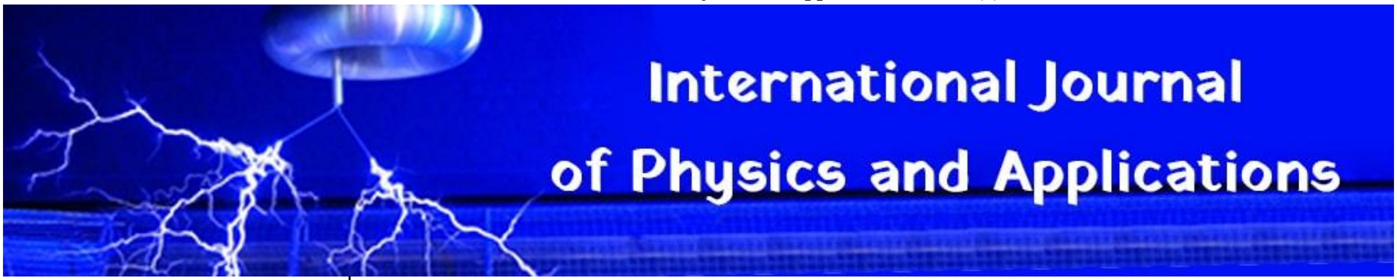

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Decay lifetime and deformation of medically important radioactive isotope 'Co'

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Abstract
The decay probability and lifetime of the nuclei are important parameters in determining the nuclear stability. In the gamma transition process of decaying a nucleus, the gamma particle energy is a crucial parameter. In this work the medically important radioactive nucleus, Co, is studied in the context of a thermodynamical nuclear system. The statistical model is executed to obtain the excitation energy, entropy, level density, etc. for Co isotopes (A=50-70) at T= 0.5 MeV. ^{61}Co is predicted to have a long life time. The E_γ reflects the level density parameter values from statistical model calculations and their influence in nuclear stability is discussed. The influence of qadrupole deformation in determining the E_γ value is also addressed.

Keywords: Radioactive nucleus, quadrupole deformation, decay lifetime, statistical model

1. Introduction

The use of radioactive isotopes in medical diagnosis and treatment is a well-established procedure, especially in diseases like cancer and tumor and also in sterilization processes [1]. The imaging techniques to reveal the disorder and functioning of organs was developed in the 1950s by physicians with an endocrine emphasis, initially using iodine-131 to diagnose and then treat thyroid disease. Radioisotopes are an essential part of medical diagnostic procedures. In combination with imaging devices which register the gamma rays emitted from within, they can study the dynamic processes taking place in various parts of the body.

In using radiopharmaceuticals for diagnosis, a radioactive dose is given to the patient and the activity in the organ can then be studied either as a two dimensional picture or, using tomography, as a three dimensional picture. Diagnostic techniques in nuclear medicine use radioactive tracers which emit gamma rays from within the body. These tracers are generally short-lived isotopes linked to chemical compounds, can be given by injection, inhalation, or orally. In fact a radioisotope used for diagnosis must emit gamma rays of sufficient energy to escape from the body and it must have a half-life short enough for it to decay away soon after imaging is completed.

Comparatively very few radioisotopes are used in therapy. External irradiation, sometimes called teletherapy, can be carried out using a gamma beam from a radioactive cobalt-60 source which has a half-life of about 5.27 years. Cobalt-60 decays by beta and gamma emission to non-radioactive nickel. Most of the radiation from the decay of cobalt-60 is in the form of gamma emissions; some are in the form of beta particles. Beta particles are generally absorbed in the skin and do not pass through the entire body. Gamma radiation, however, can penetrate the body. ^{60}Co is also used for sterilization. A number of studies suggested that ^{60}Co is more effective in modern radiation treatment [2-4], while computed tomography imaging with ^{60}Co has been performed for basic medical physics studies [5, 6].

