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PRE-EQUILIBRIUM EMISSION IN (n, α) AND (p, α) REACTIONS

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Abstract: The mechanism of α-particle emission in (n, α) and (p, α) reactions on heavy and medium-heavy nuclei was considered in view of the pre-equilibrium model particularly modified by Ribansky and Obložinsky. The introduction of this correction improves the agreement between the model and experimental data. However, part of the reaction yield depending on the incident energy and the target mass should be attributed to the emission of preformed α particles.

1. Introduction

Nuclear reactions are a suitable tool for obtaining information about the reaction mechanism and related parameters. (n, α) and (p, α) reactions on heavy and medium-weight nuclei are of particular interest, because the spectra and angular distributions of these reactions cannot be explained on the basis of equilibrium statistical models.

Before the discovery of the exciton model[1] almost all data on nuclear reactions had been analysed in terms of equilibrium statistical and direct models. These models are based on extreme assumptions concerning the time elapsed between the collision and the emission of a particle from the nucleus.

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The mechanism called pre-equilibrium emission is an intermediate process, based on the assumption that particles are emitted during the cascade initiated in a nucleus by a projectile. The application of the pre-equilibrium model to (n, α) and (p, α) reactions has already given very satisfactory results. The formulas for the energy spectra in a pre-equilibrium emission process have recently been modified[2]. We have used these modified expressions together with the expressions for the pre-equilibrium emission of preformed α particles[3] to analyse the spectra of (n, α) and (p, α) reactions.

2. *The basic formulas and the model used*

The states of a composite system in the pre-equilibrium model[4-7] are classified by the number of excitons n, i. e., $n = p + h$, where p and h are the number of particles and holes, respectively, contained in the states. Transitions in such a system are caused by residual two—body interactions, and because of the higher average density of accessible final states there is greater probability that the system will go in the direction of more complex states ($n \rightarrow n + 2$) than in the direction of simpler ones, or in the direction of other states of the same complexity ($n \rightarrow n$). Thus the system approaches a state of statistical equilibrium, which can be characterized by $n = n$. The emission of particles during this equilibration process often gives a very important contribution to the reaction yield.

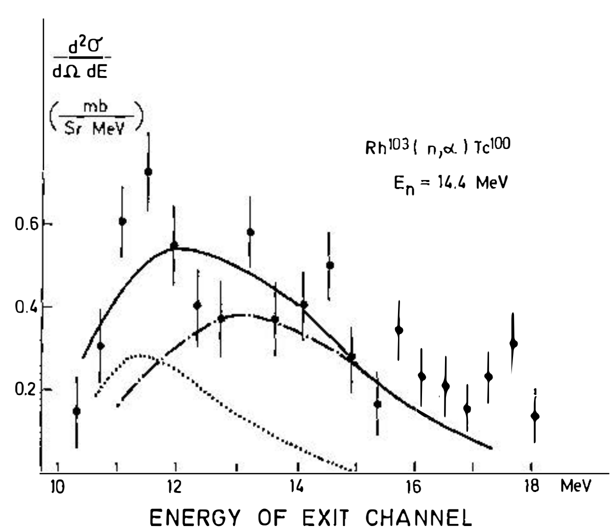

Fig. 1. Analysis of the ^{103}Rh(n, α) ^{100}Tc reaction. The dotted line represents the statistical evaporation, the dash-dotted line is the pre-equilibrium contribution (Equ. 7), and the solid line is the total theoretical spectrum.

In order to achieve a complete approach, i. e., to follow the time evolution of the composite system and to take into account all allowed transitions, one has to solve a set of coupled differential equations

$$\frac{dP(p,h,t)}{dt} = P(p-1,h-1,t)\,\lambda_+(p-1,h-1,E) + P(p+1,h+1,t)\,\lambda_-(p+1,h+1,E) - P(p,h,t)\,[\lambda_+(p,h,E) + \lambda_-(p,h,E) + \sum_{\beta=n,pr}\int_0^{\varepsilon_{max}} W_\beta(p,h,\varepsilon)\,d\varepsilon], \tag{1}$$

with

$$P(p,h,0) = \delta_{pp_0}\,\delta_{hh_0}. \tag{2}$$

Here $P(p, h, t)$ is the occupation probability of $p + h = n$ exciton states at the time t and

$$\lambda_+(p,h,E) = \frac{\pi}{\hbar}\,\overline{|M|}^2\,\frac{g\,(gE)^2}{p+h+1}, \tag{3a}$$

$$\lambda_-(p,h,E) = \frac{\pi}{\hbar}\,\overline{|M|}^2\,g\,ph\,(p+h-2), \tag{3b}$$

as calculated in Ref.[8] and corrected in Ref.[9]. The symbol E is the excitation energy of the composite nucleus, g is the single-particle state density, and $\overline{M^2}$ is the average value of the matrix-element square for residual two-body interactions.

