Effect of pairing in nuclear level density at low temperatures

A. K. Rhine Kumar,* Swati Modi, and P. Arumugam
Department of Physics, Indian Institute of Technology Roorkee, Uttarakhand - 247 667, India

Introduction

The nuclear level density (NLD) has been an interesting topic for researchers, due its importance in many aspects of nuclear physics, nuclear astrophysics, nuclear medicine, and other applied areas. The calculation of NLD helps us to understand the energy distribution of the excited levels of nuclei, entropy, specific heat, reaction cross sections etc. The behaviour of NLD can depend on shell effects, temperature, pairing of nucleons, shape of nucleus and mass number. The other parameter in NLD calculations is the level density parameter (a). It is an important parameter in statistical model calculations of several observables. Theoretical studies employing various models for NLD can be found in literature[1–4]. Recently, many experiments have been carried out to find the NLD of nuclei like ^{60}Ni, ^{98}Mo, ^{56}Fe, ^{116}Sn [5, 6] at lower temperatures where a few interesting features were pointed out which could be due to the effect of pairing correlations and shell corrections. In this work we study the effect of temperature and pairing on level-density of the nucleus ^{116}Sn.

Theoretical framework

The estimates of level densities are usually described in terms of degenerate Fermi gas model. We follow the formalism described in Refs. [1, 7] and we calculate the level densities using three different level distributions, namely (i) discrete single-particle distribution, (ii) effective single-particle distribution and (iii) quasiparticle level distribution, as outlined below.

(a) Discrete single-particle level density

The intrinsic level density of a system can be written in terms of the Laplace transform of the grand partition function as

$$\rho_{mic} = \frac{\exp(S_N + S_Z)}{4\pi^{3/2}T^{5/2}\sqrt{g_N^F g_Z^F a}} \text{ , where} \tag{1}$$

$$a = \frac{1}{2T^3}\left[\sum_i g_i^F e_i^2 - \frac{1}{Tg^F}\left(\sum_i g_i^F e_i\right)^2\right],$$

T is the temperature, S is the entropy, e_i are the single-particle energies, $g^F = (1/T)\sum_i g_i^F$, $g_i^F = n_i(1-n_i)$ and $n_i = \{1 + \exp[(e_i - \lambda)/T]\}^{-1}$.

(b) Effective single-particle level density

Within the Fermi gas model approximation, at each value of T, we define a_{eff}=$S^2/(4E^*)$, where $E^*(= E(T) - E(T=0))$ is the excitation energy. Then the effective single-particle level density shall be written as

$$\rho_{eff} = \frac{\exp(S_N + S_Z)}{4\pi^{3/2}T^{5/2}\sqrt{g_N^F g_Z^F a_{eff}}}.$$

(c) Quasiparticle level density

Including the role of pairing within BCS approach, we write the quasiparticle level density as

$$\rho_{bcs} = \frac{\exp(S^{bcs})}{4\pi^{3/2}T^{5/2}\sqrt{g_N^{bcs} g_Z^{bcs}(\bar{a}_N^{bcs} + \bar{a}_Z^{bcs})}},$$

where $g^{bcs} = \beta\left[2D_1 + \Delta^2(TA_1 - 2C_1)\right]$,

$$\bar{a}^{bcs} = \beta^3\left[2E_2 - \frac{(2D_2)^2}{(2D_1 + \Delta^2(TA_1 - 2C_1))}\right],$$

and the expressions for the constants D_1, A_1, C_1, E_2, D_2 are as given in Ref. [1]. $E_j = \sqrt{(e_j - \lambda)^2 + \Delta^2}$ is the quasiparticle energy.

