Microscopic study on staggering effect of $^{55,56,57,58}Fe$ isotopes

J. Dhivya Saranya[1], S. Prasanna Kumari[1] and
*T. R. Rajasekaran[1]
[1]*Department of Physics, Manonmaniam Sundaranar University, Tirunelveli - 627012, INDIA*
* *email:* trrajasekaran@gmail.com

Introduction

The physical origin of Staggering was noticed by evaporation models due to interplay between pairing effects in the nuclear masses and level densities. This observation suggests that these odd–even effects are low temperature ones associated with evaporation phase [1]. In finite nuclear system, the odd-even staggering (OES) is attributed to the existence of nucleonic pairing correlations [2]. Staggering phenomenon has been observed in several quantities, such as nuclear binding (separation) energies, nuclear charge radii, back bending and heat capacity of finite fermion systems. In nuclei, OES has been attributed to an experimental evidence of pairing correlations [3]. In this work, the staggering effect is examined in level density, back-shift parameter and heat capacity of $^{55,56,57,58}Fe$ isotopes, which highlight the critical role of pairing correlations.

Formalism

At present, statistical theory is used to evaluate OES effects. The logarithm of the grand partition function for the Z protons of the superfluid nuclei at a temperature T using the BCS formulation is given by

$$\ln Q_{BCS} = \sum_k \left\{ -\beta[\varepsilon_k^Z - \mu Z - E_k^Z] + (\ln\{1+\exp[-\beta(E_k^Z - \lambda m_Z^k)]\}) \right\} - \beta\Delta_Z^2 / G_Z \quad (1)$$

where $E_k^Z = [(\varepsilon_k^Z - \mu Z)^2 + \Delta_Z^2]^{1/2}$ are the proton quasiparticle energies. G_z is the pairing strength and Δ_Z is the gap parameter. The quantity β is the reciprocal of the temperature (β=1/T) and μ_z is the proton chemical potential. A systematic procedure is adopted to determine the grand canonical partition function for the superfluid nuclei at a temperature (T) with conserved particle number (Z), energy (E) and angular momentum (M) of the system and is fixed by the saddle point equations. A similar set of equations for neutrons N also exists. The inputs for the statistical theory are the microscopic single - particle levels and single-particle spins corresponding to the triaxially deformed Nilsson harmonic oscillator potential. The (κ, μ) pair used for generating the single-particle level scheme upto N = 11. The detailed computation is delineated in our earlier publication [4].

To evaluate the staggering phenomenon, we calculate the nuclear level density using the back – shifted Bethe formula (BBF)

$$\rho = \frac{\sqrt{\pi}}{12} a^{-1/4} (E^* - \delta)^{-5/4} e^{2\sqrt{a(E^*-\delta)}} . \quad (1)$$

Here, the effective single particle level density parameter is extracted using the expression

$$a = \frac{S^2}{4E^*} \quad (2)$$

and the back shift parameter (δ) is given by

$$\delta = E^* - aT^2 + T . \quad (3)$$

The heat capacity of the system can be determined from

$$C = \frac{dE^*}{dT} . \quad (4)$$

The excitation energy of the system is

$$E^* = E - E_0 \quad (5)$$

where E is the total energy and E_0 is the ground state energy.

Entropy (S) of the nuclear system is given as

$$S = \sum_k \ln\{1+\exp[-\beta(E_k^N - \lambda m_k^N)]\} + \sum_k \beta(E_k^N - \lambda m_k^N)/(1+\exp[\beta(E_k^N - \lambda m_k^N)]) . \quad (6)$$

Results and Discussion

The back-shift parameter (δ) is displayed as a function of mass number 'A' for $^{52-58}Fe$ isotopes in fig.1. Here, the solid line denotes the calculated δ which describes the odd-even staggering due to pairing effects. The Shell Model Monte Carlo (SMMC) calculation (dashed line) and the experimental value (closed circle) also plotted for comparison. In a typical empirical formula, δ is close to zero for odd-even nuclei, positive for even-even nuclei, and negative for odd-odd nuclei. Microscopic calculation is closely in agreement with the SMMC and experimental data [5].

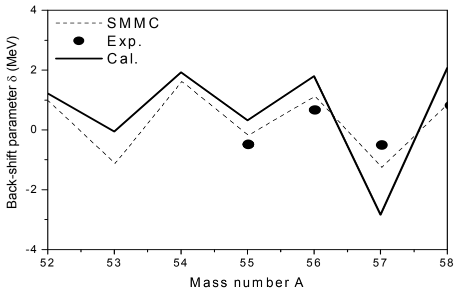

Fig. 1 Mass dependence of back-shift parameter for iron isotopes.

In fig.2, the level density is shown as a function of excitation energy. The level density increases against excitation energy and it depends upon the mass of the isotopes because of staggering.

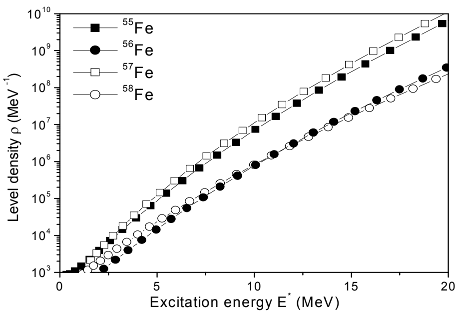

Fig. 2 Logarithmic variation of the level density ρ with the total excitation energy E^*.

Fig.3 shows the temperature dependence of heat capacity for $^{55,56,57,58}Fe$ isotopes. A smooth bump is obtained around the critical temperature region T ~ 0.8 to 0.9 MeV, indicating the second-order pairing phase transition. Here, the heat capacity increases with mass due to the increase of the density of states with mass. In fig.3, the heat capacity of ^{57}Fe is below that of both ^{56}Fe and ^{58}Fe. It depicts that the heat capacity of an odd-mass nucleus is significantly lower than that of the adjacent even-mass nuclei. Therefore, the thermal signatures of pairing correlations are identified through odd-even effects in the heat capacity which is in accordance with the SMMC method. From all of these criteria, it is argued that the pairing correlations play a vital role in these OES phenomenon.

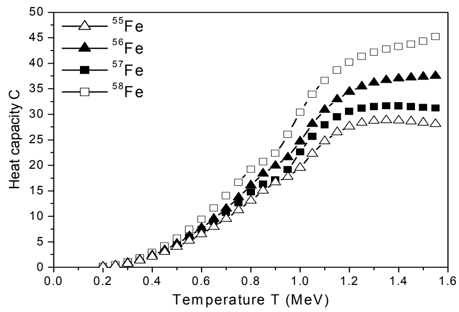

Fig. 3 Temperature dependence of heat capacity for $^{55,56,57,58}Fe$ isotopes.

Acknowledgement

This work is supported by the Department of Atomic Energy Board of Research in Nuclear Science, India under the project (No.2012/37P/37/BRNS/2017).

References

[1] B. Mei et al., Phys.Rev.C 89, 054612 (2014).
[2] Vidya Devi, Turk J Phys 37, 330-347 (2013).
[3] S. A. Changizi and C. Qi, Phys.Rev.C 91, 024305 (2015).
[4] T. R. Rajasekaran et al., Eur. Phys. J. A 35, 57–68 (2008); Acta Physica Polonica B 39, 6 (2008).
[5] Y. Alhassid et al., Phys.Rev.C 83, 21 (1999).