Structural stability and level density of doubly magic isotopes of Calcium

S. Santhosh Kumar[1],* P.Vinodini[2], P. Preetha[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

Introduction

The change in magic number is an interesting feature of the nuclei in the drip-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.

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.

Theory

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 thermodynamical approach, incorporating 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,

$$Q(\alpha_Z,\alpha_N,\beta,\gamma) = \Sigma\exp(-\beta E_i+\alpha_Z Z_i \alpha_N N_i+\gamma M_i).$$

The lagrangian multiplier γ plays the same role as the rotational frequency as in the cranking term $\omega.J_Z$. The pair breaking term γ-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 $a(M,T)=S^2(M,T)/4E^*(M,T)$ where S is the entropy and E^* is the total excitation energy. The expression for the neutron(proton) separation energy is[8],

$$S_{N(P)} = TN(Z)/\{\sum_i[(1 - n_i^{N(Z)})n_i^{N(Z)}]\}.$$

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 (γ = -120°; δ=0.1) shape at very low temperatures, except ^{42}Ca, which is oblate deformed (γ = -180°; 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 (γ = -120°; δ=0.1). Hence the isotopes of Ca are either spherical or slightly deformed (δ=0.1) at very low temperatures and at T ≥ 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 excitation energy(E^*) is a smooth Gaussian for ^{40,48,52}Ca(Fig.1). The drop in E^* for ^{54}Ca (indicated by arrow) resembles the shape transition from prolate to spherical, which may be due to the pairing phase transition at T=0.4MeV.

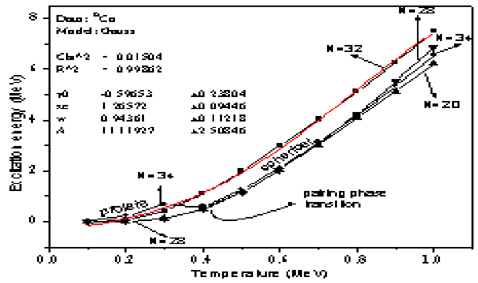

Fig. 1 Excitation energy Vs. temperature

The level density for ^{40,48,52,54}Ca show an exponential growth with temperature (Fig.2), which is proportional to mass number of the nucleus. The deviation in its growth rate refers the indication for shell gap or sub-shell closures.

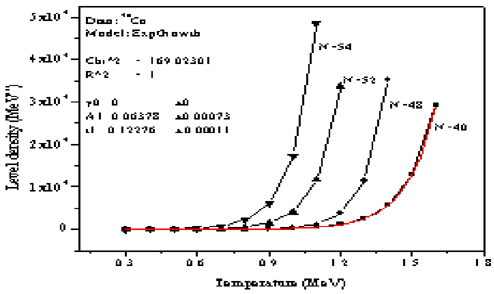

Fig. 2 Exponential nature of level density plots.

The single neutron separation energy for ^{54}Ca drops from S_n≈14.23 MeV to S_n≈8.84MeV which shows its instability against temperature (Fig.3). But ^{40,48,52}Ca show an exponential decrease at very low temperatures and became more or less constant from T≈0.9MeV.

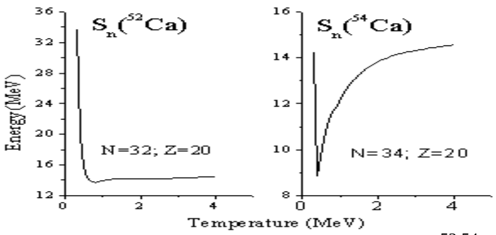

Fig.3 Single particle separation energy for ^{52,54}Ca.

The mean difference in level density parameter (ldp) value Δa= 0.1 for ΔT=0.1MeV for same spin. The minima in the dependence of ldp, on N and Z corresponds 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 has been predicted at N=32 for Ca nucleus.

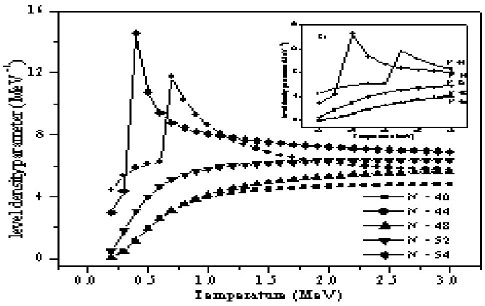

Fig. 1 Minimum in level density parameter ‘a’ shows the closed shells or sub-shells for the Ca nuclei with N=20, 24 and 32.

References

[1] G. Hagen, et al., Phys. Rev. Lett. 109, 032502 (2012).
[2] L. Coraggio, et al., Phys. Rev. C 80, 044311(2009).
[3] J. D. Holt, et al., J. Phys.G 40, 075105(2013).
[4] D.Steppenbeck et al., Nature 502, 207(2013).
[5] A. Ozawa, et al., Phys. Rev. Lett. 84 5493 (2000).
[6] R.Kanungo et al., Phys. Lett. B528, 58(2002)
[7] M. Honma et al., Phys. Rev. C 65, 061301(R) (2002).
[8] M. Rajasekaran et al., Phys. Rev. Lett. 61, 2077 (1988).