Statistical fluctuations in hot rotating ^{60}Fe

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Introduction

Nuclear level density provides information about the structure and thermodynamical properties of highly excited nuclei, and is an important ingredient in statistical model calculation of nuclear reaction cross section. In many astrophysical scenarios the statistical approach is more reliable [1] since stellar evolution is more as a thermo-dynamical one. The effect of Nuclear structure upon the value of level density parameter (ldp) can be obtained by considering shell correction, pairing correlations and collective excitation.

^{60}Fe is expected to be from a non-terrestrial source, which is a product of neutron captures at a relatively high neutron density, and can be synthesized both in massive stars exploding as supernovae and in intermediate-mass stars in their final evolutionary stages. It is the major heat source for the first compact objects in the ESS[2]. Hence it can be used as a chronometer for dating events such as supernovae and some other stars in the million-year time range. Its dominant production path, the double neutron capture process, indicates stellar production requires sufficient neutron densities[3]. In the year 2004 scientists at TU Muenchen discovered ^{60}Fe on Earth for the first time in a ferromanganese crust obtained from the floor of the equatorial Pacific Ocean.

Methodology

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 $\gamma\text{-}m_j$ 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 U is the total excitation energy. The neutron separation energy is obtained from $Sn=-T(\partial \ell_n Q/\partial\alpha_N)(\partial\alpha_N/\partial N)$.

Result and Discussion

In this work cranked Nilsson method is used to obtain the single particle energies. The predicted shape of the nucleus ^{60}Fe is prolate deformed($\gamma=-120^o;\delta=0.2$), at T>0.5MeV. When the temperature increases the deformation decreases and became spherical at T=1.3MeV. At very low temperatures, ie., T<0.5MeV, the nucleus shows a triaxially deformed shape ($\gamma=-140^o;\delta=0.2$), which coincides well with the prediction of ^{60}Fe with an axially deformed value of $\beta=0.211$ by Moller et al.,[4]

In fig.1. the temperature dependence of the excitation energy and level density parameter are shown. A small dip at T=1.3MeV in the excitation energy plot indicates possible temperature dependent transitional states. The smooth growth in excitation energy above T=1.3MeV reveals its spherical shape ($\delta=0.0$) at spin 0ħ, at higher temperatures.

In order to describe the thermal damping of shell effects with increasing excitation energy and to obtain correct nuclear level density (NLD), usually the ldp 'a' were taken from microscopic calculations[3]. Hence calculating correct ldp is an essential factor in NLD and spin cut-off parameter calculations. From the Fig.1

and 2, the ldp is a smooth Gaussian at T>1.0MeV. This may be a signature for stability of the nucleus at higher temperature against evaporation of light particles from the hot nuclei. The temperature dependent ldp at relatively low temperature can be explained by the collapse of residual interaction and at high temperature, by changes of mean field. The decreasing of level density parameter, with increasing values of spin at >6 ħ (fig.2) has to be interpreted as a signature for the collapse of nuclear residual interaction.

The thermal effect on ldp shows an increased value with increase of temperature and spin, which is separated by the converging point in the graph (fig.2) at the spin 6 ħ. The entropy 'S' increases exponentially upto the temperature T=0.6MeV with entropy S=11.008 and then grows linearly, which resembles the strong binding of the system at low temperature and no room for pair breaking even at high temperatures.

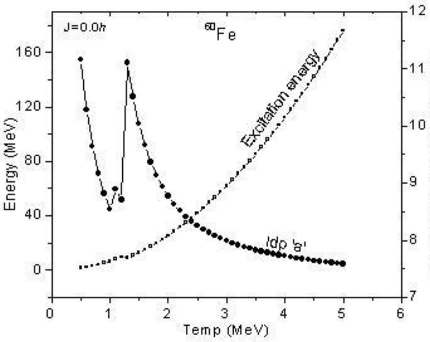

Fig. 1 Variation of E^* and ldp against temp.

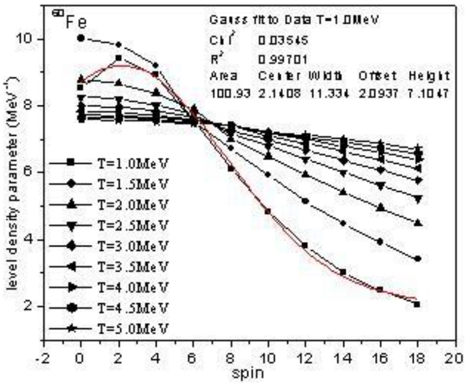

Fig. 2 ldp against spin at different temp (spin in the units of *ħ*).

The behavior of the nucleus at T=0.5MeV is predicted and plotted in Fig.3. At J=0ħ it is prolate deformed(γ=-120^o; δ=0.2) and at J=1-4ħ, it is triaxial (γ=-140^o;δ=0.2). At J>5ħ the system shows an oblate deformed shape (γ=-180^o; δ=0.1). The neutron separation energy increases with spin while proton separation energy decreases, which shows the stability of the nucleus against neutron evaporation with increasing excitation energy. An immediate rise in level density parameter at J=5ħ, shows the shape stability against spin, ie., became spherical from the fluctuation such as prolate and triaxial.

The proton-neutron monopole interaction has a substantial impact on the ordering of single particle states in neutron-rich nuclei. In the *pf* shell, the proton-neutron monopole interaction between the spin-orbit partners $\pi f_{7/2}$ and $\nu f_{5/2}$ was expected to result in the emergence of new shell structure at N = 32 and 34 [5]. ^{60}Fe is also having 34 neutrons and in this isotope the magicity is missing as obtained for ^{54}Ca.

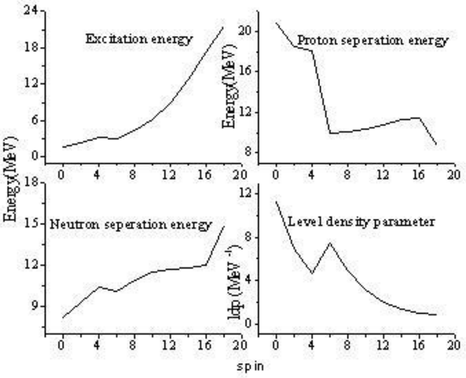

Fig. 3 Behaviour of ^{60}Fe at T=0.5MeV.

References

[1] T.Rauscher et al., Phys.Rev.C56,1613 (1997).
[2] A. Shukolyukov and G.W.Lugmair, Science 259,1138 (1993).
[3] A. Wallner et al, Phys.Rev.Lett. 114, 041101 (2015).
[4] P. Moller et al., At. Data. Nucl. Data Tables, 59, 185 (1995).
[5] T. Otsuka, et al., Phys. Rev. Lett. **87,** 082502 (2001).