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### Structural Stability of Long Lived Superheavy Nucleus <sup>298</sup>114 By S. Santhosh Kumar & A. Victor Babu

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*Abstract-* Synthesis of superheavy nuclei has been achieved recently through hot fusion reactions. A systematic theoretical calculation of determining the stability of the superheavy nucleus Z=114 is studied in the context of angular momentum and temperature. The level density can provide clues to the applicability of the statistical model which is only correct for a high density of excited states. The collapse of pairing correlation at moderately higher spin and at low temperature causes a shape change and stability at higher spin is also expected. The drop in separation energy is closely associated with the structural changes in the rotating nuclei; relative increase in neutron emission probability around certain values of temperature may be construed as evidence for the shape transition. Such effects are not obtained for <sup>298</sup>114. Hence this statistical study reveals a higher stability for <sup>298</sup>114 against temperature and angular momentum.

*Keywords:* superheavy nucleus; level density; separation energy; nucleon emission; shape transition.

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## Structural Stability of Long Lived Superheavy Nucleus <sup>298</sup>114

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Abstract- Synthesis of superheavy nuclei has been achieved recently through hot fusion reactions. A systematic theoretical calculation of determining the stability of the superheavy nucleus Z=114 is studied in the context of angular momentum and temperature. The level density can provide clues to the applicability of the statistical model which is only correct for a high density of excited states. The collapse of pairing correlation at moderately higher spin and at low temperature causes a shape change and stability at higher spin is also expected. The drop in separation energy is closely associated with the structural changes in the rotating nuclei; relative increase in neutron emission probability around certain values of temperature may be construed as evidence for the shape transition. Such effects are not obtained for 298114. Hence this statistical study reveals a higher stability for 298114 against temperature and angular momentum.

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#### I. INTRODUCTION

e are living in an exciting period of time when new superheavy elements (SHE) are being discovered, one after another. This journey across the sea of instability has been possible because of a tremendous progress in theory, experiments and accelerator technologies. Upcoming radioactive ion beam (RIB) facilities now promise to lead us to the ultimate magic island where the neutron-rich SHE resides. Search for SHE in nature is the current interest of nuclear physicists, and are expected from terrestrial matter, meteorites and cosmic rays (Aleksandrov, 2013).

Microscopic nuclear theories suggest a significant enhancement in nuclear stability when approaching the closed spherical shells with Z = 114, or, Z = 120, 122 and N = 184. Still there is a dilemma whether 114 or/and 126, 120 is the proton shell closure and 172 or/and 184 is the neutron shell closure.

Several theoretical investigations have been carried out using the microscopic– macroscopic method and the self-consistent mean field in both the relativistic and non-relativistic formalisms. The primary aim in early studies has been to predict the combination of neutron number (N) and proton number (Z) where Spherical shell closure may occur. An "island of

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stability'' had been predicted around the hypothetical doubly magic <sup>298</sup>114 (N = 184) about 30 years ago. More recently, nuclei in this vicinity are expected to be spherical or almost so with longer half-lives. Most theories do predict N = 184 as being magic, however, there is no consensus on the location of the proton magic number due to differences in the treatment of the large Coulomb term and the spin–orbit interaction.

Microscopic-Macroscopic models, which assume a prior knowledge about the densities and single-particle potentials, include the Finite Range Droplet Model with folded Yukawa single-particle potentials (FRDM + FY) (Moller et al., 1997) and the Yukawa plus Exponential model with Woods-Saxon single-particle potentials (YPE + WS) (Muntian et al., 2003a, 2003b), both of which confirm the prediction of <sup>298</sup>114<sub>184</sub> as being the next spherical doubly magic nucleus. Non-relativistic microscopic models such as the Skyrme-Hartree-Fock-Bogoliubov method (Cwiok et al., 1999), where the spin-orbit term has to be manually introduced, predict Z = 120 may be as probable as Z = 114, indicating that magic shells in this region are isotope dependent (Greiner, 1995; Rutz et al., 1997). Such techniques tend to overestimate the splitting of levels due to the spin-orbit coupling which may effect predictions for shell closures. With the large density of single-particle states which in turn characterizes this mass region, the SHE serve as a sensitive probe for distinguishing between the various theories that attempt to predict shell structure, especially when these models describe stable nuclei with comparable accuracy. Also, it has been known for some time that deformation effects are important to the understanding of stability in this region(Cwiok et al., 1999). Bohr and Mottelson (1969) have observed that deformation may enhance stability.

