DOI: 10.15415/jnp.2015.22009

Structural Stability and Level Density of Hot Rotating Doubly Magic Isotopes of Calcium

S. SANTHOSH KUMAR[1]*, P. PREETHA[2], P.VINODINI[2] AND T. R. RAJASEKARAN[3]

[1]Department of Physics, Avvaiyar Govt. College for Women, Karaikal – 609 602, U.T. of Puducherry, India

[2]Department of Physics, EGS Pillay Arts & Science College, Nagapattinam- 611 002, TamilNadu, India

[3]Department of Physics, Manonmaniam Sundaranar University, Tirunelveli-627 012, TamilNadu, India

***Email: santhosh.physics@gmail.com**

Received: November 20, 2014 | Revised: November 30, 2014 | Accepted: November 30, 2014

Published online: February 10, 2015

Abstract: The recently reported doubly-magic nuclei ^{52}Ca and ^{54}Ca are discussed in comparison with the other magic isotopes of Calcium. The temperature effect is included in this study and hence the statistical approach to obtain the particle emission and level density are discussed in the context of temperature effect. We predict an increase in neutron emission for ^{54}Ca due to the abrupt decrease in neutron separation energy around T=0.4MeV. Since the drop in the 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 ^{40,48,52}Ca isotopes. Hence this statistical study reveals the higher stability of magic nature of ^{52}Ca than ^{54}Ca, against temperature.

Keywords: Level density; separation energy; nucleon emission; shape transition; structural changes

1. INTRODUCTION

The advancement in the radioactive ion beam facilities enables us to study the behavior of nuclei near or even beyond the neutron and proton drip-lines and to investigate the emergence of new modes of nuclear behavior. The change in magic number is one among the interesting features of the nuclei in the drip-

Journal of Nuclear Physics, Material Sciences, Radiation and Applications
Vol. 2, No. 2
February 2015
pp. 125–133

line region. It is now established that the dynamic effects of nucleon-nucleon interaction result in the evolution of shell structure and hence the new magic number sequence in drip-line region. Over the last few decades, there is an ongoing argument about the nature of the ^{54}Ca nucleus [1-3]. However, these studies could not reach a common conclusion about the magicity of the ^{54}Ca nucleus. But from the spectroscopic study of the neutron-rich ^{54}Ca nucleus using proton knock-out reactions, the doubly magic nature of it was revealed very recently [4].

The origin of magic nucleon numbers (2, 8, 20, 28, 50, 82 and 126) had been explained by the phenomenon of complete filing of nucleus shells. The nuclei having magic numbers of nucleons in comparison with neighboring isotopes and isotones have more spherical shape, more nucleon separation energy values, specific scheme of lowest energy levels – resonance liked behavior of the first 2^+ state energies $E(2^+{}_1)$, ratios $E(4^+{}_1)/E(2^+{}_1)$, quadrupole deformation parameters δ. It was found out that those specific features of nucleus having closed proton shell (magic proton number) are maintained for all its isotopes and, vise versa, of nucleus having closed neutron shell (magic neutron number) – for all isotones.

The very interesting common property of these nuclei is that new "magicity" is achieved when the specific structure of upper sub-shells near the Fermi energy is realized. The first evidence for N = 16 to be magic number in oxygen was observed from an evaluation of neutron separation energies on the basis of measured masses [5]. The new magic number at N = 32 has been observed experimentally by Kanungo et al. [6].

Theoretically, shell model with new effective interaction GXPF1 (G-matrix effective interaction for pf-shell nuclei) and monopole component of tensor interaction, predict the shell closure at N = 34 [7]. However, the spherical Hartree-Fock calculations with the semi-realistic NN interactions give the shell closer at N = 32. Therefore, it is interesting to study the structural properties of N = 32 and 34 for Ca isotope.

