Experimental studies on nuclear level density

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Abstract

The nuclear level density (NLD) is an important physical quantity in the statistical calculation of compound nuclear decay and therefore, useful for both pure and applied research. The variation of the NLD with the mass number (A), excitation energy, angular momentum, parity, isospin, shell effect and paring have been studied both experimentally and theoretically for over many decades. The recent development of the state of the art experimental techniques, namely CERN n-TOF experiment through neutron resonance spectroscopy, Oslo method for study of continuum gamma rays in coincidence with the particles in transfer induced reactions, Mumbai method for the study of continuum particle spectra in coincidence with the particles (ejectiles) in the breakup-fusion reaction, provide opportunities to study many important problems pertaining to the level density. The recent progress in the measurements highlighting various aspect of the nuclear level density is discussed.

1. Introduction to Nuclear Level Density

The NLD is a fundamental property of the atomic nucleus, defined as the number of energy levels per unit energy at an excitation energy \( E_x \). It is used for the calculations of reaction rates relevant to nuclear astrophysics, nuclear reactors, and spallation neutron sources. It is also an essential quantity for obtaining the thermodynamical properties of an excited atomic nucleus, namely entropy, temperature and specific heat. The NLD was first calculated by Bethe using a non-interacting Fermi gas model [1,2]. The simplest picture is the equidistant model where the single particle levels are equispaced and non-degenerate. The leading factor in the analytical form is \( \rho(E_x) \sim e^{\gamma(a E_x)} \), where \( a \) is the level density parameter. \( a \) is known as the level density parameter and is given by \( a = \pi^2 g/6 \) and \( g \) is the sum of the neutron and proton single particle level density at the Fermi surface. It increases rapidly with excitation energy. The analytic form deduced by Bethe within the frame work of Fermi gas model has been used as the basis for building the most of the phenomenological formula such as constant temperature model (CTM) and Gilbert and Cameron for the fitting of the experimental data or calculating reaction cross section [3-5]. Apart from the thermodynamic approach [1,2] which based on the grand partition function, the other techniques used for the calculating the NLD are: combinatorial method which requires large scale computation for estimating the number of ways the nucleons can be distributed among the available single particle levels and sorting them according to a given \( E_x \) and \( J \), and spectral distribution method where the energy and angular momentum dependent level density being evaluated from the first few moments of the nuclear Hamiltonian. Recently developed a powerful shell model Monte Carlo (SMMC) method [9], which has been used to calculate the nuclear level density in the presence of correlations. The SMMC method enables calculations in model spaces that are many orders of magnitude larger than those that can be treated by conventional methods. This method was employed to calculate the level densities in nuclei up to \( A \sim 160 \) and are in good agreement with the data from various experiments [10].

2. Experimental Probes to Study Level Density

The experimental evidences of the nuclear level density are obtained from (a) counting the discrete levels and resonances populated by neutron and charged particle reactions, (b) the inelastic scattering of neutron, proton, alpha and transfer reaction populating the low excitation
energy, (c) the Ericson fluctuation analysis in the compound nuclear reaction which is restricted to light mass nuclei (A≤60) and (d) the analysis of evaporation spectra. In the first two methods the NLD is obtained by direct counting of the nuclear levels with necessary correction for unresolved and unobserved levels and therefore provide an absolute measure of the nuclear level density. The information of the NLD is limited to near stable nuclei and very low excitation energy (up to binding energy of the nucleon) and angular momentum pertaining to mainly s and p wave. The extrapolated to higher J values is made to estimate the angular momentum summed or total NLD. Recently, CERN has developed a neutron time of flight (n-TOF) facility to investigate nuclear structure at high excitation energies and obtain crucial information on level densities from neutron resonance spectroscopy. Oslo method is used to study the continuum gamma ray spectra following inelastic scattering and transfer reactions, namely \(^{(3}\text{He},^{3}\text{He} \gamma)\) and \(^{(3}\text{He},^{4}\text{He} \gamma)\) and extract the nuclear level density data and gamma ray strength function relevant to nuclear astrophysics [11]. The last method does not provide the absolute value of the NLD, but has been used to study its variation over wide range of the excitation energy and the angular momentum. The excitation energy (Ex) and angular momentum (J) dependence of the NLD has been inferred from the statistical model analysis of the measured low energy γ-ray multiplicity gated particle evaporation spectra. An unusual structure has been observed in the angular momentum gated charged particle spectra [12]. The observed enhancement in the extracted NLD in \(^{104}\text{Pd}\) with Ex and J is the first experiment evidence of pairing reentrance in finite hot rotating nuclei [13]. The NLD also depends on the shell effect and collective modes excitation such as rotational and vibrational. The total NLD inferred from various measurements show that on average the level density parameter \(a\) increases linearly with the mass number of the nucleus as \(\approx A/8\text{ MeV}^{-1}\). This smooth behaviour with respect to mass is due to the liquid drop like properties of the nucleus. However, there is a significant departure from this liquid drop value at shell closures. This departure is the largest for the doubly magic nucleus \(^{208}\text{Pb}\), where the effective \(a\) is as low as \(A/26\text{ MeV}^{-1}\) at neutron binding energy. This shell effect on the NLD parameter is expected to wash out with excitation energy so that \(a\) approaches its liquid drop value at \(E_X \geq 40\text{ MeV}\) [14,15] as shown in the figure between entropy square verses excitation energy.