#### II. IMPORTANCE OF THE NUCLEUS

The issue of the existence of super heavy nuclei is of utmost importance for understanding the properties of nuclear matter. It is highly interesting to verify the prediction of a significantly increasing stability of nuclei in the vicinity of the magic numbers Z=114 and N =184, which could lead to the existence of "stability islands" of the relatively stable superheavy nuclei. The lifetimes of some isotopes of this superheavy nucleus is several seconds and even minutes, which exceeds tens

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of thousands of times the lifetimes of nuclei with smaller charges.

The knowledge of nuclear level densities is a crucial input in various fields/applications such as the description of excited nucleus properties and the nuclear reaction cross-section calculations for many branches of nuclear physics, nuclear astrophysics, nuclear medicine, and applied areas (medical physics, etc.) (Bethe, 1936; Gilbert and Cameron, 1965; Von Egidy and Bucurescu, 2005; Ignatyuk and Yu Shubin, 1969; Ahmadov et al., 2002; Okuducu et al., 2003; 2006a; 2006b; 2009; 2010; 2011; Bucurescu and Von Egidy, 2005; Kataria et al., 1978). The neutron capture cross-sections, required for both design and nuclear model calculations in nuclear science and technologies, are approximately proportional to the corresponding level densities around the neutron resonance region. In nuclear medicine, the cross-section data obtained from nuclear level density approaches are needed to optimize production of radioactive isotopes for purposes, for example, biomedical therapeutic applications such as production of medical radioisotopes and cancer therapy and acceleratordriven incineration/transmutation of the long-lived radioactive nuclear wastes.

Nuclear reactions calculations based on standard nuclear reaction models play an important role in determining the accuracy of various parameters of theoretical models and experimental measurements. Especially, the calculations of nuclear level density parameters for the isotopes can be helpful in the investigation of reaction cross-sections. The analytical expressions used for the nuclear level density calculations (Bethe, 1936; Gilbert and Cameron, 1965; Ignatyuk and Yu Shubin, 1969) are based on the Fermi gas model. The most widely used description of the nuclear level density is the Bethe formula, based on the thermodynamic relation between entropy and the average energy of a system considered in the framework of non-interacting particles of the Fermi gas. The traditional Bethe theory of the nuclear level density calculation, which uses the assumption that the individual neutrons and protons occupy a set of low energy levels in the ground state and fill up the higher individual states at any excitation energy, has been successfully used so far, with different contributions made to this model in the form of shell, pairing, deformation effects (Von Egidy and Bucurescu, 2005; Huang et al., 2000; Newton, 1956; Ericson, 1958), finite size effects (Bohr and Mottelson, 1969), and thermal and guantal effects, as well as improvements in the determination of the spin cutoff factors (Santhosh Kumar, 2009). However, such contributions do not take into account the collective effects, which may play a basic role in describing the nuclear level density of some deformed nuclides.

The level density is a fundamental property of a many-body system as all thermo-dynamical quantities can be derived from it. In nuclear physics, level densities are important because, according to Fermi's golden rule, they are critical for estimating nuclear reaction rates. The calculation of statistical nuclear reaction rates requires knowledge of the angular momentum distribution of the nuclear level density. An empirical formula for the angular momentum distribution of the level density at fixed excitation energy assumes uncorrelated and randomly coupled single-particle spins.

The compound nucleus formed either through cold (Pb or Bi targets) or hot(actinide targets) fusion reactions are in excited state and hence their decay will be greatly influenced by thermal and collective excitations. Hence a statistical model approach will be more suitable and the code is developed pertaining to the evaluation of sp level density, separation energy and emission probability, and the sp energies are obtained by cranked Nilsson model.

#### III. THEORETICAL FORMALISM

The statistical quantities like excitation energy, level density parameter and nuclear level density which play the important roles in the nuclear structure and nuclear reactions can be calculated theoretically by means of the Statistical or Partition function method. In this work we have followed the statistical model approach to probe the dynamical properties of the nucleus in the microscopic level.

The nuclei formed in collision may be in excited states and hence their decay or emission for stability will greatly influenced by thermal and collective excitation. Hence a thermo dynamical approach, which incorporates thermal and rotational excitations, is the appropriate methodology.

