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# ANGULAR-MOMENTUM EFFECTS IN THE PRE-EQUILIBRIUM STATISTICAL MODEL

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The role of the angular-momentum conservation in the pre-equilibrium statistical model is illustrated by the excitation function of the $^{41}$K ($\alpha$, $n$) reaction in the $\alpha$-energy range of 8–40 MeV. It has been found to be most important for the low initial exciton configurations and to have a similar character as in the equilibrium statistical model for the higher ones.

## I. INTRODUCTION

The pre-equilibrium statistical model (PESM), recently introduced by Griffin [1] and Blann [2] has shown great promise in the analyses of excitation and emitted-particle spectra for a number of reactions at medium excitation energies (e.g. [3, 4]). These successes of the spin-independent version of the model, which has been studied so far, as well as the analogy with the equilibrium statistical model (ESM) lead to the assumption that the influence of the angular-momentum effect on calculations is small. However, this assumption has not been verified directly. It is the purpose of this paper to demonstrate a role of the angular-momentum conservation in the PESM in calculations of the excitation functions. The reaction $^{41}$K($\alpha$, $n$), measured by Matsuo et al. [5] in the $\alpha$-energy range of 8 to 40 MeV, is chosen for the present analysis.

## II. CALCULATIONS

In the PESM each state of the system is characterized by the particle number $p$, the hole number $h$ and the total exciton number $n = p + h$. The approach to the equilibrium is due to a series of two-body interactions starting from the initial exciton number $n_0$ and finishing at the most probable exciton number $\bar{n}$. The spin-dependent expression for the emission rate of a particle

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from a composite system at the energy $E_c$ and the spin $J_c$, leading to a residual nucleus at the energy $E_R$ and the spin $J_R$, is given by [6]

$$R(E_c, J_c; E_R, J_R)\,\mathrm{d}E_R = \frac{\mathrm{d}E_R}{h} \sum_{\substack{n=n_0 \\ \Delta n=+2}}^{\bar{n}} \frac{\Omega_{p-\nu,h}(E_R, J_R)}{\Omega_{p,h}(E_c, J_c)} \sum_{S=|J_R-s|}^{J_R+s} \sum_{l=|J_c-S|}^{J_c+S} T_l(\varepsilon), \qquad (1)$$

where $\Omega_{p,h}$ is the level density, $\nu$ represents the nucleon number of the emitted particle, $S$ is the channel spin, $s$ is the spin of the emitted particle and $T_l(\varepsilon)$ denotes the transmission coefficient for the emitted particle with the energy $\varepsilon$ and the orbital angular momentum $l$.

The level density is assumed to have the form proposed by Williams [7]

$$\Omega_{p,h}(E, J) = \frac{g(gE - A_{p,h})^{p+h-1}}{p!\,h!(p+h-1)!} \frac{2J+1}{2(2\pi)^{1/2}\sigma_{p,h}^3} \exp\left[-\frac{(J+\frac{1}{2})^2}{2\sigma_{p,h}^2}\right], \qquad (2)$$

where $g$ is the density of the single-particle levels at the Fermi level and

$$A_{p,h} = \tfrac{1}{4}(p^2 + h^2) + \tfrac{1}{4}(p - h) - \tfrac{1}{2}h \qquad (3)$$

is the correction term for the Pauli principle.

The spin cut-off parameter $\sigma_{p,h}$ can be related to the moment of inertia $I$ and temperature $t_{p,h}$ by

$$\sigma_{p,h}^2 = \frac{I}{\hbar^2} t_{p,h}, \qquad (4)$$

where

$$t_{p,h} = \frac{gE - A_{p,h}}{g(p+h-1)}. \qquad (5)$$

The relation between the excited particle and the hole numbers was taken to be $p = h + 1$ and the quantity $\bar{n} \approx 2(0.299\,g_c E_c)^{1/2}$ [7], where the subscript $c$ refers to the composite system.