2. THEORETICAL FRAMEWORK

The search for and clarification of the origin of non-traditional magic nuclei is one of the topical fields of present day investigations. More and more data on the new non-traditional magic nuclei become available as new experimental, theoretical and evaluation techniques. [8,9]. New magic nuclei properties were investigated for many oxygen isotopes in [10].

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

$$Q(\alpha_z,\alpha_N,\beta,\gamma) = \sum \exp(-\beta E_i + \alpha_Z Z_i + \alpha_N N_i + \lambda M_i) \tag{1}$$

The Lagrangian multiplier λ plays the same role as the rotational frequency as in the cranking term $\omega.J_Z$. The pair breaking term $\lambda\text{-}m_j$ is temperature dependent and will generate the required angular momentum. The temperature effect creates particle hole excitation.

The total excitation energy is obtained using

$$E^* = U(M,T) = U_{eff}(T) + E_{rot}(M) \tag{2}$$

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

$$\alpha(m,T)\frac{S^2(M,T)}{4U(M,T)} \tag{3}$$

where S is the entropy and U is the total excitation energy. The neutron or proton separation energy is obtained from [11]

$$S_n = -T\frac{(\partial \ell_n Q)}{(\partial \alpha_N)}\frac{(\partial \alpha_N)}{(\partial N)} \tag{4}$$

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

$$\rho(U,M) = \left\{\frac{(2M+1)}{2\sigma^2}\right\}\exp\left\{\frac{[-M(M+1)]}{2\sigma^2}\right\}\rho(U) \tag{5}$$

where ρ(U) is the level density and is given by

$$\rho(U) = \exp\frac{\left[2(a(U-E_i)^{1/2}\right]}{12(2\sigma^2)^{1/2}a^{1/4}(U-E_i)^{5/4}} \tag{6}$$

The Binding energy per nucleon is one of the important parameter in determining the stability of the nucleus. Thus the isotones of N=32 and 34 are calculated through the droplet model mass formula [12].

3. RESULTS AND DISCUSSION

In this work cranked Nilsson method is used to obtain the single particle energies. The predicted shapes of the isotopes differ with mass number. Increasing temperature does not affect the shape of the doubly magic isotopes of Ca (N=20 and 28) which is spherical (δ=0.0) always. The nuclei $^{42-50}$Ca show a prolate deformed ($\gamma = -120^o$; δ=0.1) shape at very low temperatures, except ^{42}Ca, which is oblate deformed ($\gamma = -180^o$; δ=0.1). It is noteworthy to report here that ^{52}Ca shows spherical shape even at very low temperatures but ^{54}Ca does not, which is prolate deformed ($\gamma = -120^o$; δ=0.1). Hence the isotopes of Ca are either spherical or slightly deformed (δ=0.1) at very low temperatures and at T $\geq$ 0.5MeV they behave as spherical at J=0$\hbar$. This effect may be due to the proton magicity of Ca (Z=20). Hence in the context of magicity due to sphericity, ^{52}Ca is the next doubly magic nucleus in the neutron drip line.

The BE/A value for N=32 isotones lead the N=34 isotones upto Z=26 and which is vice-versa from Z=28. (Fig.1). The BE/A of 52 Ca is 0.16MeV

