Nuclear level density and thermal properties of ^{56}Fe and ^{62}Ni

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Introduction

According to the modern theory of stellar nucleosynthesis, heavier elements than hydrogen and helium were produced by nuclear fusion in stars, and then spread around the universe by supernovae, stellar winds, planetary nebulae and so on. One of the interesting predictions of this theory is that some elements were not produced as they exist today, but as radioactive precursors. For example, the most abundant isotope of iron, ^{56}Fe, originates from an unstable isotope of nickel, ^{56}Ni. This isotope is produced in supernovae and decays first to Cobalt and then to iron. Heavy elements that contain a large number of protons are stabilized through an excess of neutrons. But supernovae generally contain material with equal numbers of neutrons and protons. Nuclei formed from nuclear burning are often unstable, later decaying to a stable isotope with excess neutrons. Indeed, it is this radioactive decay of ^{56}Ni that makes a supernovae shine for months after its explosion. Very recently Sezer and Gok [1] also detected Fe-rich ejecta in the supernovae remnant. In astrophysics, the rates of neutron-capture reactions in r and s processes are proportional to the nuclear level densities (NLD) and are important in the synthesis of elements heavier than iron. Therefore nuclei in iron group are of particular interest.

Shell corrections to the nuclear free energy are temperature dependent and they collapse at temperatures, T, of the order of 2 MeV[2]. The collapse of pairing correlations occurs at lower temperatures, T=0.5MeV [3] and collective excitations collapse at T=1MeV[4]. It has been shown that the temperature dependence of nuclear correlations can affect the value of ldp at low temperatures[5], and which disappear at T=4MeV. In 1994, Fewell [6] discussed about the statement of Bethe[7] that ^{56}Fe is the most strongly bound nucleus, which cannot be as per the existing theories. According to him, the tightly bound nucleus has A≈58.3 and Z≈26.6, if the shell effects are switched off. At this juncture, still the question of existence of ^{56}Fe than ^{62}Ni in supernovae is unanswered, even though the mean binding energy difference is of no importance to the theory of supernovae. Truran, Cameron and Gilbert [8] favoured ^{56}Fe has the highest BE/A, but Clifford and Taylor[9] are the first to identify ^{62}Ni has the highest mean binding energy. In this work we tried to answer the reason for the existence of ^{56}Fe than ^{62}Ni in supernovae remnants in the context of excitation energy, level density and thermal fluctuation, etc.

Methodology

The binding energy per nucleon in the mass region A=50-64 using Droplet model mass formula[10] is calculated and found the nuclei ^{58}Fe(8.76681MeV) and ^{62}Ni(8.76789MeV) are strongly bound than ^{56}Fe(8.74831MeV) , which is in correlation with Fewell[6].

The level density parameter (ldp) is determined, under statistical assumptions, by the relation between excitation energy and entropy. Nuclear structure effects upon the ldp can be considered by the inclusion of shell corrections, pairing correlations and collective excitations.

In search of the reason, why the existence of ^{56}Fe is highly probable than ^{62}Ni, we have performed a systematic analysis on the basis of statistical theory, and the interrelation between structure and rotational effects, level density and entropy, and temperature effect.

Results and discussion

The nucleus ^{56}Fe shows a prolate(γ=-120^o) deformed shape (δ≈0.2/0.1) at very low temperatures (T=0.0-0.4MeV). From T=0.5MeV it behaves as spherical, but, it changes from spherical to oblate at J≈2ℏ via triaxial(γ=-140°) while increasing the spin. At T=1MeV it changes its shape from spherical to oblate deformed (γ=-180°; δ≈0.1)at J≈10ℏ, and it shows a higher deformation (δ≈0.2) from J≈16ℏ. This character persists till the temperature T = 2.0MeV, which shows its stability in shape against temperature.

The nucleus ^{62}Ni is slightly prolate deformed (γ=-120°; δ≈0.1)at very low temperatures(T=0.1-0.4MeV) and from T=0.5MeV it behaves as spherical(δ≈0.0). For higher spin values it again shows a deformed (δ≈0.1)structure along the oblate axis(γ=-180°) at J≈4ℏ and from J≈10ℏ it elongates to δ≈0.2. At higher temperature (T=0.5-2.0MeV)also such a fluctuated status is observed.

The temperature dependence of excitation energy for ^{56}Fe, ^{59}Co and ^{62}Ni is plotted in Fig.1. The circled region in this plot shows the temperature dependent transitional state. A deviation in excitation energy at T≈0.5MeV for ^{62}Ni and another at T≈0.9MeV for ^{56}Fe may be due to the collapse of pairing correlations [3] and collective excitations collapse [4], respectively.

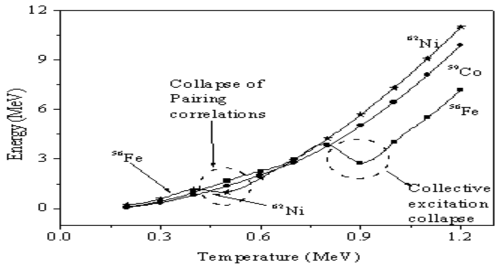

Fig. 1 Dependence of Excitation energy upon temperature

The temperature dependence of nuclear correlations can affect the value of the level density parameter at low temperatures [5]. The effect of level density parameter against temperature is plotted in Fig.2. The drastic fluctuation at low temperatures become smooth around temperature T≈0.9MeV and it decreases with increasing temperature. The humps obtained for ^{62}Ni and ^{56}Fe at T≈0.5MeV and T≈0.9MeV respectively are having nearly the same level density parameter value, which has a critical influence in its reaction study, level density and spin cut-off parameter. The decrease of the ldp, with increasing temperature, has been interpreted as a signature for the collapse of nuclear residual interactions.

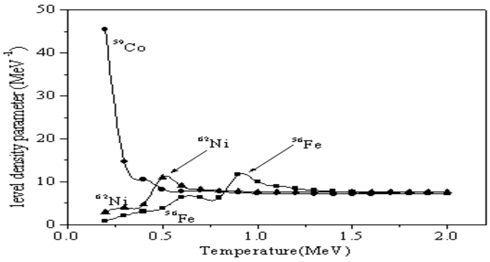

Fig. 2 Dependence of ldp upon temperature

Level densities are affected by pairing. Under the influence of short range attractive force, nucleons prefer to form pairs (Cooper pairs) can break up at higher temperature. The thermal breaking of Cooper pairs leads to increasing level density and entropy. The step structure formed in the level density versus excitation energy plot (Fig.3) for ^{56}Fe may be interpreted as the breaking of Cooper pairs and quenching of pair interaction.

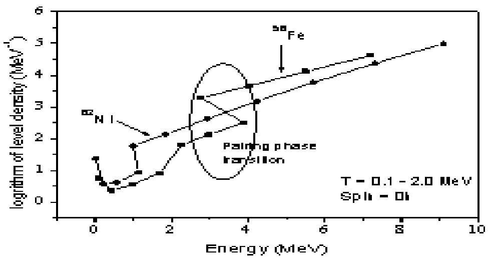

Fig. 3 Dependence of level density upon excitation energy

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