Compound nucleus temperatures from particle and gamma ray emissions: Effects due to the temperature dependence of the level density parameter

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Partial widths and branching ratios, for neutron and gamma ray emission from compound nucleus states, are calculated using a temperature dependent level density parameter. The results show that the corresponding emission temperatures, extracted from calculated neutron and gamma ray spectra, differ significantly from values obtained with a constant level density parameter.

The statistical description of particle and gamma ray emission from an equilibrated compound nucleus is based on the assumption that thermal equilibrium is reached, namely that a nuclear temperature could be defined from the compound nucleus excitation energy.[1] Different models have been proposed[2–7] for the temperature dependence of the level density parameter, $a(T)$, which is one of the quantities of physical interest which could be extracted from data.[8,9] Compound nucleus temperatures, derived from the slope of energy spectra for particle emission from compound nucleus states, could therefore be affected by sensitivities to single particle and collective effects. In order to study these effects, in this paper we describe the competition between particle and gamma ray emission from a compound nucleus as a function of the temperature dependence of the level density parameter.

The analysis of decay modes from a compound nucleus depends strongly on the assumption that, at high excitation energy, the nuclear level density parameter could be evaluated with the Fermi gas model.[10] However, since the decay modes go through different excited states, the validity of this approximation could be limited, particularly at low excitation energies.

As has been shown,[5] phase transitions from a superfluid to a normal phase should be considered in dealing with the temperature dependence of the level density parameter. In fact, the nuclear level density $\rho(E,I)$ can be written as[10]

$$\rho(E,I)=\frac{(2I+1)e^{-(I+1/2)^2/2\sigma^2}}{2(2\pi)^{1/2}\sigma^3}\rho_{\rm int}(E) , \tag{1}$$

where σ is the spin cutoff factor and

$$\rho_{\rm int}(E)=\frac{e^{S(E(T))}}{(2\pi)^{3/2}D(T)T^{5/2}} \tag{2}$$

is the intrinsic level density, S being the nuclear entropy, T the nuclear temperature, and where the determinant $D(T)$ is given by

$$D(T)=(2g_N^0g_Z^0a_0)^{1/2} , \tag{3}$$

for the Fermi gas model[10] and by

$$D(T)=[2g_N(T)g_Z(T)a(T)]^{1/2} , \tag{4}$$

for a temperature dependent description.[5]

The density of states, g, and the level density parameter, $a(T)$, are functions of T, particularly

$$a(T)=\tfrac{1}{2}\sum_{q=N,Z}\frac{dS_q(T)}{dT} , \tag{5}$$

and blocking effects and the collapse of pairing correlations and collective excitations, induced by thermal excitations, would manifest themselves in the temperature dependence of $a(T)$.[5] Therefore, the above defined value of $a(T)$ could differ greatly from the constant value $a_0\approx A/10$ MeV^{-1}, prescribed by the Fermi gas model.[10]

The present description of the temperature dependence of $a(T)$ (Ref. 5) has to be considered a crude approximation of more elaborate treatments[14,15] based on self-consistent techniques. In fact, a complete formalism which allows for the calculation of nuclear properties at finite temperatures has been developed by Kerman, Levit, and Troudet[14] and by Kerman and Troudet.[15] In these references[14,15] the temperature dependence of the nuclear level density has been determined from a functional integral representation of the nuclear many body grand partition function which includes collective effects, therein represented by temperature dependent random-phase-approximation contributions to $\rho(E,A)$, as well as quasiparticle contributions like those which we include here.

We have calculated the values of $a(T)$ for the nucleus ^{146}Sm, including pairing effects in a single particle space which contains up to nine harmonic oscillator shells. The single particle energies have been calculated by using Nilsson's parametrization, and the residual two body interaction has been represented by a separable pairing interaction with constant matrix elements. In this fashion we have avoided a more involved, although more realistic, Hartree-Fock-Bogoliubov treatment of the mean field at finite temperature. In this respect the present results should be considered on qualitative basis. The results are shown in Table I. The values of Table I show a departure from the constant value $a_0\approx 15$ MeV^{-1} at $T<1.5$ MeV,

TABLE I. Temperature dependent level density parameter, $a(T)$, as a function of the temperature, T, for the case of the nucleus ^{146}Sm.

T (MeV)	$a(T)$ (MeV^{-1})
0.1	1.00
0.2	16.18
0.3	24.00
0.4	20.00
0.5	9.40
0.6	8.00
0.7	8.00
0.8	9.40
0.9	11.00
1.0	12.60
1.1	14.00
1.2	14.80
1.3	15.40
1.4	15.80
1.5	16.00
1.6	16.10
1.7	16.10
1.8	16.10
1.9	16.10
2.0	16.10

while for higher values of T the discrepancy amounts to less than 10%. The critical temperatures associated with the collapse of proton and neutron pairing gaps were found to be of the order of 0.55 and 0.44 MeV, respectively.

