Level density of radioactive doubly-magic nucleus ^{56}Ni

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Introduction

^{56}Ni is an important nucleus to study since its role in astrophysical evolutions. During the supernova explosions explosive Si burning produces radioactive isotope ^{56}Ni. The released energy by its decay to ^{56}Fe via ^{56}Co becomes the dominant energy source to power the optical light of most of supernova explosions [1].

Discoveries of phenomena such as the island of inversion and halo nuclei have shown that the exotic nuclei may not have the same structure as stable nuclei. The first magic number created in the inclusion of the spin-orbit interaction is 28. The number 28 is created by a minor shell gap between the $1f_{7/2}$ and $2p_{3/2}$ shells. The nucleus ^{56}Ni with N=Z=28, is the first radioactive doubly magic nucleus. Studying the region around the N=Z=28 shell closure provides some light as to whether radioactive nuclei have the same magic numbers and shell closures as stable nuclei. The entropy of the first excited state of ^{56}Ni[2] appears to agree with the trends of stable doubly magic nuclei such as ^{40}Ca and ^{90}Zr. The transition rate from the first excited state of ^{56}Ni to the ground state was first measured in 1973 using Doppler-shift attenuation method[3] and the transition probability agreed with predictions based on the behavior of stable nuclei for a good-closed shell nucleus. Later, shell model calculations assumed a good shell structure for the ^{56}Ni nucleus for calculating B(E2) transition. This lent further credence to the view that radioactive ^{56}Ni behaves like stable doubly-magic nuclei.

In this work the single particle energies are obtained by diagonalising the Nilsson Hamiltonian in the cylindrical basis and are generated up to N=11 shells for the isotopes of Ni from A=48-70, emphasizing the three magic nuclei viz, ^{48}Ni, ^{56}Ni and ^{68}Ni.

Formalism

The statistical quantities like excitation energy, level density parameter and nuclear level density which play the important roles in the nuclear structure and nuclear reactions can be calculated theoretically by means of the Statistical or Partition function method. Hence the statistical model approach is followed to probe the dynamical properties of the nucleus in the microscopic level.

The entropy of the system is given by

$$S = S_Z + S_N, \text{ where,}$$

$$S_{Z(N)} = -\sum_i [n_i^{Z(N)} l_n n_i^{Z(N)} + (1-n_i^{Z(N)}) l_n(1-n_i^{Z(N)})],$$

Where, the $n_i^{Z(N)}$ is the average occupation probability for proton (neutron).

The total excitation energy is obtained using

$$E_{ex} = U(M,T) = U_{eff}(T) + E_{rot}(M)$$

The single particle level density parameter a(M,T) is extracted using the equation

$$a(M,T) = S^2(M,T) / 4\, U(M,T).$$

The expression for the neutron(proton) separation energy is

$$S_{N(P)} = TN(Z)/\{\sum_i[(1 - n_i^{N(Z)})n_i^{N(Z)}]\}$$

From the above expressions it is possible to calculate the nuclear level density, back shift energy and hence the spin cut-off parameter using Gilbert-Cameron expression[4] were extracted and studied for the said range of nuclei.

Results and Discussion

The difference in excitation energy between the angular momentum 2ħ and ground state is 871keV for ^{56}Ni and 201keV for ^{68}Ni, which indicates a lower transition probability for ^{68}Ni than ^{56}Ni, even though both the nuclei are having proton and neutron magic numbers, and the difference in energy coincides with Ref.[5]. Also our calculations show a lower transition probability for ^{54}Ni than ^{56}Ni, which reinforces the doubly magic status of ^{56}Ni nucleus. Among the Ni isotopes studied, the excitation energy against mass number plot gives three peaks at A=48, 56 and 68 (fig.1). A small drip from A=64 to 66 shows the nucleus ^{64}Ni is sensitive to rotational shapes since at higher spins the shape fluctuates from spherical to oblate. The level density parameter 'a' is lower for ^{56}Ni than other magic isotopes of Ni, such as ^{48}Ni and ^{68}Ni, which again reinforces the doubly magic status of ^{56}Ni (fig.2).

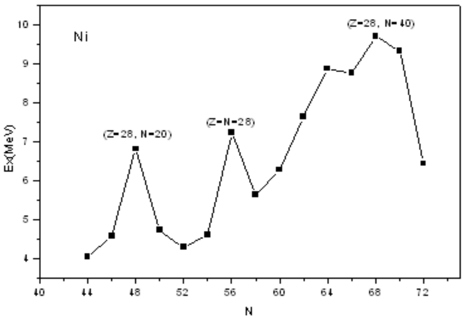

Fig.1 Excitation energy as a function of mass number for Z=28, at spin=0ħ.

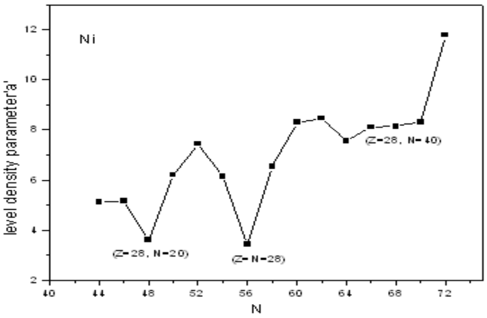

Fig.2 Level density parameter 'a'(in units of $(\mathrm{MeV})^{-1}$) as a function of mass number for Z=28, at spin=0ħ.

According to CNS calculations the energy of the predicted terminating state at I=20 is 26.00MeV relative to the observed ground state[6], and our calculation gives an energy at the state I=20 is 25.168MeV, which is in close agreement with Ref[6], which is given in the comparative plot of excitation energy of three magic nuclei against spin (fig.3). The nucleus ^{56}Ni is spherical in shape upto 10ħ and becomes oblate deformed (γ=-180o; δ=0.2) from 12ħ. But ^{48}Ni and ^{68}Ni show a shape change from spherical to oblate deformed even at 6ħ itself.

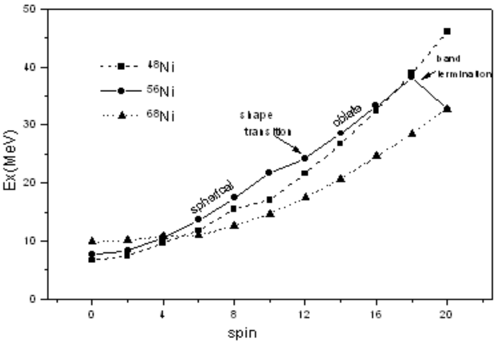

Fig.3 Excitation energy against spin (in units of ħ) for Ni magic isotopes.

The calculated neutron separation energy (S_n) show a higher value for ^{48}Ni (12.861MeV) and much higher value for N=28, (22.789MeV) but the S_n obtained for N=40 of the Ni isotope shows a comparatively lower value (10.431MeV) (fig.4), which indicates the higher stability of the nucleus against neutron emission. This work will be extended further to know whether the properties of radioactive doubly magic nucleus mirror the stable closed shell nuclei.

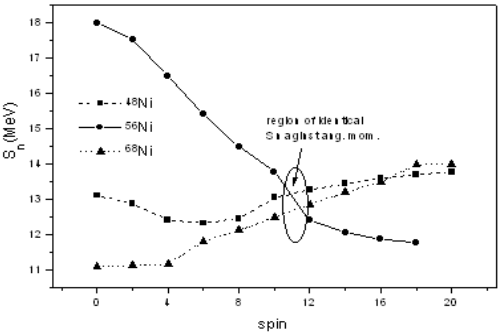

Fig.4 Neutron separation energy against spin(in units of ħ) for Ni magic isotopes.

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