Nuclear stratosphere formation and its effects upon statistical particle emission processes

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Effects induced by a nuclear stratosphere upon statistical particle emission processes are discussed. The calculations are based on the compound nucleus emission model and they include the formation of a nuclear stratosphere. This degree of freedom is accounted for by effective potentials for particle emission channels. The radial dependence of these potentials is adjusted in order to reproduce the temperature-dependent shape evolution of nuclear radial distribution functions. Results are discussed for $^{1}H/^{4}He$ emission rates from the compound nucleus ^{28}Si.

I. INTRODUCTION

The question about the formation of a nuclear stratosphere in high energy nuclear reactions leading to highly excited compound nucleus has been raised recently.[1–3] Data on angular and energy distributions for ^{4}He in correlation with ^{1}H, reported in Ref. 2, indicate important barrier reductions for highly excited compound nuclei compared to those for cold nuclei. Moreover, statistical model predictions for $^{1}H/^{4}He$ correlation functions[1,2] have been shown to be in conflict with standard model assumptions about the behavior of hot nuclei. Although the data exhibit characteristic features normally associated with compound nucleus evaporation, predictions based on the standard model are definitely at odds with them and cannot be improved by changing its basic physical features. It should be noted that the above mentioned analysis[1,2] has been performed very carefully and that the existence of a clear contradiction between data and theoretical results can unamiguously be pointed out.

Among other possibilities, i.e., barrier reductions, static deformations, and angular momentum dependent effects,[1,2] the formation of a surface tail has also been discussed[3] as a possible reason for the above mentioned differences between data and predictions.

It is our aim to discuss, hereon, the effects upon statistical particle emission channels due to the temperature dependent evolution of a nuclear stratosphere. This mechanism can be related to the finding of,[1–3] and to theoretical evidences about, the structure of nuclear density distribution functions at high excitation energies.[4]

Particle emission channels from compound nucleus states are currently described by the statistical model of nuclear reactions.[5] The basic ingredients of this model are nuclear level densities and optical model transmission coefficients.[5] The problem associated with the temperature, or energy, dependence of nuclear level densities has been investigated in detail in works dealing with single particle and collective aspects of nuclear degrees of freedom at finite temperature.[6–9] Results related to the effects of these degrees of freedom upon statistical particle emission have been reported recently.[10,11] Therefore, while the temperature dependence of nuclear level densities has been explored in some detail,[6–11] the study of the behavior of optical mode potentials at finite temperature has received less attention. On the other hand, studies of the self-consistent nuclear radial distribution functions[12–13] show the appearance of surface effects which could influence the shape of the radial dependence of optical model potentials. Since the tail of these potentials, at the surface region, follows that of the nuclear radial distribution functions, it could be argued that the formation of an elongated tail at the nuclear surface would be accompanied by a similar elongation of the potentials. The formalism, which is described in Sec. II, is based on the assumption that effective, temperature-dependent, optical model potentials for statistical particle emission can be extracted from the temperature dependence of the nuclear radial distribution functions. As an example, we have calculated, with these potentials, ^{1}H and ^{4}He emission channels from the compound nucleus ^{28}Si. The results are presented in Sec. III. Finally, some conclusions are drawn in Sec. IV.

II. FORMALISM

Theoretical results concerning the formation of a nuclear stratosphere have been reported in Ref. 4. These calculations, which are based on the temperature dependent Hartree-Fock treatment of a realistic effective Hamiltonian,[12,13] show that self-consistent nuclear density distributions for hot nuclei evolve into a contracted volume region and into an elongated surface tail. The increase of density values at the surface region, for increasing temperatures, develops at the expense of the decrease of density values at the volume or interior region. The evolution of the surface, or exterior region, determines the formation of a nuclear stratosphere. More generally, at high temperatures, as the nucleus becomes more excited, a balance between the decrease of the density distribution at the interior and the increase of the density distribution at the exterior has to be established. This balance results in the contraction of the volume part, which could not decrease its density value indefinitely, and in the expansion of the surface part by the occupation of high lying single particle orbits. The increase of the mean radius of the surface region, as a function of the temperature has, as a direct consequence, the formation of a nuclear stratosphere with the subsequent enhancement of particle emission channels. If we now think of the radial dependence of the optical model potentials as being determined by the radial dependence of nuclear distribution functions, it becomes clear that the effects due to the formation of a nuclear stratosphere upon statistical particle emission could be investigated by incorporating this radial dependence in the standard statistical model calculations. It should be noted that this shape evolution of the optical model potential is in fact temperature dependent, since it results from the temperature dependence of the nuclear radial distribution functions. This means that, as the nucleus deexcites by particle emission and becomes less hot, different emission temperatures would eventually be associated not only with the central, thermally equilibrated, density region but also with the more excited surface, or peripherical, tail.