The net spectra emitted up to the time T at which the system is said to have reached statistical equilibrium are obtained in several steps. The occupation probability $P(p, h, t)$ is multiplied by the average rate of emission of particles of a given type β ($W_\beta(p, h, \varepsilon)$) and by the cross-section for formation of the composite nucleus (σ_C). Next, the summation is performed over the number of excitons and the integration is carried out over the time t (from 0 do T). The average rate of particle emission from some exciton state $p + h = n$ is expected to depend on the ratio o state densities

$$W_\beta(p,h,\varepsilon) \sim \varepsilon\,\sigma_{inv}(\varepsilon)\,\frac{\omega(p-p_\beta,h,U)}{\omega(p,h,E)}\,\omega(p_\beta,0,E-U), \tag{4}$$

where $U = E - \varepsilon - B_\beta$ is the excitation energy of the residual nucleus.

The simple form of the state density as given by Ericson[10] is

$$\omega(p,h,E) = \frac{g\,(gE)^{p+h-1}}{p!\,h!\,(p+h-1)!}. \tag{5}$$

Rewriting

$$\omega(p, h, E) = \frac{g^n E^{n-1}}{(n-1)! \left(\frac{n-1}{2}\right)! \left(\frac{n+1}{2}\right)!}, \tag{5a}$$

$$\omega(p-1, h, U) = \frac{g^{n-1} U^{n-2}}{(n-2)! \left(\frac{n-1}{2}\right)! \left(\frac{n-1}{2}\right)!}, \tag{5b}$$

$$\omega(p-4, h\, U) = \frac{g^{n-4} U^{n-5}}{(n-5)! \left(\frac{n-1}{2}\right)! \left(\frac{n-7}{2}\right)!}, \tag{5c}$$

(n odd) and taking into account only $n \to n+2$ transitions, we obtain simple closed-form expressions for the emission of α particles (as well as for other particles).

$$\left(\frac{d\sigma}{d\varepsilon}\right)_{\substack{\text{pre-eq.}\\ \text{preformed}}} = f\sigma_C \frac{\mu_a\, \varepsilon_a\, \sigma_{\text{inv}}(\varepsilon_a)(2s+1)}{2\pi^3 \hbar^2\, |\overline{M}|^2\, g^4 E^3} \sum_{\substack{n=n_0\\ \Delta n=2}}^{\bar{n}} \left(\frac{U}{E}\right)^{n-2} (n+1)(n^2-1), \tag{6}$$

$$\left(\frac{d\sigma}{d\varepsilon}\right)_{\text{pre-eq.}} = \gamma_a \sigma_C \frac{\mu_a\, \varepsilon_a\, \sigma_{\text{inv}}(\varepsilon_a)(2s+1)}{16\pi^3 \hbar^2 |\overline{M}|^2 g^7 E^6} \sum_{\substack{n=n'_0\\ \Delta n=2}}^{\bar{n}} \left(\frac{U}{E}\right)^{n-5} (n+1)^2 (n-1)^2 (n-2) \cdot$$

$$\cdot (n-3)^2 (n-4)(n-5) \cdot \frac{g^3 (E-U)^3}{3!4!}, \tag{7}$$

(the $(n+1)$ factor in both formulas comes from $\frac{1}{\lambda_+} \sim (n+1)$). Here f is related to the probability for the existence of preformed α particles in the nucleus and γ_a to the probability that an α particle will be formed of two excited protons and two excited neutrons of a composite system.

