Thermodynamic temperature and level density of SHN

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Introduction

Nuclear reaction rates are the quantities of fundamental importance in Nuclear Astrophysics [1]. The use of theoretical predictions is still required for the estimation of experimentally unknown values. Hence extrapolation is the mathematical tool to use for further prediction like thermonuclear reactions and heavy ion fusions either by cold or hot fusion process in r-, p- and rp- processes of nuclear synthesis, of fused compound systems of high N/Z ratio, which are capable to overcome the Coulomb repulsion and hence form short lived super heavy nuclei. After the synthesis of Z=117, search for further heavier nuclei are in progress. The nuclear masses and deformations are the vital parameters in determining stable isotopes through the binding energy calculations. The FRDM calculations of Moller et al. [2] gives more accurate values of binding energy close to the experimental value. Recently ETFSI method also been used for extrapolating the binding energy for nuclei far away from the experimentally known region. Nuclear level density is the major ingredient in nuclear reaction and Astrophysical calculations. Popularly used BSFG model estimates the spin dependent NLD, which has been derived from the analytical formulation of Bethe by introducing some essential phenomenological improvements. Inclusion of drastic approximation causes shortcomings in matching the experimental data. Hence a much more sophisticated formulation of NLD becomes mandatory for its exact prediction of nuclei far from stability region. One such sophisticated model is based on the statistical approach making use of single particle level distribution. This approach has the advantage of treating in a natural way, shell, pairing and deformation effects of all the thermodynamic quantities. However this model is not free from uncertainty due to its strong dependence on the choice of single particle potential and pairing strength. In this context the microscopic model based on the partition function method making use of single particle levels of rotating system, pairing strength and deformation may give a more reliable reproduction of experimental values with regard to the structure and reaction studies. Very recently the statistical code PACE2 was used to calculate the level density in the mass region A≈110 by Prajapati et al. [3] and Roy et al.[4].

Methodology

In this study we have used cranked Nilsson Strutinsky model to obtain the single particle levels. By diagonalising the Nilsson Hamiltonian in cylindrical bases the single particle energies E_i and spin projections m_i as a function of deformation parameter δ are obtained and which are generated upto N=11 shells. To start with the statistical formalism, the grand canonical partition function $Q(\alpha,\beta,\gamma)$ of a deformed nuclear system of N neutron and Z proton is considered as,[5,6]

$$Q(\alpha_Z,\alpha_N,\beta,\gamma) = \Sigma \exp(-\beta E_i+\alpha_Z Z_i,\alpha_N N_i+\gamma m_i). \qquad \text{------(1)}$$

The lagrangian multiplier γ plays the same role as the rotational frequency as in the cranking term $\omega.J_Z$. The pair breaking term $\gamma\text{-}m_j$ is temperature dependent and will generate the required angular momentum. The temperature effect creates particle hole excitation. The level density parameter a(M,T) as a function of angular momentum and temperature is extracted using the equation[7-9],

$$a(M,T)=S^2(M,T)/4E^*(M,T) \qquad \text{------(2)}$$

where S is the entropy and E^* is the excitation energy and is given by,

$$E^*(M,T) = E(M, T) - E_o, \qquad \text{------(3)}$$

where E(M,T) is the total energy and E_O is the ground state energy. From the above equations it is possible to deduce the thermodynamical temperature, and can be written as[10],

$$t = E^{*}(M,T)/a, \text{ in MeV.} \qquad \text{------(4)}$$

Results and Discussion

A total of 666 nuclides from Z=104 to Z=140 are studied using the statistical model code developed by our group, for excitation energy and level density. Fixing of these 666 nuclides is according to the shape of the isotopes, nearly spherical.

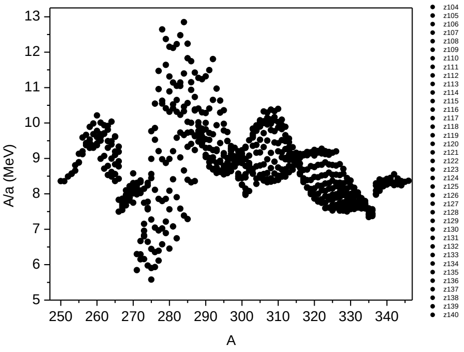

Fig. 1 Inverse level density parameter for the isotopes of Z=104-140.

The pattern of inverse level density parameter values obtained for the isotopes studied,(Fig.1) suggests the grouping of nuclei in accordance to the characteristic change. Accordingly, it is classified as nuclei with charge no. Z, <110, 111-120, 120-136 and >136. Among the nuclei grouped from 111 to 120, Z=114 shows more stable and in the range 120-136, Z=126 shows comparatively higher stability, since the A/a values of the isotopes of these nuclei are placed at the top of the corresponding regions. The gap found at Z=136 represents the less probability of placing the nuclei >136 in the line of N/Z ratio of superheavy region and hence the isotopes beyond Z=136 may be with different N/Z ratio, and can be classified as hyperheavy nuclei.

The thermodynamic temperature using the Excitation energy and the level density parameter by equation (4), is plotted against neutron number in Fig.2. The minimum energy obtained at N ≈184, for the isotopes of nuclei Z=128-138 is the signature of neutron magicity at N=184. The scattered values at the range N=160-175 pronounces a considerable difference in energy which helps to distinguish while synthesising the nuclei, but at N=175-200 the energy difference is too less to distinguish the isotopes. Hence in synthesising these isotopes, new procedures may be followed than the currently adopted procedures for elements upto Z=118.

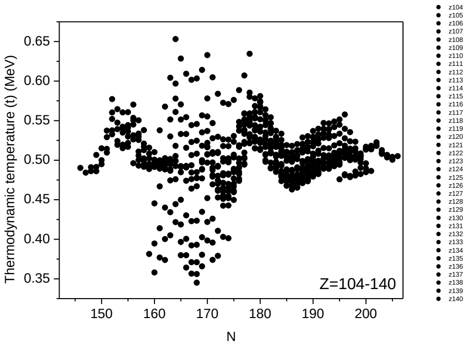

Fig. 2 Thermodynamic temperature for the isotopes of Z=104-140.

References

[1] M. Arnould and K. Takahashi, Rep. Prog. Phys. 99, 1 (1998).

[2] P. Moller, et al., At. Data Nucl. Data Tables, 59, 185 (1995).

[3] G. K. Prajapati et al., Phys. Rev. C102, 054605 (2020).

[4] P. Roy et al., Phys. Rev. C103, 024602 (2021).

[5] J. R. Huizenga and L. G. Moretto, Annu. Rev. Nucl. Sci. 22, 127 (1972).

[6] L. G. Moretto, Nucl. Phys. A182, 641 (1972); A185, 145 (1972); A216, 1 (1973).

[7] M. Rajasekaran, T. R. Rajasekaran and N. Arunachalan Phys. Rev. C37, 307 (1988).

[8] T. R. Rajasekaran, S. Selvaraj S. Santhosh Kumar, Pramana J. Phys, 60, 75 (2003).

[9] S. Santhosh Kumar, Pramana J. Phys. 71, 175 (2008).

[10] H. Baba, Nucl. Phys. A159, 625 (1970).