The spin-independent emission rate can be obtained from eq. (1) by summation over $J_R$ under the assumption that the level density varies with the angular momentum as $(2J + 1)$. This can be shown in a similar way as done by Thomas [8] in the ESM.

The cross section of the reaction $(\alpha, i)$ in the closed form formulation of Griffin's model is given by

$$\sigma(\alpha, i) = \sum_{J_c} \sigma_c(E_c, J_c) \frac{\Gamma_i(E_c, J_c)}{\sum_j \Gamma_j(E_c, J_c)} \qquad (6)$$



where $\sigma_c(E_c, J_c)$ is the composite-nucleus cross section and $\Gamma_j(E_c, J_c)$ represents the emission width for the channel $j$. The $\Gamma_j$ can be obtained from eq. (1) by performing summation over $J_R$ and integration over $E_R$. Eq. (6) contains an implicite assumption that the half-life of an $n$-exciton state is constant, as proposed by Blann [2]. Though the validity of this approximation is limited, as shown by a detailed analysis in ref. [14], it can be considered as sufficient for our purposes.

Calculations were performed on the CDC 3300 computer of the United Nations Research Computing Centre in Bratislava using the program described in ref. [6]. The spectra of the emitted neutrons and cross sections were evaluated by using the transmission coefficients of Mani et al. [9] for neutrons and protons, for $\alpha$-particles the parabolic approximation of the optical potential was applied [10]. The single-particle level densities were taken from ref. [11]. The conventional pairing energy corrections were taken into account by using the data of Nemirovsky and Adamchuk [12]. The moment of inertia was assumed to be that of a rigid body. The binding energies were those of Garvey et al. [13].

In the PESM, the initial configurations with $n_0 = 3, 5, 7$ were investigated. For comparison, the calculations were performed also in the ESM with the level density of Gilbert and Cameron [11].

## III. RESULTS AND DISCUSSION

The excitation functions of the reaction $^{41}$K $(\alpha, n)$ are shown in Fig. 1. At low energies, especially below the threshold of the $(\alpha, 2n)$ reaction, the cross section calculated in the spin-dependent PESM are practically the same as in the spin-independent version of the model. This fact is due to a small influence of the angular momentum effects on the relative intensity of the competing channels. At higher energies, the cross sections calculated in the spin-dependent and spin-independent PESM differ from one another mostly for $n_0 = 3$, with the increasing $n_0$ the discrepancies vanish and are close to the ESM results. In order to make this behaviour clear the spectra of emitted neutrons are presented in Fig. 2. All spectra are normalized to the same area. It can be concluded from Fig. 2 that in the spin-dependent PESM the terms with a low $n$ in eq. (1) favour, in comparison with the spin-independent PESM, the high- energy part of the spectra contrary to the action of the high-$n$ terms. Indeed, in the spin-dependent part of the level density given by eq. (2) we have the factor $1/\sigma_{p,h}^3$, which prefers the emission of fast particles, whereas the exponential term prefers the emission of slow particles. The total effect depends on $n$. With regard to the ESM, the spectrum calcu-