3. *Analysis of some (n, α) and (p, α) reactions at intermediate energies*

(n, α) reactions around 14 MeV. It is a well established fact that equilibrium statistical theories can explain (n, α) spectra and absolute values of cross-sections at incident energies around 14 MeV only in the region $20 < A < 80$ and that for heavy nuclei both the magnitude and spectral shapes as derived from these theories are in serious disagreement with experimental data. Pre-equilibrium emission starts to play a significant role in the mass region $A > 80$. The »normal« pre-equilibrium contribution, as given by Equ. (7), together with the equilibrium sta-

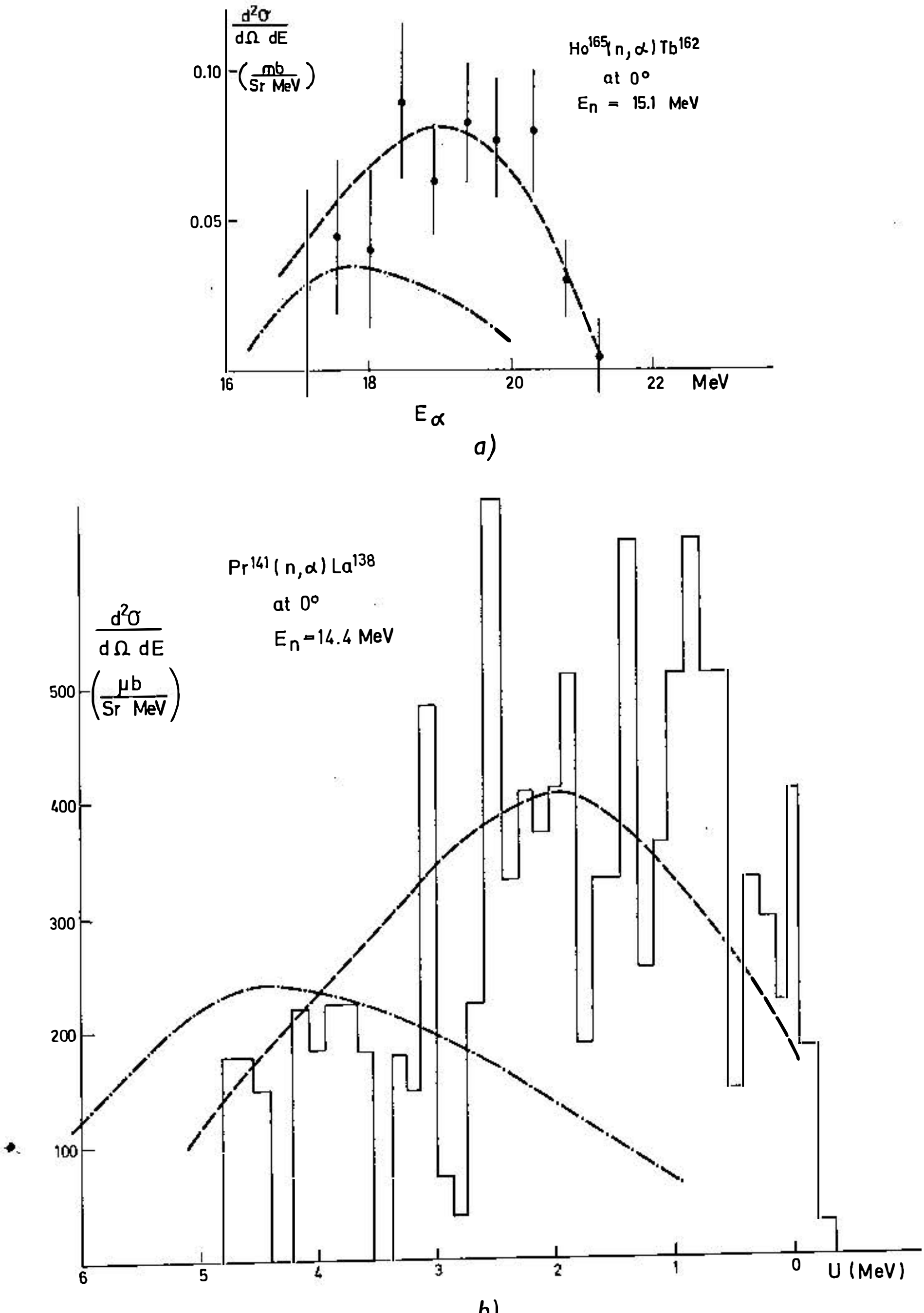

Fig. 2.a) Comparison of the ^{165}Ho(n, *a*) ^{162}Tb spectrum with calculations. The dashed line represents the preformed pre-equilibrium emission of a particles (Equ. 6). The »normal«pre-equilibrium contribution is seen to have a different shape from the experimental one.
b) Same for the ^{141}Pr(n, *a*) ^{138}La spectrum.

tistical contribution accounts for the main part of the spectra for medium-weight nuclei, its importance decreasing with higher A values. So, for heavy nuclei ($A >$ > 140) the shape of this contribution is different from the experimental shape even if the factor $\omega\,(p_\beta,\, 0,\, E - U)/g = (E - U)^3 g^3/(3!4!)$ is used. This factor was recently introduced to take into account all distinguishable configurations of excited nucleons from which a complex particle can be formed[2].

