Temperature-dependence in Seeger's liquid drop energy and the dynamical cluster-decay model

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Introduction

Seeger's semi-empirical mass formula [1] is revisited for two of its constants (bulk constant $\alpha(0)$ and neutron-proton asymmetry constant a_a) readjusted to obtain the ground-state (g.s.) binding energies of nuclei within a precision of <1.5 MeV and for nuclei up to Z=118. The aim is *not* to obtain a new parameter set of Seeger's liquid drop energy V_{LDM}, but to include the temperature T-dependence on experimental binding energies [2]. The T-dependence, in the constants of V_{LDM}, is introduced as per the work of Davidson *et al.* [3], where the pairing energy $\delta(T)$ is modified as per new calculations on compound nucleus (CN) decays. The newly fitted constants of V_{LDM} at T=0 are made available in a (small) tabular form for use of other workers interested in developing computer codes on nuclear dynamics of hot and rotating nuclei. The main purpose of this work is to give a procedure for calculating the fragmentation potentials of nuclei at the incident energies used in heavy ion reactions, i.e., using the T-dependent experimental binding energies, as demonstrated here for the decay of CN ^{56}Ni*.

Methodology

The collective fragmentation potential V(η,R,T) that brings in the structure effects of the CN in to the dynamical cluster-decay model (DCM) of Gupta and collaborators [4, 5], is calculated according to the Strutinsky renormalization procedure ($B = V_{LDM} + \delta U$), using the T-dependent liquid drop model energy V_{LDM}(T) of Davidson *et al.* [3] and the empirical shell corrections δU of Myers and Swiatecki [6], for spherical nuclei, also made T-dependent to vanish exponentially with T_0=1.5 MeV. It is given as

$$V(\eta, R, T) = \sum_{i=1}^{2}[V_{LDM}(A_i, Z_i, T)] + \sum_{i=1}^{2}[\delta U_i] \exp(-T^2/T_0^2) + V_C(Z_i, \beta_{\lambda i}, \theta_i, T) + V_P(A_i, \beta_{\lambda i}, \theta_i, T) + V_l(A_i, \beta_{\lambda i}, \theta_i, T), \quad (1)$$

where nuclear proximity V_P, Coulomb V_C and the angular momentum (l) dependent V_l potential are for oriented nuclei and are also T-dependent. The V_{LDM} here, based on the semi-empirical mass formula of Seeger [1], is

$$V_{LDM}(A, Z, T) = \alpha(T)A + \beta(T)A^{\frac{2}{3}} + \Big(\gamma(T) - \frac{\eta(T)}{A^{\frac{1}{3}}}\Big)\Big(\frac{I^2 + 2|I|}{A}\Big) + \Big(\frac{Z^2}{r_0(T)A^{\frac{1}{3}}}\Big) \times\Big(1 - \frac{0.7636}{Z^{\frac{2}{3}}} - \frac{2.29}{[r_0(T)A^{\frac{1}{3}}]^2}\Big) + \delta(T)f(Z, A)/A^{\frac{3}{4}}, \quad (2)$$

with $I = a_a(Z - N)$, $a_a = 1$ and, respectively, for even-even, even-odd and odd-odd nuclei, $f(Z, A) = (-1, 0, 1)$.

Seeger [1] fitted the constants of V_{LDM} to the ground state (T=0) binding energies (BEs) of some 488 nuclei available at that time (in 1961). These constants certainly require modification due to the availability of large amount of data [2, 7] on ground-state BEs. The temperature dependence of the constants of V_{LDM} in Eq. (2) are given in Fig. 1 of [3].

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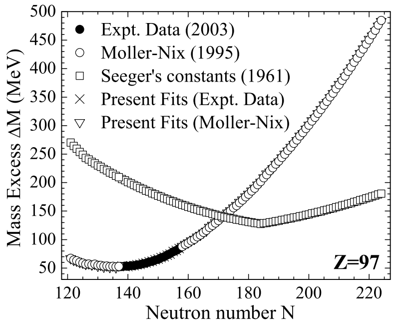

FIG. 1: The mass excess $\Delta M (= M_A - A = NM_n + ZM_p + B(Z, N) - A)$ (in MeV) as a function of neutron number N for Z=97 nuclides.

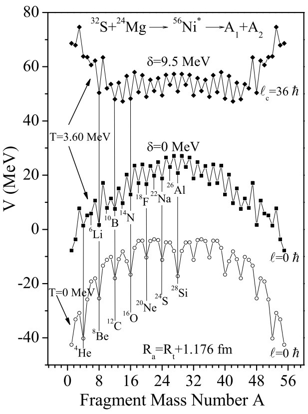

FIG. 2: Fragmentation potential [Eq. (1)] calculated for the decay of ^{56}Ni* formed in ^{32}S+^{24}Mg reaction at T=3.60 MeV for ℓ=0 and 36 $\hbar$, and also at T=0 for ℓ=0 $\hbar$.

Calculations and Discussions

In Table 3.1 of Ref. [5], we have presented the fitted constants for the experimental [2] and theoretical [7] BEs. The fitted constant $\alpha(0)$ is working as an overall scaling factor, and a_a controls the curvature of the experimental parabola, depicted in Fig. 1 for Z=97 nuclides. Fig. 1 shows the excellent agreement between the present fits (crosses and down open triangle) corresponding to experimental data [2] (solid circles) and theoretical data [7] (open circle), respectively. The fits are obtained between 0-1.5 MeV of the available experimental and theoretical data. The calculated BEs using the 1961 Seeger's constants are also shown in Fig. 1 (hollow square), which shows the requirement and extent of fitting required.

Next, we consider an application of the readjusted V_{LDM} with an idea to impress upon the need and to propose here at least a partially modified variation of the pairing constant δ with temperature T, as compared to that of Davidson *et al.* [3]. Fig. 2 shows the fragmentation potential V(A) for the decay of ^{56}Ni* (a complete mass spectrum) into light particles (LPs) and intermediate mass fragments (IMFs) at T=3.60 MeV for two different ℓ values (ℓ=0 and 36 $\hbar$), compared with one at T =0 MeV for ℓ=0 $\hbar$. We notice that at T =0 MeV for ℓ=0 $\hbar$, the pairing effects are very strong since all the even-even fragments lie at potential energy minima. On the other hand, if we include the temperature effects as per prescription of Davidson *et al.*, we find that δ=0 MeV in V_{LDM} for T>2 MeV, and hence in Fig. 2 for T=3.60 MeV, δ=0 MeV, the odd-odd fragments, like ^{10}B, ^{14}N, ^{18}F, etc., become equally probable as the even-even fragments, since minima are now equally stronger. However, if we empirically choose δ=9.5 MeV for T=3.60 MeV (for the best fit to IMFs data), the situation becomes again favorable. In other words, Fig. 2 for T=3.60 MeV, δ=9.5 MeV shows once again that the even-even fragments, like ^{12}C, ^{16}O, etc., are favored over odd-odd ^{14}N, ^{18}F, etc. These calculations lead us to modify the variation of δ as function of T. Apparently, many more calculations are needed.

References

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