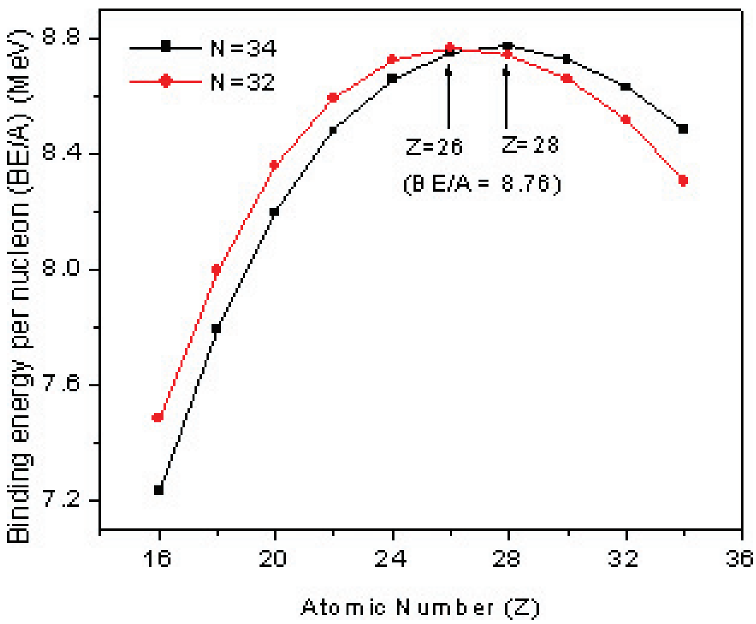

Figure 1: Binding energy of nuclei with N=32 and N=34 from Z=16 to Z=34.

higher than that of 54 Ca (8.19MeV). But it is interesting to note that the BE/A is same for Z=26 & N=32 and Z=28 & N=34 (8.76MeV), also which is the highest BE/A obtained in these series of isotones, i.e., Fe (Z=26) of A=58 and Ni(Z=28) of A=62 are having the highest BE/A, which coincides well with the statement of Bethe [13] that ^{56}Fe is the most strongly bound nucleus. Truran, Cameron and Gilbert [14] favoured ^{56}Fe has the highest BE/A, but Clifford and Taylor[15] are the first to identify ^{62}Ni has the highest mean binding energy. According to Fewell [16], the tightly bound nucleus has A≈58.3 and Z≈26.6, if the shell effects are switched off. Whereas the isotones with Z=26 & N=34 and Z=28 & N=32 (8.74MeV) and Z=24 & N=34 and Z=30 & N=32 (8.65MeV) are having same BE/A values. It is noteworthy to mention here the droplet model for binding energy pronounces the higher binding for Ca isotope is with N=32.

The excitation energy (E^*) for the magic isotopes of Calcium (N=40, 48, 52 & 54) against temperature is plotted in Fig.2, and which is increasing with temperature. It shows the excitation energy is a smooth Gaussian for ^{40,48,52}Ca, ie., 52 Ca shows similar character of other magic isotopes of Calcium, but ^{54}Ca shows a drop at temperature T=0.4MeV. This temperature is not so high to the mass of the nucleus studied. This drop in E^* for ^{54}Ca (indicated by arrow) resembles the shape transition from prolate ($\gamma = -120^o$) to spherical ($\delta = 0.0$), which may be due to the pairing phase transition at T=0.4MeV.

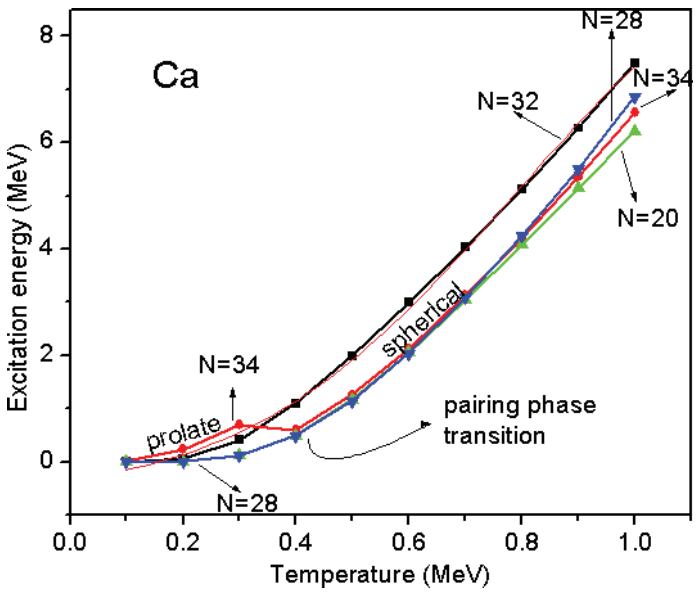

Figure 2: Excitation energy Vs. temperature for ^{40,48,52,54}Ca.