We have adopted the following approximations for the radial dependence of the central potentials to be used in the calculation of optical model transmission coefficients for particle emission: Woods-Saxon (WS), contracted Woods-Saxon plus a surface centered Gaussian (CWSG), and contracted Woods-Saxon plus a tail at the surface region (CWST). Standard WS potentials, for protons and alpha particles, have been taken from the compilation of Perey and Perey[14] and their volume, surface, and spin-orbit (SO) terms are defined by

$$\begin{aligned} V(r) &= -V_0 f_v(x_v) \\ &\quad + (\hbar/m_\pi c)^2 V_{SO}(\mathbf{s}\cdot\mathbf{l})\frac{1}{r}\frac{d}{dr}[f_{SO}(x_{SO})] , \\ W(r) &= -W_v f_w(x_w) + 4W_s\frac{d}{dx_s}[f_s(x_s)] , \end{aligned} \tag{1}$$

where

$$f_i(x_i) = (1+\exp x_i)^{-1} \text{ for } x_i = (r-R_i)/a_i .$$

The Coulomb potential, in the uniform charge approximation, can be written as

$$V_C(r) = \begin{cases} Z_1 Z_2 e^2/r & (r \ge R_C) , \\ Z_1 Z_2 e^2/2R_C(3-r^2/R_C^2) & (r \le R_C) . \end{cases} \tag{2}$$

The potentials which correspond to the CWSG case are given by Eq. (1), with radial functions f_i

$$f_i^{\text{CWSG}}(x_i) = f_i(x_i+1) + h^{\text{CWSG}} \exp[-(x_i-1)^2] \tag{3}$$

for the real and imaginary volume terms, respectively. The corresponding Coulomb term is given by Eq. (2) with $R_C^{\text{CWSG}} = R_C - a_v$, which is consistent with the contraction of the volume region of the radial density distribution function, as it has been discussed in Ref. 4. The parameter h^{CWSG} is fixed at the value $h^{\text{CWSG}} = 0.1$. This approximation for the radial dependence of the potentials (1) follows the behavior of a radial density distribution function which, at finite temperature, is contracted in its volume part and displays a cluster localization on its surface region. We have adopted a Gaussian shape for the cluster spatial distribution in order to allow for surface dominated particle emission processes. The CWST potentials are defined by the following radial dependence:

$$f_i^{\text{CWST}}(x_i) = \begin{cases} (1+\exp x_i)^{-1}, & r \le r_i^M \\ h, & 0 \le r - r_i^M \le b \\ 0, & r \ge r_i^M + b , \end{cases} \tag{4}$$

where $x_i = (r - 0.8R_i)/a_i$ and $r_i^M = 0.8R_i + a_i \ln[(1-h)/h]$, for the real and imaginary volume terms. In the same approximation we have defined a Coulomb radius $R_C^{\text{CWST}} = 0.8R_C$. This form is consistent with a radial density distribution function which displays a volume contraction and a tail at the surface region.

Optical model transmission coefficients,[14] $T_l^k(\varepsilon)$, calculated with these potentials would account for energy dependent changes of the surface region. With them we can define particle emission widths Γ_k, which are given by the statistical model expression[5]

$$\Gamma_k = \sum_{l,I_R} \int_0^{E_c - B_k} d\varepsilon\, \rho_k(E_c - B_k - \varepsilon, I_R) \times T_l^k(\varepsilon)\Delta(\mathbf{I}_c, \mathbf{s}+\mathbf{l}) , \tag{5}$$

with $\mathbf{s} = \mathbf{I}_R + \mathbf{s}_k$, and corresponding differential cross sections

$$\begin{aligned} \frac{d\sigma_k^{\text{emission}}}{d\varepsilon_k} &= \frac{1}{\Gamma_T}\sum_{I_c} \sigma^{\text{formation}}(E_c, I_c)\frac{d\Gamma_k}{d\varepsilon_k} , \\ \frac{d\sigma_k^{\text{emission}}}{d\Omega_k} &= \frac{1}{4\pi\Gamma_T}\sum_{I_c,l,I_k} \Delta(\mathbf{I}_c, \mathbf{s}+\mathbf{l})\sigma^{\text{formation}}(E_c, I_c) \\ &\quad \times \int_0^{E_c - B_k} d\varepsilon\, \rho_R(E_c - B_k - \varepsilon, I_R) T_l^k(\varepsilon)(2I_c+1) \\ &\quad \times \sum_{m=-l}^{+l} \sum_{L=0}^{\min(2I_c, 2l)} (2L+1)(2l+1) \begin{pmatrix} l & l & L \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} l & l & L \\ m & -m & 0 \end{pmatrix} \\ &\quad \times \begin{pmatrix} s & l & I_c \\ m & -m & 0 \end{pmatrix}^2 (-1)^m P_l(\cos\theta_k) , \end{aligned} \tag{6}$$