Fig. 1 shows a fit for the ^{103}Rh $(n, \alpha)^{100}$Tc reaction at $E_n = 14.4$ MeV obtained by formula (7), which represents the »normal« pre-equilibrium contribution. The spectrum of this reaction was mesured by Veselić and Tudorić[11] using the telescopic counter technique. We obtained a similar result for the spectrum of the ^{107}Ag$(n, \alpha)^{104}$Rh reaction taken from Ref.[12].

The reaction yield on heavy nuclei is attributed to some kind of direct process that can be pictured as knocking out of preformed α particles and described approximately in the framework of the pre-equilibrium model using Equ. (6), particularly when only the first term in the summation is dominant.

The spectra of the ^{141}Pr $(n, \alpha)^{138}$ Ta and ^{165}Ho $(n, \alpha)^{162}$Tb reactions measured by Kulišić et al.[13] and Kitazawa[14], respectively, illustrate the fact that the emission from heavy nuclei is due to preformed α particles, as can be seen from Figs. 2a and 2b.

(p, α) reactions on heavy nuclei. The study of the ^{197}Au $(p, \alpha)^{194}$Pt reaction at 32 MeV and 41.3 Mev proton energies, as performed by Kost[15], has shown that even for backward angles equilibrium statistical theories are unable to give a satisfactory treatment. The introduction of the pre-equilibrium contribution, especially with the factor of Ribansky and Obložinsky, enables one to describe low- and medium-energy parts of the spectra.

The spectrum of the ^{197}Au $(p, \alpha)^{184}$Pt reaction at 41.3 MeV shown in Fig. 3 and the (p, α) spectra used in the next subsection were measured at the University of Manitoba Cyclotron[16].

Our analysis shows that there are still emitted particles in the high-energy part of the spectra that cannot be explained by »normal« pre-equilibrium emission, and it seems that preformed α particles play an important role. This question will be examined in detail in the next subsection.

Analysis of the high-energy part of the spectra. The high-energy part of α spectra cannot be explained by »normal« pre-equilibrium emission (Equ. 7), so slope analysis was used to examine closely the high-energy part of α spectra in nucleon-induced reactions. We see from Equ. (5) that

$$\log\left(\frac{\sigma_{\text{exp.}}}{\varepsilon\sigma_{\text{inv.}}}\right) \sim C + (n-1)\log U, \tag{8}$$

for low values of U. Thus, analysing the highest kinetic energy part of the spectra, we expect to obtain, in a log-log diagram, a straight line with a slope equal to (n_f — — 1). Here n_f is the number of excitons in the simplest residual-nucleus states. If the emitted particle is a nucleon, then from the analysis we can immediately obtain the initial number of excitons n_0, because there is only one exciton less in the residual nucleus than in the initial compound state, i. e., the slope is $n_0 - 2$.

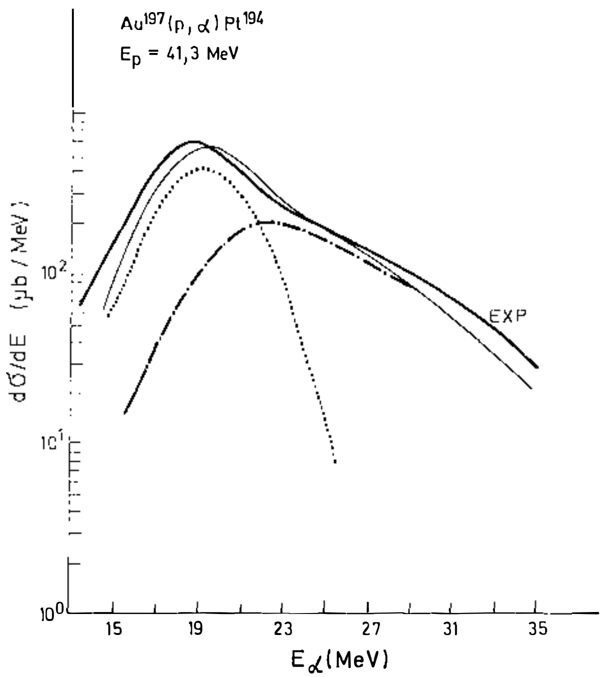

Fig. 3. Analysis of the ^{197}Au(p, α) ^{194}Pt spectrum. The pre-equilibrium model (Equ. 7) gives a good fit for the medium-energy part of the spectrum.