The above mentioned results are relevant for our calculation of the probabilities associated with neutron and gamma ray emissions from the compound nucleus ^{147}Sm. We have calculated the corresponding partial widths for neutron emission, as defined in Ref. 1, and for gamma ray emission we have adopted the formalism given in Ref. 11. The strength functions for gamma rays[11] $f(\epsilon_\gamma)=h,\ \epsilon_\gamma^r$, include a retardation factor, h, which accounts for the nonstatistical behavior of the gamma ray transitions at low energies, and an exponent, r, which for pure statistical, energy independent transitions has the value $r=2\lambda+1$. For correlated particle-hole transitions its value is given by $r=2\lambda+2$, λ being the multipolarity of the emitted gamma rays.[11]

We have further assumed that the main decay channel for gamma rays occurs for electric dipole transitions, $\lambda=1$, and with different values of h and r we can describe collective and statistical gamma ray decays. Compound nucleus temperatures have been extracted for cascades consisting of gamma rays and neutrons, starting from different excitation energies, E_0, of the compound nucleus. These temperatures have been obtained from the condition of equal probabilities for both channels. The results, for various values of h and r, are shown in Table II both for the temperature dependent parameter $a(T)$ and for the constant one, a_0. The behavior of the relative probabilities, for neutron and gamma ray emissions, are shown in Fig. 1. As shown in Fig. 1, significant shifts of the values corresponding to limiting energies for particle emission are observed when a temperature dependent level

TABLE II. Compound nucleus temperature associated with the opening of neutron emission. The values correspond to the crossing points shown in Fig. 1. The values of h and r are taken from Ref. 11 and, for each set of values, the results are denoted by (a) temperature dependent approximation and (b) temperature independent value, respectively, for the temperature dependent level density parameter and for the constant one. The values indicated by E_0 are the compound nucleus excitation energies associated with the compound nucleus temperature T_{CN}.

h	r		E_0 (MeV)	T_{CN} (MeV)
10^{-3}	3	(a)	16.40	1.04
		(b)	11.90	0.90
10^{-4}	3	(a)	12.35	0.85
		(b)	7.65	0.72
10^{-4}	4	(a)	13.60	0.92
		(b)	9.10	0.79

density parameter is considered. We have observed the same effects in a detailed description of different cascades leading to definite states in a final, particle stable nucleus.[12]

In summary, the probabilities for particle emission and for gamma ray emission from a compound nucleus are

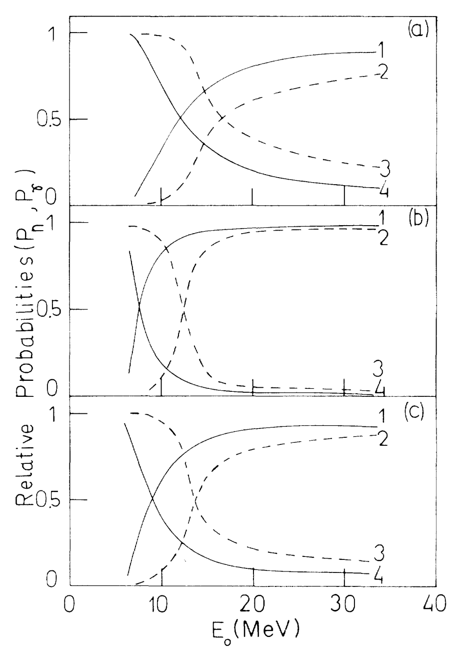

FIG. 1. Relative probabilities for neutron, P_n, and gamma ray emission, P_γ, from the compound nucleus ^{147}Sm, as a function of the excitation energy E_0. Solid lines (1) and (4) correspond to P_n and P_γ, respectively, evaluated with a constant level density parameter $a_0=15\ \mathrm{MeV}^{-1}$. Dashed lines (2) and (3) correspond to P_n and P_γ, respectively, evaluated with a temperature dependent level density parameter. The cases (a)–(c) correspond to the following parametrization in terms of the retardation factor h and of the exponent r for gamma ray emission (Ref. 11): (a) $h=10^{-3}$, $r=3$; (b) $h=10^{-4}$, $r=3$; (c) $h=10^{-4}$, $r=4$.

strongly sensitive to the temperature dependence of the level density parameter, particularly at low excitation energies. To a certain extent, the inclusion of this temperature dependence, mainly represented by the thermal collapse of pairing correlations, could affect the values of compound nucleus temperatures derived from the slopes of neutron spectra if these values are obtained from analysis based on the high temperature approximation of the nuclear level density.[13]

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[1]E. Vogt, in *Advances in Nuclear Physics,* edited by M. Baranger and E. Vogt (Plenum, New York, 1968), Vol. I, p. 261.
[2]D. Vautherin and N. Vinh Mau, Nucl. Phys. **A422**, 140 (1984).
[3]P. Bonche, S. Levit, and D. Vautherin, Nucl. Phys. **A436**, 265 (1885).
[4]W. Besold, P-G. Reinhard, and C. Toepffer, Nucl. Phys. **A431**, 1 (1984).
[5]O. Civitarese and A. L. De Paoli, Nucl. Phys. **A440**, 480 (1985).
[6]G. Handloser and W. Stöcker, Nucl. Phys. **A441**, 291 (1985).
[7]N. Vinh Mau and D. Vautherin, Nucl. Phys. **A445**, 245 (1985).
[8]J. Rekstad *et al.*, Phys. Lett. **117B**, 382 (1982).
[9]J. Rekstad *et al.*, Phys. Scr. T **5**, 45 (1983).
[10]A. Bohr and B. Mottelson, *Nuclear Structure* (Benjamin, New York, 1969), Vol. I, pp. 152–156 and 281–293.
[11]R. J. Liotta and R. A. Sorensen, Nucl. Phys. **A297**, 134 (1978).
[12]G. Batko, O. Civitarese, and A. L. De Paoli, Z. Phys. A (in press).
[13]H. M. Xu *et al.*, Phys. Lett. **182B**, 155 (1986).
[14]A. K. Kerman, S. Levit, and T. Troudet, Ann. Phys. (N.Y.) **148**, 436 (1983).
[15]A. K. Kerman, and T. Troudet, Ann. Phys. **154**, 456 (1984).