Such a shape change at this small temperature change indicates the non-stability of its structure, compared to ^{52}Ca. Also it is noted here that the change in shape is from prolate (γ = -120°; δ = 0.1)to spherical may enhance the support of its magicity as far as shape is concerned.

In the last few decades there have been considerable efforts to develop microscopic methods for the calculation of accurate values of level densities as a function of excitation energy [17-19]. One of these methods which is of present interest is based on statistical theory. Nuclear level density provides information about the structure of highly excited nuclei, and is an important ingredient in statistical model calculation of nuclear reaction cross section, which are needed in many applications from astrophysical calculations to fission or fusion reactor designs.

Level densities are affected by pairing of nucleons. Under the influence of a short range attractive force, nucleons prefer to form pairs. Nucleon pairs(Cooper pairs) can break up at higher temperatures. The thermal breaking of Cooper pairs leads to increasing level density and entropy [20]. Also the spin dependence of nuclear level density is of principal interest and of a more practical importance for the calculation of cross sections within the framework of the statistical model nuclear reactions.

The level density for the magic isotopes ^{40,48,52,54}Ca show an exponential growth with temperature (Fig. 3), which is proportional to mass number of

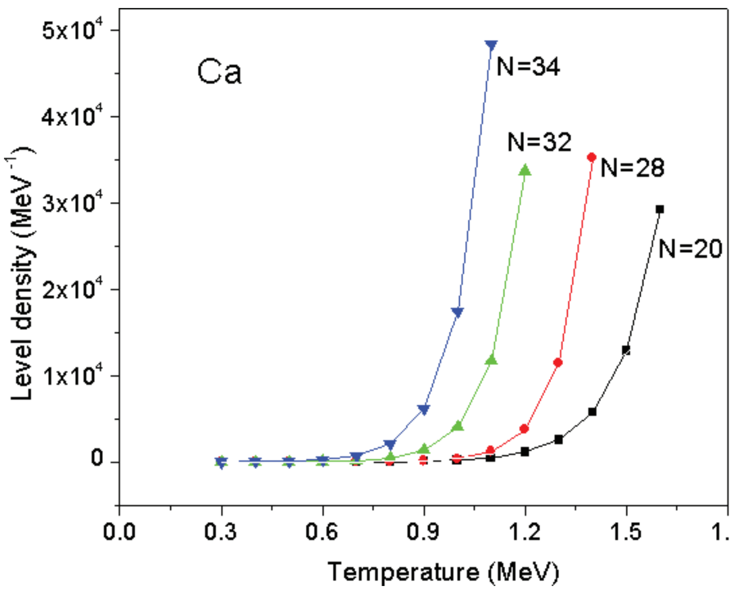

Figure 3: Exponential nature of level density against temperature.

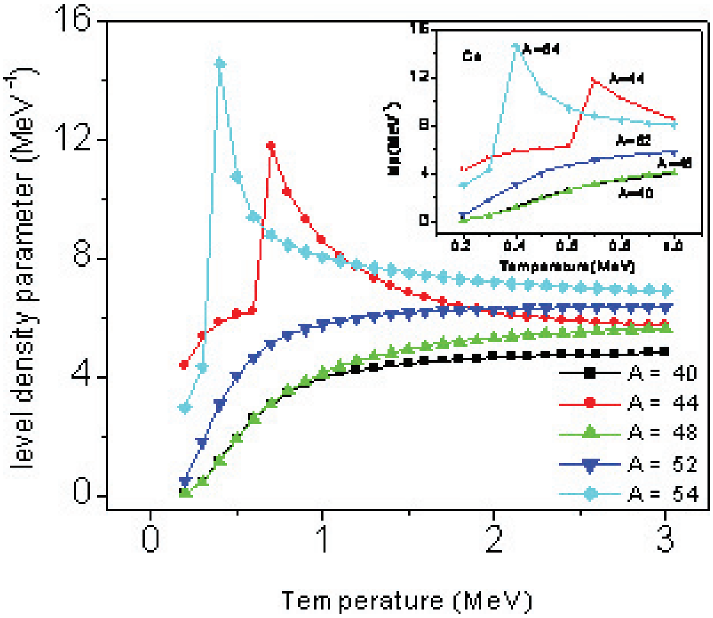

Figure 4: Level density parameter 'a' minimum shows the closed shells or sub-shells for the Ca nuclei with N=20, 24 and 32.

