Determination of next feasible superheavy isotope through thermodynamic temperature

M. Geetha[1], G. Suresh[1] and S. Santhosh Kumar[2*]
[1]*Department of Physics, Annamalai University, Chidambaram – 608 002, Tamil Nadu, INDIA*
[2]*Department of Physics, Kanchi Mamunivar Government Institute for Postgraduate Studies and Research, Puducherry – 605 008, U. T. of Puducherry, INDIA*
** email: santhosh.physics@gmail.com*

Introduction

The quest for synthesizing artificial elements started decades before and the race towards heavier elements is ever fascinating one, leading to the island of stability of SHN, which has been proposed by the shell model in 1960's. Among the unanswered questions in the island of SHE the magic number concept as well as the double shell closure has an important position in the field of nuclear structure and reaction physics. Different theoretical approaches suggest N=184 as good magic number for Z=120. But it was reported by Pattnaik et al.[1] that it is N=182.

Approaching the nucleus as a hot and rotating system is more ideal in studying the dynamical aptitude of heavier systems since it is believed that these nuclei are all being formed in supernovae explosion; synthesis in laboratory is either through hot or cold fusion reaction. In simple, the study on the thermodynamic effect of a nucleus during its formation under hot environment may reveal the feasibility of synthesizing such nuclei artificially in laboratories. The one, which is being synthesized in many laboratories worldwide, i.e., Z=120 is considered in this work and is been studied for N=172-190 through statistical model calculation, coded by us, to understand its structural change under the influence of temperature and angular momentum to affirm the neutron magic number N=184, since recent studies[1] deviated from earlier predictions [2] and the modified two centre shell model (TCSM)[3].

Methodology

Inclusion of temperature in the statistical model may lead to conceive the atmosphere of compound nuclear formation in a thermodynamic environment. And hence the excitation energy, thermodynamic temperature, single particle separation energy are been extracted for different temperatures and thus also able to predict the limiting temperature of nuclear existence.

To start with the statistical formalism, the grand partition function $Q(\alpha,\beta,\gamma)$ of a deformed nuclear system of N neutron and Z proton is considered as,[4]

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

The Lagrangian multipliers α_Z, α_N, γ in the partition function (eqn.1) conserve the proton number, neutron number and total angular momentum along the Z-direction for a given temperature $T=1/\beta$. The pair breaking term γ-m_j is temperature dependent and will generate the required angular momentum. The temperature effect creates particle hole excitation.

Excitation energy E* of the system for an angular momentum state M is given by

$$E^*(M,T)=(\Sigma n_i^Z\varepsilon_i^Z-\Sigma e_i^Z)+(\Sigma n_i^N\varepsilon_i^N-\Sigma e_i^N) \quad \text{----(2)}$$

The level density parameter a(M,T) as a function of angular momentum and temperature is extracted using the equation [5,6],

$$a(M,T)=S^2(M,T)/4E^*(M,T) \quad \text{----(3)}$$

where S is the entropy.

From the above equations it is possible to deduce the thermodynamical temperature, [7],

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

The neutron separation energy S_N, can be obtained from the free energy Ω of the system as $S_N = \partial\Omega/\partial N$, where $\Omega = -T \ln Q(\alpha,\beta,\gamma)$. Since Ω is the function of T and angular momentum M, S_N is also a function of T and angular momentum. S_N can be written explicitly in terms of the single particle occupation number n_i as,

$$S_{N(P)} = TN/[\Sigma(1 - n_i)n_i]. \quad \text{----(5)}$$

Results and Discussion

The difference in excitation energy at the point of shape transition from spherical (δ=0.0) to oblate non-collective (γ=-180°; δ=0.1) is plotted in Fig.1. This pronounces the magic neutron number corresponding to higher difference at N=184 and a quasi magic number at N=178. The difference in E^* value at the point of transition is very close to each other and a non-orderly difference is observed when N > 186 and hence an overlap of energy levels may possible.

By varying the angular momentum the shape transition occurs from spherical to oblate. No prolate deformation is observed at any temperature and hence fission is hardly possible.

