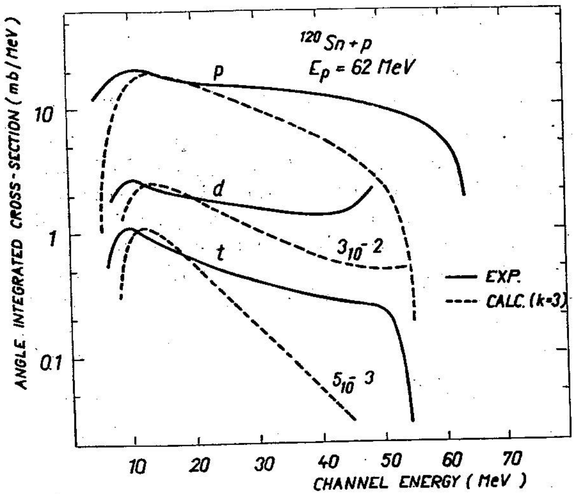

Fig. 1. Spectra of deuterons and tritons calculated by the extended hybrid model are compared with experimental results. The numbers beside the curves represent the corresponding values of the formation factor γ_β. Proton spectra are also shown.

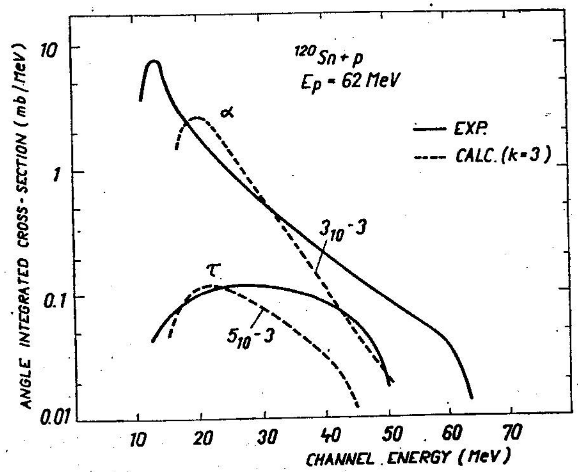

Fig. 2. The same as Fig. 1, but for τ and α-particles.

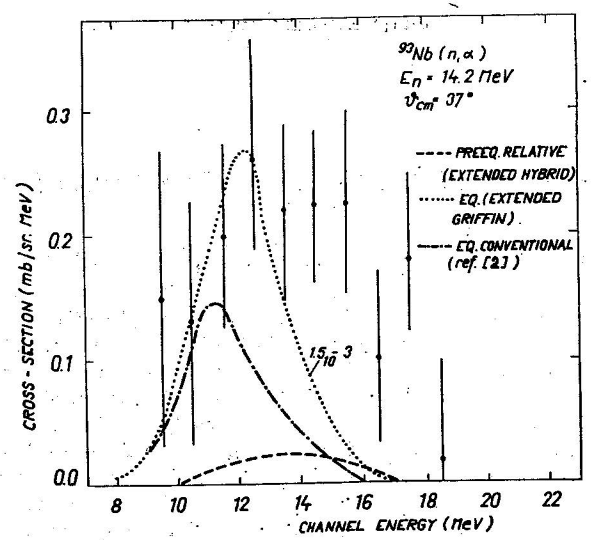

Fig. 3. Experimental and calculated spectra of α-particles for 14.2 Me Vneutrons incident on ^{93}Nb. The dashed curve shows the relative shape of the pre-equilibrium spectrum calculated by the extended hybrid model, the dotted one is the equilibrium spectrum according to [5] and the dash-dotted curve represents the conventional equilibrium spectrum taken from Ref. [2].

be due to the equilibrium emission. The latter was calculated in accordance with Ref. [5], i.e. by applying consistently the adopted mechanism of the complex-particle emission also after the statistical equilibrium was established. The required value of the forming factor was $\gamma_\alpha = 2 \times 10^{-3}$. It is noteworthy that the spectrum differs markedly from the conventional one which requires a considerable increasing pre-equilibrium contribution through the factor $\gamma_\alpha = 2 \times 10^{-1}$.

We can conclude that the proposed extension to the hybrid model gives rather good results especially for light particles. A further improvement should be obtained within the geometry dependent hybrid model.

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