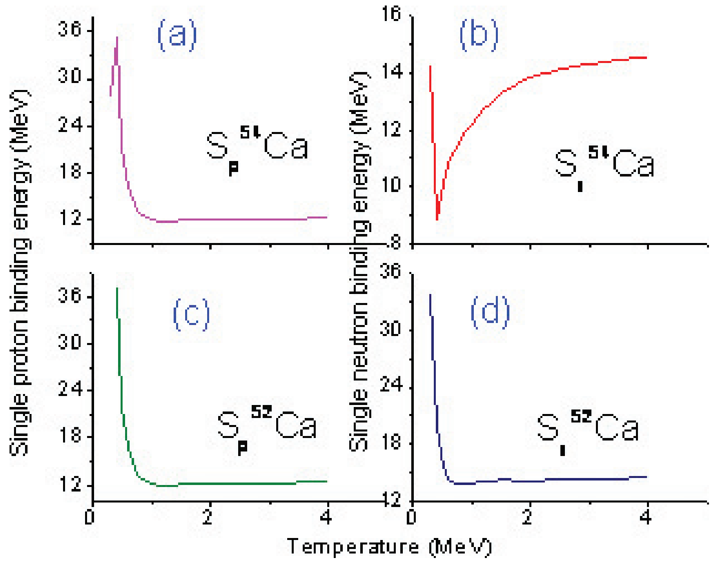

Figure 5: Single particle separation energy for ^{52,54}Ca. A drop of S_n is observed in ^{54}Ca only (b).

Kumar, S.S.
Preetha, P.
Vinodini, P.
Rajasekaran, T.R.

the nucleus. The deviation in its growth rate refers the indication for shell gap or sub-shell closures of the particular mass number of the nucleus. The heavier isotopes deviate at lower temperatures, i.e., the thermal breaking of heavier nucleus is at lesser temperatures.

The mean difference in level density parameter (ldp) value for same spin $\Delta a= 0.1$ for $\Delta T=0.1$MeV. The minima in the dependence of ldp on N and Z correspond to the closed shells or sub-shells. Fig. 4 reveals that N=20, 28, & 32 are minimum compared to N=24, & 34. In conclusion, from our calculations, a sub-shell closure can be predicted at N=32 other than N=20 & 28 for Ca nucleus.

As for as the proton separation energy is concerned the magic isotopes ^{40,48,52}Ca shows an exponentially decreasing nature of energy with increasing temperature and around T = 1.2MeV the proton separation energy is minimum,(Eg.: S_p=11.864 MeV for ^{52}Ca; S_p=12.015MeV for ^{54}Ca). Hence the influence of temperature on neutron separation energy is the critical factor in this comparative study of magicity of Ca isotopes. The single neutron separation energy for 54Ca drops from $S_n\approx14.23$ MeV to $S_n\approx8.84$MeV (Fig. 5(b)), which shows its instability against temperature. But ^{40,48,52}Ca show an exponential decrease towards low temperatures and became more or less constant from $T\approx0.9$MeV (The figs. for ^{52}Ca and ^{54}Ca only are given) . Thus the resemblance of ^{52}Ca with other magic isotopes is highly pronounced than ^{54}Ca

3. SUMMARY

In this work we have employed the Myer's droplet model to calculate the binding energy and the statistical approach is followed for the structure study of Ca isotopes with the aim of exploring the possible magic nature of ^{52}Ca and ^{54}Ca, since there is a lot of ongoing debates about the magicity of these isotopes. Our study revealed the following conclusions:

1. The binding energy using the Myer's droplet model shows strong binding in ^{52}Ca than ^{54}Ca.
2. The excitation energy is smooth growing with temperature for all magic isotopes except ^{54}Ca, in which a shape change from prolate to spherical at temperature T=0.4MeV is observed.
3. A thermal breaking of heavier nucleus at lower temperatures is the common behavior of the magic isotopes of Calcium.
4. A strong fluctuation in the level density parameter plot against temperature for ^{44}Ca and ^{54}Ca reveals the magic nature of ^{52}Ca is in phase with other magic isotopes ^{40,48}Ca.

5. The drop in neutron separation energy for ^{54}Ca shows it is less stability against particle decay even at temperature T=0.4MeV.

REFERENCES

[1] G. Hagen, et al., Phys. Rev. Lett. 109, 032502 (2012). http://dx.doi.org/10.1103/PhysRevLett.109.032502

[2] L. Coraggio, et al., Phys. Rev. C 80, 044311(2009). http://dx.doi.org/10.1103/PhysRevC.80.021305

[3] J. D. Holt, et al., J. Phys.G 40, 075105(2013). http://dx.doi.org/10.1088/0954-3899/40/7/075105

[4] D.Steppenbeck et al., Nature 502, 207(2013). http://dx.doi.org/10.1038/nature12522

[5] A. Ozawa, et al., Phys. Rev. Lett. 84 5493(2000). http://dx.doi.org/10.1103/PhysRevLett.84.5493

[6] R.Kanungo et al., Phys. Lett. B528, 58(2002) http://dx.doi.org/10.1016/S0370-2693(02)01206-6

[7] M. Honma et al., Phys. Rev. C 65, 061301(R)(2002).

[8] S.N. Liddick et al., Phys. Rev. Lett. 92, 072502 (2004). http://dx.doi.org/10.1103/PhysRevLett.92.072502

[9] B.A. Brown,W.A.Richter, Phys. Rev.C72, 057301 (2005). http://dx.doi.org/10.1103/PhysRevC.72.057301

[10] I. N. Boboshin et al., Bull. Rus. Acad. Sci. Phys. 72, 283 (2008). http://dx.doi.org/10.3103/S1062873808030040

[11] M Rajasekaran, T R Rajasekaran, et al., *Phys. Rev. Lett.* 61, 2077 (1988). http://dx.doi.org/10.1103/PhysRevLett.61.2077

[12] W.D.Myers and W.J.Swiatecki, Ann. Phys. 55, 395 (1970). http://dx.doi.org/10.1016/0003-4916(69)90202-4

[13] H. A. Bethe, Phys. Today 43, 24 (1990). http://dx.doi.org/10.1063/1.881233

[14] W. Truran et al., Can. J. Phys. 44, 563 (1966) http://dx.doi.org/10.1139/p66-011

[15] F.E.Clifford and R.J.Tailor, Mem. R. Astron. Soc. 69, 21 (1964).

[16] M.P. Fewell, Am. J. Phys.63, 653 (1995). http://dx.doi.org/10.1119/1.17828

[17] F.C. Chang, J.B. French, T.H.Thio, Ann Phys.(N.Y) 66, 137 (1971). http://dx.doi.org/10.1016/0003-4916(71)90186-2

[18] J.B. French, V.K.B. Kota, Phys. Rev. Lett. 51, 2183 (1983). http://dx.doi.org/10.1103/PhysRevLett.51.2183

[19] G.H. Lang, C.W. Johnson, S.E. Koonin, W.E. Ormand, Phys. Rev. C. 48, 1518 (1993). http://dx.doi.org/10.1103/PhysRevC.48.1518

[20] Z. Kargar N. Ghahramani, A. Moradi, Commun. Theor. Phys. 48, 531 (2007).