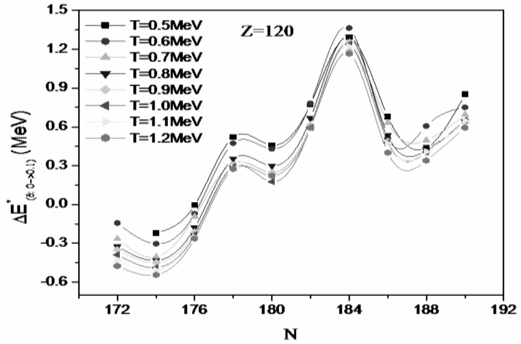

Fig.1. Difference in E* at the point of shape transition at diff. temperatures.

Difference in thermodynamic temperature at the point of shape transition from spherical (δ=0.0) to oblate (γ=-180°; δ=0.1) is plotted in Fig.2. This pronounces the magic neutron number corresponding to higher difference at N=184 and a quasi magic number at N=178.

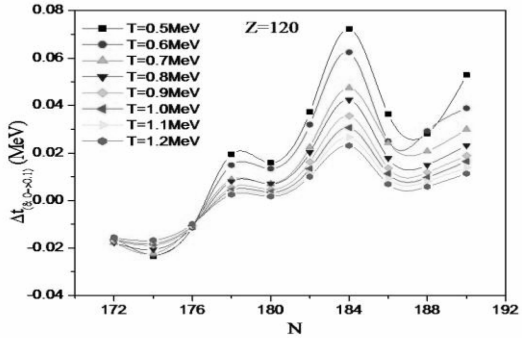

Fig. 2. Difference in 't' at the point of shape transition at diff. temperatures.

Unlike the excitation energy, E^*, the difference in thermodynamic temperature at the point of transition is widely spread and distinguishable to each other even after N > 186. The higher value of S_N at N=184, 178 and 170 shows the (semi) magic nature, but, the decrease in S_P at N=168 indicates the feasibility of having alpha decay than particle emission from A > 286.

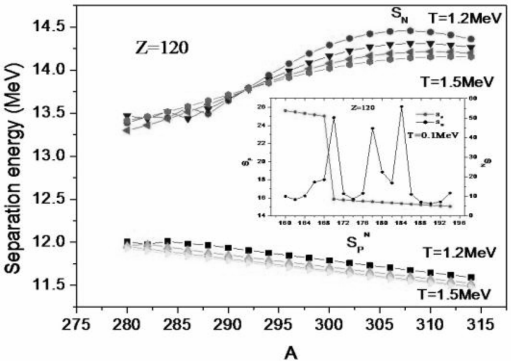

Fig.3.Proton and Neutron separation energy. (Fig inserted is at T=0.1MeV)

When temperature increases, S_N get reduced ie., at T≈1.0MeV the difference in S_N is ($\Delta S_N \approx 0.1$MeV) when Δt=0.1MeV, and at T=1.5MeV, Δt=0.01MeV. Hence the change in temperature above T=1.0MeV does not alter the particle separation energy which reveals the concept of structural instability. The shell effect vanishes completely at this point and so the limiting temperature of nuclear existence of Z=120 is deduced to be T≈1.1MeV.

Acknowledgement:

This work was funded by SERB, DST, Govt. of India (CRG/2022/003126).

References

[1]. J A Pattnaik et al., Pramana J Phys. 97, 136 (2023)
[2]. M. Bender, et al., Rev. Mod. Phys., 75, 121 (2003).
[3]. N V Antonenko et al., EPJ web Conf. 66, 02003 (2014).
[4]. L. G. Moretto, Nucl. Phys. A182, 641 (1972)
[5]. M. Rajasekaran, T. R. Rajasekaran and N. Arunachalam, Phys. Rev. C37, 307 (1988).
[6]. S. Santhosh Kumar, Pramana J. Phys. 71, 175 (2008).
[7].A Gilbert and A G W Cameron, Can. J. Phys. 43, 1446 (1965).