The statistical theory of hot rotating nucleus can be easily obtained from the grand canonical partition function

$$Q(\alpha_{Z_i}\alpha_N,\beta,\gamma) = \sum \exp(-\beta E_i + \alpha_Z Z_i \alpha_N N_i + \gamma M_i)$$

The Lagrangian multiplier  $\gamma$  plays the same role as the rotational frequency as in the cranking term  $\omega$ .JZ. The pair breaking term  $\gamma$ -mj is temperature dependent and will generate the required angular momentum. The temperature effect creates particle hole excitation. The total excitation energy is obtained using

$$E^* = U(M,T) = U_{eff}(T) + E_{rot}(M)$$

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

$$a(M,T) = \frac{S^2(M,T)}{4U(M,T)}$$

where S is the entropy and U is the total excitation energy. The neutron or proton separation energy is obtained from (Rajasekaran, 1988),

$$S_n = -T \frac{(\partial \ell_n Q)}{(\partial \propto_N)} \frac{(\partial \propto_N)}{(\partial N)}$$

where N is the number of neutrons or protons. The dependence of the nuclear level density  $\rho,$  on angular momentum M, can be written as

$$\rho(U,M) = \left\{\frac{(2M+1)}{2\sigma^2}\right\} exp\left\{\frac{[-M(M+1)]}{2\sigma^2}\right\} \rho(U)$$

where  $\rho(U)$  is the level density and is given by

$$\rho(U) = exp \frac{[2(a(U - E_i)^{1/2}]}{12(2\sigma^2)^{1/2}a^{1/4}(U - E_i)^{5/4}}$$

#### IV. Results and Discussion

In this work we have studied the structural stability of hot rotating SHN <sup>298</sup>114 using statistical theory. The angular momentum impact at a particular temperature is mainly considered here especially on excitation energy, single neutron separation energy and nuclear level density. The shape deformation due to spin and temperature effect is also determined.

The system shows a spherical shape at low spin and temperature T< 0.8 MeV. From spin J=18 $\eta$  it shows an oblate deformation ( $\gamma$ =-180°;  $\delta$ =0.1) and which increases with temperature. From the excitation energy Vs spin plot (Fig.1) it is evident that there is a drop in excitation energy at certain angular momentum and temperature. At about T = 0.8MeV, the excitation energy becomes a smooth Gaussian (Fig.2), and the shape of the nucleus become spherical ( $\delta$ =0.0).

The neutron separation energy is an important parameter in determining the stability of the nucleus against particle decay/emission. The nucleus <sup>298</sup>114 shows a decreasing effect of neutron separation energy to angular momentum up to T<0.8MeV (Fig.3), and which decreases gradually with temperature. At higher temperatures, ie., T>1.0MeV, the neutron separation energy becomes almost constant, which indicates the plasma state of the nucleus.

Since the SHN formed through fusion reaction will reach the stable state mainly via alpha decay and terminate with spontaneous fission, the proton separation energy also gets equal importance in determining the stability against angular momentum. In fig.3, we have shown its effect at T=1.0MeV, in comparison with the effect of neutron decay possibility and we found both are in similar track while the excitation energy shows an exponential growth with spin in the energy range from 42MeV to 49MeV, and hence this nucleus will not undergo any single particle decay instead possibility of alpha decay is highly probable. The level density parameter against spin is plotted in Fig.4, for low temperatures. The shift in level density parameter at  $J=16\hbar$ ,  $20\hbar$  and  $22\hbar$  for temperatures T=0.3MeV, 0.4MeV and 0.5MeV respectively, may a signature for collapse of pairing correlation.

#### V. Conclusion

For the system <sup>298</sup>114, the observed changes in excitation energy, separation energy (neutron & proton) and level density parameter, the increase in deformation from spherical to oblate may a signature of increased stability as stated by Bohr & Mottelson (1969), at low temperatures. The shift in single particle binding energy reveals its phase change at higher temperatures. Due to the collapse of pairing correlation at spin J>14 $\hbar$  at low temperatures causes a shape change and provides stability at higher spin.

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*Figure 1* : Excitation energy Vs. spin( $\hbar$ ); The drop in excitation energy is due to the shape transition.



Figure 2 : Particle separation energy Vs.  $spin(\hbar)$  (Excitation energy plot is not to axis scale)



*Figure 3* : Influence of spin (in units of  $\hbar$ ) on Neutron separation energy at different Temperatures



Figure 4 : Pairing phase transition at different spin with respect to temperature

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