---

*Electronic address: `rhinekumar@gmail.com`

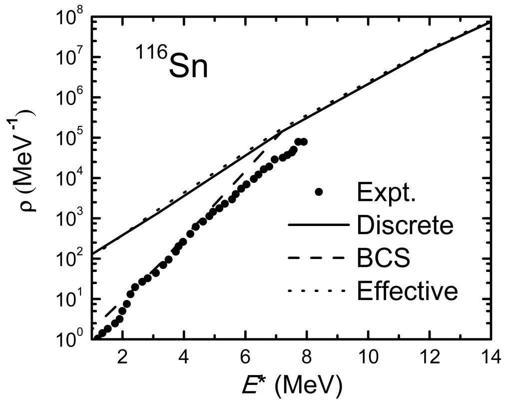

FIG. 1: The dependence of nuclear level density on excitation energy. The experimental values (solid circles) are shown along with the our calculations using three different methods.

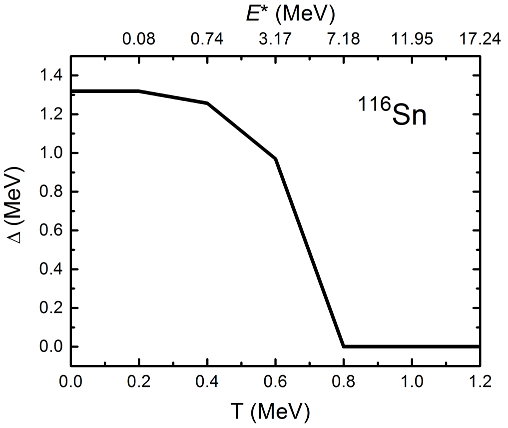

FIG. 2: Neutron pairing gap (Δ) as a function of temperature (T) and excitation energy (E^*).

Results

The single-particle energies are obtained with a modified Nilsson potential and the excitation energies are calculated with temperature dependent shell correction approach using the formalism given in Ref. [7]. The level densities obtained from our calculations are shown along with the experimental data [6] in Fig. 1. Level densities calculated with BCS pairing show a good agreement with experimental values. We have used the values of pairing force strength (G) a given in Ref. [8]. The proton pairing gap is zero in ^{116}Sn and the calculated neutron pairing gap as a function of temperature and excitation energy is plotted in Fig. 2. We can see that at $T = 0.8$ MeV, the neutron pairing also vanishes where the system is changing from a superfluid to normal phase by breaking the Cooper pairs. At this temperature, both the results from discrete and BCS methods match with each other. The calculations without pairing over estimates the level densities at lower temperatures. The level densities ρ_{eff} and ρ_{mic} are found to be similar. The deviation of ρ_{bcs} from the experimental value above $T \gtrsim 0.8$ MeV suggests that the pairing could be present even this temperature. Such a sustained pairing could be possible if we consider the thermal fluctuations in the shape or the pairing field. The sustained pairing could also mean that the pairing phase transition could be of second order in nature. Work is in progress to extend our calculations to incorporate this features.

Conclusion

The effect of pairing correlations are very significant in nuclear level density at low temperatures. A more rigourous work can reveal the existence of pairing beyond the critical temperature suggested by the BCS approach.

References

[1] O. Civitarese and A.L. De Paoli, Nucl. Phys. A**440**, 480 (1985).

[2] B. K. Agrawal and A. Ansari, Phys. Lett. B **421** 13 (1998).

[3] M. Bonett-Matiz et. al, Phys. Rev. C **88**, 011302(R) (2013).

[4] N. Q. Hung, D. T. Dung and T. D. Trong, Comm. Phys., **22**, 297 (2012).

[5] H. K. Toft et. al, Phys. Rev. C **81**, 064311 (2010).; E. Algin et. al, Phys. Rev. C **78**, 054321 (2008).

[6] U. Agvaanluvsan et. al, Phys. Rev. C **79**, 014320 (2009).

[7] P. Arumugam, G. Shanmugam, and S. K. Patra, Phys. Rev. C **69**, 054313 (2004).

[8] S. G. Nilsson, et. al, Nucl. Phys. A**131, 1** (1969).