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Improved Simulation of the Pre-equilibrium Triton Emission in Nuclear Reactions Induced by Nucleons

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A new approach is proposed for the calculation of non-equilibrium triton energy distributions in nuclear reactions induced by nucleons of intermediate energies. It combines models describing the nucleon pick-up, the coalescence and the triton knock-out processes. Emission and absorption rates for excited particles are represented by the pre-equilibrium hybrid model. The model of Sato, Iwamoto, Harada is used to describe the nucleon pick-up and the coalescence of nucleons from exciton configurations starting from (2p,1h) states. The contribution of the direct nucleon pick-up is described phenomenologically. Multiple pre-equilibrium emission of tritons is accounted for. The calculated triton energy distributions are compared with available experimental data.

I. INTRODUCTION

Nearly twenty years ago articles [1],[2],[3] were published concerning the precompound cluster emission in nuclear reactions induced by nucleons of intermediate energies. The model proposed has been one of the first applications of the coalescence pick-up model [4] and the first application of the hybrid model [5] to the description of the non-equilibrium deuteron and α-particle emission in nuclear reactions.

The model [2],[3] was in competition with the model of complex particle emission [6] which was formulated based on the theory of pre-equilibrium emission. During long time both models were used for the qualitative description of complex particle emission spectra in nucleon induced reactions. The need in reliable nuclear data at primary nucleon energies up to 150 MeV in a new way raised a question about the accuracy of model calculations. The requirement of quantitative description of nuclear reaction characteristics has acquired a special importance. The pre-equilibrium exciton model [6] has been renewed in Refs.[7],[8] and the model [3] in Ref.[9], and the success of both models in the prediction of energy distributions of complex particles has been demonstrated in a number of works , see, for example, Refs.[8],[9],[10],[11].

The present work concerns the further development of the approach [3],[9] formulated basing on the exciton coalescence pick-up model [4], knock-out model, and the hybrid model [5].

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II. MODEL DECRIPTION

As in Ref.[9] it is supposed that the non-equilibrium triton emission in nucleon induced reactions results from: i) the pick-up of nucleons with the energy below the Fermi energy (E_F) after the formation of the (2p,1h) initial exciton state, ii) the coalescence of excited nucleons with energies above E_F, iii) the knock-out of the "preformed" triton, iv) the direct process resulting in the triton formation and escape. The non-equilibrium triton spectrum is calculated as a sum of different components

$$\frac{d\sigma}{d\varepsilon_t} = \frac{d\sigma^{P-U,C}}{d\varepsilon_t} + \frac{d\sigma^{K-O}}{d\varepsilon_t} + \frac{d\sigma^{D}}{d\varepsilon_t}, \qquad (1)$$

where the first term relates to the pick-up and the coalescence after the formation of the (2p,1h) exciton state, the second component describes the contribution of the triton knock-out and the last term relates to the direct process.

The analytical expressions for each component of the triton emission spectrum were obtained using basic statements of the hybrid model [5].

A. Pick-up and Coalescence

The exciton coalescence pick-up model proposed in Ref.[4] is used for the calculation of the $d\sigma^{P-U,C}/d\varepsilon_t$ spectrum component

$$\frac{d\sigma^{P-U,C}}{d\varepsilon_t} = \sigma_{non}(E_0) \sum_{n=n_0} \sum_{k+m=3} F_{k,m}(\varepsilon_d + Q_t) \times \frac{\omega(p-k,h,U)}{\omega(p,h,E)} \frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t) + \lambda_t^+(\varepsilon_t)} g_t D(n), \quad (2)$$

where σ_{non} is the cross-section of nonelastic interaction of the nucleus and the primary particle with the kinetic energy E_0; $F_{k,m}$ is the triton formation factor [4]; the residual excitation energy U is equal to $E-\ Q_t-\epsilon_t$, and E is the excitation energy of the composite nucleus, Q_t is the separation energy for the triton; $\omega(p,h,E)$ is the density of exciton states with p particles and h holes, ϵ_t is the channel emission energy corresponding to the triton emission; λ_t^e is the triton emission rate; λ_t^+ is the intranuclear transition rate for the absorption of the formed triton in the nucleus; g_t is the density of single states for the triton; $D(n)$ is the factor describing the "depletion" of the n-exciton state due to the particle emission; n_0 is the initial exciton number, ($n_0 = 3$).