![Figure 1: Plot, S^2 vs Ex, shows the washing out of shell effect with excitation energy in the doubly closed shell \(^{208}\text{Pb}\) nucleus. The shell correction energy for \(^{208}\text{Pb}\) is -13.4 MeV. The solid line is the asymptotic behavior at high excitation energy [14].](image)
3. Shell effect and its damping with Ex

The nucleus $^{208}$Pb, formed in the excitation energy range 19 - 23 MeV corresponds to alpha energy from 13.5 - 19.5 MeV, decays predominately by the neutron emission populating the residual nucleus in the Ex ~ 3 - 14 MeV. The statistical model(SM) analysis of the measured neutron spectra shows the expected large shell correction energy (~13.1MeV) for the nuclei in the vicinity of doubly magic $^{208}$Pb and a small value (2.2 MeV) around $^{184}$W (see figure: 2a-b). An exclusion plot between the damping parameter and the inverse level density parameter $\delta a$ ($= A/\tilde{a}$) has been made for the first time as shown in Fig. 3(c). It is observed that the acceptable range of $\delta a$ lies between 8.0 and 9.5 MeV. The shell damping parameter $\gamma$ constrained to $(0.060^{+0.10}_{-0.020})$ MeV$^{-1}$ [16].

![Figure 2](image)

**Figure 2:** (a) Neutron spectrum from $^{208}$Pb at Ex =20.8 MeV and solid and dashed lines are the statistical model calculation using shell correction energy ($\Delta S$) 13.1 and 2.2 MeV, respectively, for $a=A/8.5$ MeV$^{-1}$ and $\gamma=0.055$ MeV$^{-1}$ . (b) Same as (a) except for $^{184}$W at Ex =20.6 MeV and (c) the exclusion plot between $\delta a$ ($= A/\tilde{a}$) and $\gamma$. The allowed a values of a and $\gamma$ are within the contour.

4. Summary

The nuclear level density is an important physical quantity for both the basic and applied research. We have understood generic behaviour of the level density as a function of excitation energy and angular momentum within the framework of Fermi gas model. Many experiments reveal correlations which are not included in the Fermi gas model such as pairing, shell effect and also the collective effects. Many correlations are important at low excitation energy for the study of level density are taken care in the shell model Monte Carlo calculations and are limited to the heavy mass nuclei up to A~160. We have inferred the damping of the nuclear shell effect over a wide excitation energy from an exclusive measurement of the neutron spectra in the $^7$Li breakup followed by fusion of triton with $^{205}$Tl. The measured neutron spectra show a large shell effect in the vicinity of $^{208}$Pb. An exclusion plot between the parameter $\gamma$ which relates the damping of the nuclear shell effect and the asymptotic nuclear level density parameter a, has been made for the first time. The precision of the measurement of the damping factor can be improved by using the liquid scintillator detector array for fast neutron measurement and also the Si- strip/CD detector for identification of the light charged particles. In future, the collective enhancement of the nuclear level density and its damping with excitation energy can be addressed using the same experimental technique.
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References