From the analysis of (p, n), (n, p), (p, p') and (n, n') reactions it is known that the composite system is formed in states $n_0 = 3$ in nucleon-induced reactions. We assume that for preformed α particles in (n, α) and (p, α) reactions the situation is similar to the nucleon case and the number of excitons n_f should be $n_f = 2$, i. e., the slope should be equal to $n_f - 1 = 1$.

The results are summarized in the Table. All calculations have been performed using the inverse cross-sections from Huizenga and Igo[17)] and the Q values from Maples et al.[18)].

Slope analysis shows that the data are consistent with a knock-out process for the high-energy part of the spectra, especially when we note that ^{209}Bi is in the vicinity of closed-shell nuclei, where the emission of particles in near ground--state transitions should be inhibited because of the reduced number of low-energy states in the residual nucleus and is parametrized as a higher value of n_0[5)].

Table

Target nucleus	Reaction	Incident energy (MeV)	n_f	Angle	Ref.
^{165}Ho	(p, α)	40	2.4 ± 0.5	20°	16)
^{181}Ta	(n, α)	21.3	2.0 ± 0.2	0°	19)
^{197}Au	(n, α)	21.0	$2.3 {+0.4 \atop -0.3}$	0°	19)
^{197}Au	(p, α)	23.0	1.9 ± 0.2	angle integrated	15)
^{209}Bi	(p, α)	40	2.8 ± 0.5	60°	16)

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References

1) J. J. Griffin, Phys. Rev. Lett. **17** (1966) 478;

2) I. Ribansky and P. Obložinsky, Phys, Lett. **45B** (1973) 318;

3) L. Colli-Milazzo and G. M. Marcazzan-Braga, Phys. Lett. **38***B* (1972) 155;

4) M. Blann, Phys. Rev. Lett. **21** (1968) 1357;

5) C. K. Cline and M. Blann, Nucl. Phys. **A172** (1971) 225;

6) M. Blann and F. M. Žanzafame, Nucl. Phys. **A142** (1970) 559;

7) C. K. Cline, Nucl. Phys. **A193** (1972) 417;

8) F. C. Williams Jr., Phys. Lett. **31B** (1970) 184;

9) I. Ribansky, P. Obložinsky and E. Betak, Nucl. Phys. **A205** (1973) 545;

10) T. E. Ericson, Advances in Physics **9** (1960) 425;

11) Đ. Veselić, J. Tudorić-Ghemo, Nucl. Phys. **A110** (1968) 225;

12) M. Irfan and W. Jack, Proc. Phys. Soc. **81** (1963) 808;

13) P. Kulišić, V. Ajdačić, N. Cindro, B. Lalović and P. Strohal, Nucl. Phys. **54** (1964) 17;

14) H. Kitazawa, Nucl. Phys. **A149** (1970) 513;

15) C. J. Kost, Thesis, Univervisty of Manitoba, Canada 1968;

16) W. R. Falk, R. Kidney, P. Kulušić and G. K. Tandon, Annual Report 1968; Cyclotron Laboratory, University of Manitoba, 19—25;

17) J. R. Huizenga and G. Igo, Nucl. phys. **29** (1962) 462;

18) C. Maples, G. W. Goth and J. Cerny, Nuclear Reaction Q-values, UCRL-16964, Berkeley California;

19) A. Rubbino and D. Zubke, Nucl. Phys. **85** (1966) 606.

MEHANIZAM PREDRAVNOTEŽNE EMISIJE U (n, α) I (p, α) REAKCIJAMA

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Sadržaj

Razmatran je mehanizam emisije α čestica u (n, α) i (p, α) reakcijama na teškim i srednje teškim jezgrama primjenjujući model nepotpune ravnoteže u nešto modificiranom obliku, koji su izveli Ribansky i Obložinsky. Uvođenje korekcije poboljšava slaganje modela i eksperimentalnih podataka, ali dio doprinosa u reakciji ovisno o upadnoj energiji i masi jezgre mete treba se pripisati emisiji preformiranih α čestica.