The triton emission rate is calculated with the following formula

$$\lambda_t^e = \frac{(2S_t+1)\,\mu_t\,\varepsilon_t\,\sigma_t^{inv}(\varepsilon_t\,)}{\pi^2\,\hbar^3\,g_t}, \quad (3)$$

where S_t and μ_t are spin and reduced mass of the outgoing triton; σ_t^{inv} is the inverse reaction cross-section for triton. The triton absorption rate is equal to

$$\lambda_t^+ = 2\,W_t^{opt}/\hbar, \quad (4)$$

where W_t^{opt} is the imaginary part of the optical potential for triton.

As an illustration, Fig. 1 shows the calculated pick-up and coalescence contribution in the triton emission spectrum for ^{54}Fe irradiated with 61.5 MeV protons.

B. Knock-out

By the analogy with the α-particle emission [2],[12] the knock-out component of the precompound triton emission spectrum is written as follows

$$\frac{d\sigma^{K-O}}{d\varepsilon_t} = \sigma_{non}(E_0) \sum_{n=n_0} \Phi_t(E_0) \frac{g}{g_t p} \frac{\omega(p-1,h,U)}{\omega(p,h,E)} \times \frac{\lambda_t^e(\varepsilon_t)}{\lambda_t^e(\varepsilon_t) + \lambda_t^+(\varepsilon_t)} g_t D(n), \quad (5)$$

where the factor $g/(g_t p)$ justifies the substitution of the level density $\omega(\pi,\tilde{\pi},\nu,\tilde{\nu},d,\tilde{t},E)$ for the three-component system (neutron, proton, triton) [2], [9] by the one-component state density $\omega(p,h,E)$ in Eq.(5). The factor Φ_t describes the initial number of excited triton clusters in the nucleus $\Phi_t = 2F_t(E_0)$, here F_t is the probability of interaction of the incident particle with the "preformed" triton resulting in its excitation in the nucleus; factor of two reflects the normalization on the number of particles in the initial exciton state n_0

$$F_t = \frac{\varphi\,\sigma_{xt}(E_0)}{\frac{Z'}{A'}\sigma_{xp}(E_0) + \frac{(A'-Z')}{A'}\ \sigma_{xn}(E_0) + \varphi\,\sigma_{xt}(E_0)}, \quad (6)$$

where "x" refers to the initial proton or neutron; σ_{xt}, σ_{xp} and σ_{xn} are the cross-sections of the elastic interaction of projectile with triton, proton and neutron, respectively corrected for a Pauli principle; φ is the number of "preformed" tritons in the nucleus; Z' and A' are number of protons and nucleons in the nucleus corrected for a number of tritons clustered. The general energy dependence for F_t was taken the same as for deuterons from Ref.[9]; an improvement is addressed in a the future work. Fig. 1 shows the calculated contribution of the triton knock-out in the triton emission spectrum for ^{54}Fe(p,x)t reaction induced by 61.5 MeV protons. Parameters used for the calculation are discussed below.

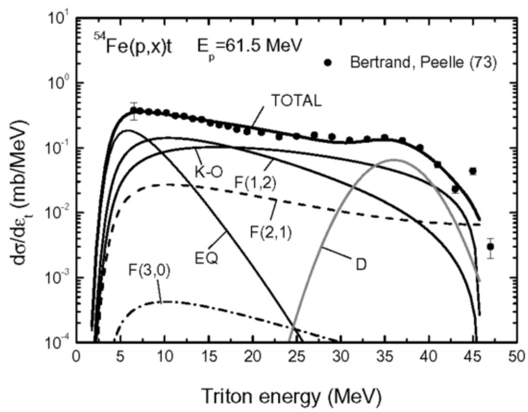

FIG. 1. The calculated contribution of different nuclear processes in the triton emission in reactions p+^{54}Fe induced by 61.5 MeV protons: the equilibrium emission (EQ), the pick-up of nucleons from the exciton states starting from (2p,1h) (F(1,2) and F(2,1)), the coalescence of two excited nucleons (F(3,0)), the knock-out of reformed triton cluster (K-O), and the direct pick-up (D). Also the total spectrum (TOTAL) is shown.

C. Multiple Pre-equilibrium Emission

The multiple particle emission gives a noticeable contribution in precompound emission spectra of composite particles forming in nuclear reactions induced by nucleons with energies above 50 MeV [2],[12].

The multiple pre-equilibrium emission of tritons has been simulated by the analogy with the emission of α-particles and deuterons, as discussed in Refs.[2], [9].