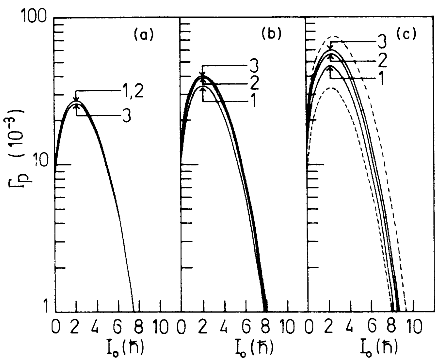

FIG. 1. Partial width for statistical proton emission from the compound nucleus ^{28}Si at the excitation energy $E_c = 37.67$ MeV. The values are displayed as a function of the compound nucleus angular momentum, I_c. Dashed, dot-dashed, and solid lines correspond to WS, CWSG, and CWST results, respectively. Lines denoted by 1, 2, and 3 correspond to $h = 0.05$, 0.10 and 0.15, respectively; while cases a, b, and c correspond to $b = 1$, 2, and 3 fm, respectively. The meaning of the parameters h and b and of the approximations indicated by WS, CWSG, and CWST are given in the text.

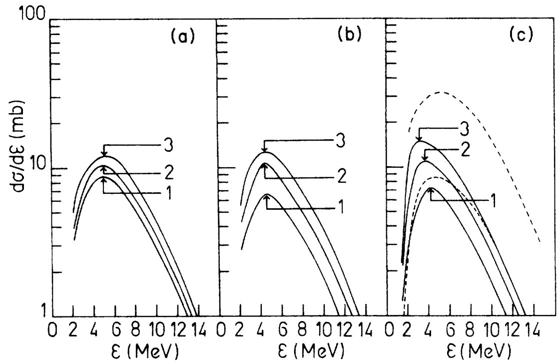

FIG. 3. Energy distribution for statistical proton emission from the compound nucleus ^{28}Si, as a function of the proton center of mass kinetic energy. The lines are indicated as in Fig. 1.

with $\Gamma_T = \Sigma_k \Gamma_k$. The nuclear level density $\rho_R(E,I)$, which appears in Eqs. (5) and (6) is given by the standard parametrization of,[15] and $\sigma^{\text{formation}}(E_c, I_c)$ stands for the compound nucleus formation cross section.

III. RESULTS AND DISCUSSION

We have calculated particle emission channels for the case of the reaction ^{12}C(^{16}O,k)$^{28-k}$Res, at $E_{\text{lab}} = 49$ MeV, where $k =$ n, p, α, d, t where Res is the corresponding residual nucleus. For this case, proton and alpha particle channels dominate the contributions to the total decay width Γ_T. The corresponding partial widths are shown in Figs. 1 and 2, and they have been calculated with the optical model potentials which have been described in the previous section. From the results of Fig. 1, we can conclude that statistical proton emission from a nuclear stratosphere dominates over the emission from a Gaussian shaped surface. While the enhancement of proton emission widths, for the elongated surface region, becomes evident from the results of Fig. 1, a less important effect is observed for the case of statistical alpha particle emission, as it is shown in Fig. 2. The effects due to the above mentioned radial dependences upon the energy spectrum of the emitted particles are shown in Figs. 3 and 4, for proton and alpha particles, respectively. In both cases a shift of the peaks to lower energies is observed. The effect is more pronounced for protons and it is also more evident for the case of the potentials which are parametrized in order to include an extended surface tail. This trend could not be obtained by lowering the corresponding Coulomb barriers, as we have observed from the results of our calculations. The emission temperature of the compound nucleus ^{28}Si* is of the order of $T_{\text{cn}} = 3.514$ MeV, a value which is of the order of the shape transition temperatures for light and medium nuclei.[16] Since, in the present calculations, the shapes of the optical model potentials for particle emission do evolve with temperature, effects due to a nuclear surface tail would manifest at emission temperatures of the order of the shape transition temperatures. The results shown in Figs. 1–4 seems to confirm this statement, particularly for the case of statistical proton emission. The enhancement of ^{1}H/^{4}He emission rates appears to be favored in

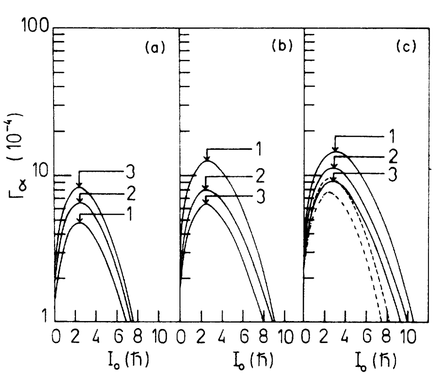

FIG. 2. Partial width for statistical alpha particle emission from the compound nucleus ^{28}Si. Results corresponding to the approximation WS, CWSG, and CWST, for $h = 0.05$, 0.10, and 0.15, and $b = 1$, 2, and 3 fm, are indicated in Fig. 1.