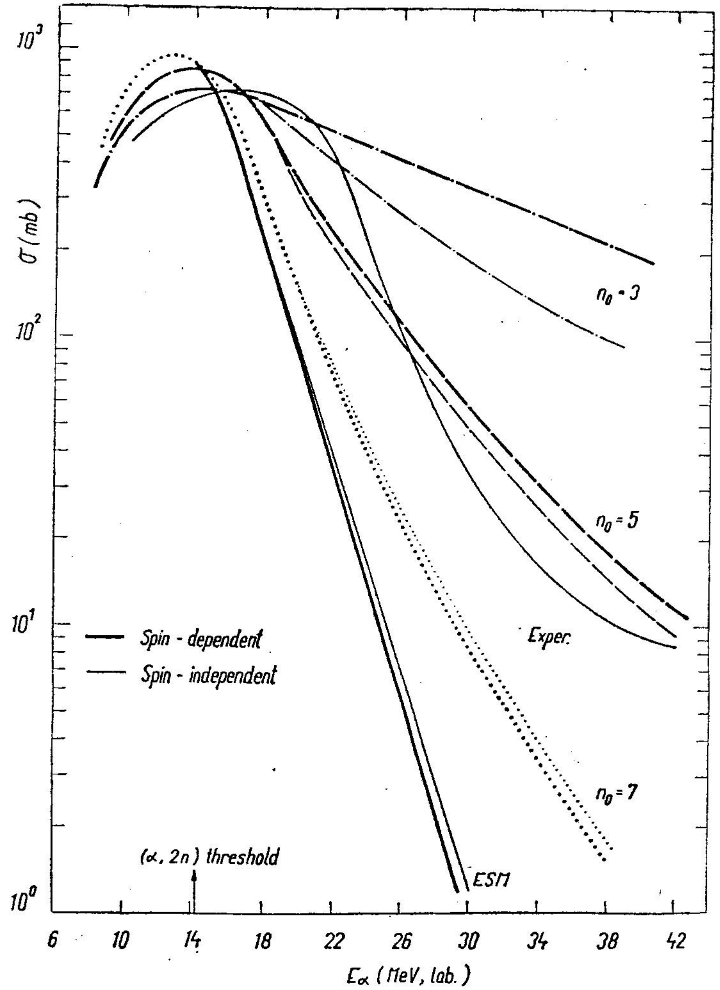


Fig. 1. Comparison of the excitation functions calculated in the spin-dependent (heavy curves) and spin-independent (thin curves) PESM and ESM. The experimental values are from ref. [5].

lated in the spin-independent version of the model cannot be reasonably distinguished from the spin-dependent one because of the scale used in Fig. 2.

In spite of sensible differencies in the cross section at high energies, which were found for $n_0 = 3$, one can conclude that the inclusion of the angular momentum conservation in the PESM does not influence the results essentially.



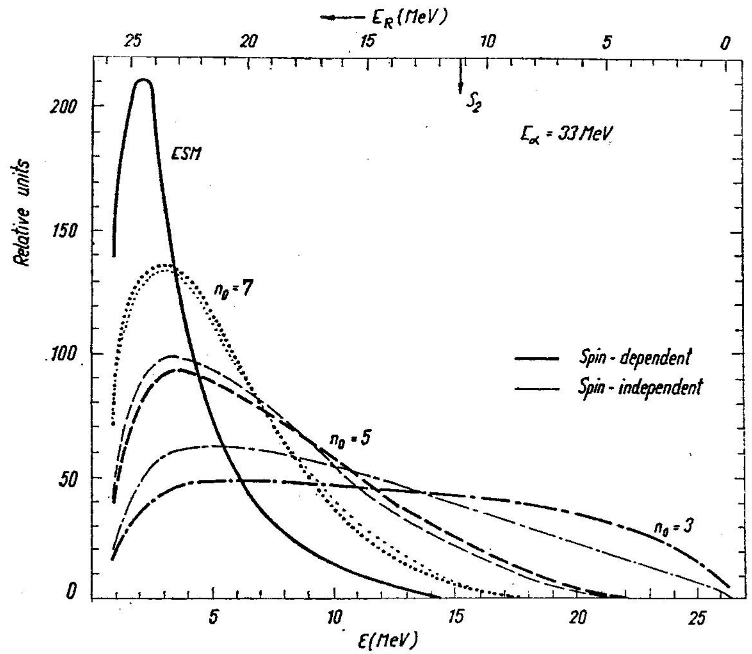


Fig. 2. Comparison of the neutron energy spectra calculated in the spin-dependent (heavy curves) and spin-independent (thin curves) PESM and ESM for $E_\alpha = 33$ MeV. The quantity $S_2$ is the separation energy of the second neutron.

If the fit to experiment requires a higher value of $n_0$, say, $n_0 = 5$ as our sample reaction, one can expect that both the spin-dependent models give practically the same results.

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