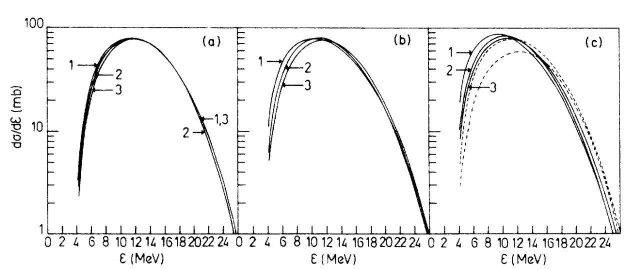

FIG. 4. Energy distribution for statistical alpha particle emission from the compound nucleus ^{28}Si, as a function of the alpha particle center of mass kinetic energy. The lines are indicated as in Fig. 1.

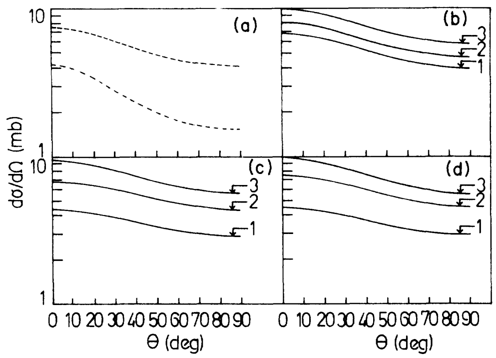

FIG. 5. Angular distributions for statistical proton emission from the compound nucleus ^{28}Si. Dashed and dot-dashed lines which correspond to WS and CWSG approximations, respectively, are shown in case (a). Solid lines 1, 2, and 3 correspond to CWST approximations, with $h=0.05$, 0.10, and 0.15, respectively. Cases (b), (c), and (d) correspond to CWST results with $b=1$, 2, and 3 fm, respectively.

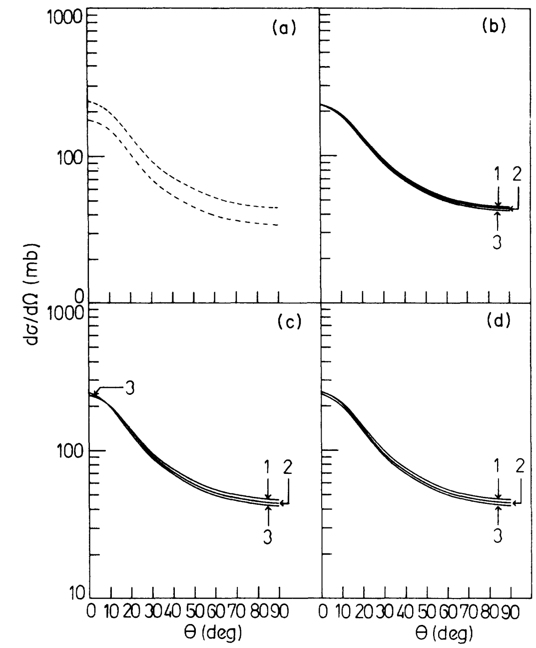

FIG. 6. Angular distributions for statistical alpha particle emission from the compound nucleus ^{28}Si. The lines are indicated as in Fig. 5.

the cases which correspond to CWST potentials with elongations of the order of $b=2-3$ fm. These results corroborate the finding of Refs. 1–3 both concerning the dominance of proton channels over alpha particle channels as well as the shift of the energy spectra of the emitted particles. Results for angular distributions of the emitted particles are shown in Figs. 5 and 6, for proton and alpha particles, respectively. Again in these cases the results corresponding to elongated nuclear stratosphere shapes seem to reproduce the observed trend.[1–3] In fact, proton angular distributions are more sensitive than alpha particle angular distributions to the shape of the associated optical model potentials.

IV. CONCLUSIONS

In this paper we have studied the effects of a nuclear stratosphere upon particle emission channels from a hot nucleus. The results seem to confirm the picture advanced in Refs. 1–3 concerning the formation of an elongated surface region, namely, a nuclear stratosphere, wherefrom particle emission is favored at temperatures near the shape transition temperatures. The results appear to reproduce the trend of experimental observations, particularly the enhancement of ^{1}H/^{4}He emission rates and changes in the anisotropies for ^{1}H and ^{4}He emissions. Since the radial dependence of the optical model potentials used in the calculations has been adjusted in order to reproduce temperature dependent evolutions of self-consistent nuclear distribution functions,[4,12,13] the existence of a nuclear stratosphere, at temperatures of the order of 3–4 MeV, could be tentatively established. We think that a systematic exploration of this effect would contribute to elucidate the role of temperature dependent nuclear shape transitions upon nuclear stability conditions at high energy.

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