In this work we are concentrating on the isotopes of Cobalt nuclei to study about the energy of the gamma particle emitted (E_γ), since it provides precession information on the structural and dynamics of the nuclei considered. In stable nuclei, large gaps exist between nuclear shells of magic proton or neutron number. These gaps found at neutron or proton number equal to 2, 8, 28, 50, 82, and 126 [7], result in large transition energy values between the ground and first excited states, relatively low quadrupole collectivities and small neutron capture cross sections. Due to nuclear structure effects the value of magic number is not preserved but evolve for unstable nuclei.

Since the nuclei in excited state will be hot rotating due to higher agitation of nucleons (higher internal excitation), a temperature of optimum value is included in the suitable statistical model and the excited levels are calculated. From these energies the E_γ values are obtained [8] and is used for calculating decay time and deformation.

The lifetime of an excited state decaying by γ-ray emission is determined by the transition energy, its multipolarity and the transition matrix elements. Nuclear gamma transitions belong to the large class of electromagnetic transitions. In gamma decay, nucleus changes from a higher energy state to a lower energy state through the emission of electromagnetic radiations. In fact, the properties of first excited states and associated quadrupole deformation parameter are very important in nuclear structure physics and are the main focusing objectives in studying the transition probability.

2. Mathematical Formalism

In order to get the values of mean life of γ-particle, τ_γ, and the quadrupole deformation, β, we have calculated the E_γ values from the values of ground state and first excited state, through the statistical model calculations [9-11]. In even-even nuclei the ground state is a 0^+ state and the first excited state is taken as 2^+ state, but in this work we have taken the medically important radioactive nuclei of odd Z system, Cobalt, of atomic number 27, and hence the first excited state $(5/2)^+$ and the ground state $(1/2)^+$ are considered for odd A systems and the 0^+ and 2^+ states are considered for even A isotopes.

A lot of literatures are available for the mean life of γ-particle in the decay process. Hasen and Sayeed [12] and Jabbar and Obeed [13] studied the γ-transition energy of ^{22}F and ^{92}Nb & ^{92}Mo isotopes respectively. The energy levels of ^{130}Ba isotopes were calculated by Al-Slami *et al*., [14] using IBM-1. Moghadasi [15] calculated the γ-transition between the ground state and the excited states in the ^{5}He (p, γ) ^{6}Li radiation capture reaction with the Woods-Saxon and M3Y potentials.

Minkov and Palffy [16] predicted the transition probabilities for the radiative decay of the ^{229}Th to the ground state within a detailed nuclear-structure model approach. A reference data for the E2 transition of even-even nuclei can be obtained from the studies of Raman *et al*., [17], and Pritychenko *et al*., [18].

The statistical model approach has been employed in the calculations of thermonuclear reaction rates for astrophysical purposes by many researchers [19, 20]. A high level density in the compound nucleus at the appropriate excitation energy allows to make use of the statistical model approach for compound nuclear reactions [21, 22]. Most statistical model calculations use the back-shifted Fermi-gas description [23]. The statistical quantities like level density parameter, nuclear level density, nuclear temperature for shell effect, etc. [24] play important roles in the nuclear structure and nuclear reactions. All these quantities are extracted here for the isotopes of Cobalt (N=23-43).

The statistical theory of hot rotating nucleus [25, 26] can be obtained from the grand canonical partition function Q(α, β, γ) of a deformed nuclear system of N neutrons and Z protons as[27,28],

$$\ln Q = \Sigma_i \ln\left[1+\exp(\alpha_N + \gamma m_i^N - \beta\varepsilon_i^N)\right] + \Sigma_i \ln\left[1+\exp(\alpha_Z + \gamma m_i^Z - \beta\varepsilon_i^Z)\right] \quad (1)$$

The Lagrangian multipliers α, β and γ conserve the particle number (N), total energy (E) and angular momentum (M) through the saddle point of the system [29] for T = 1/ β, and which are projected out of the partition function by the equations.

$$-\frac{\partial \ln Q}{\partial \beta} = \langle E \rangle ;\ \frac{\partial \ln Q}{\partial \alpha N} = \langle N \rangle ;\ \frac{\partial \ln Q}{\partial \alpha Z} = \langle Z \rangle ;\ \frac{\partial \ln Q}{\partial \gamma} = \langle M \rangle \quad (2)$$

The Lagrangian multiplier γ plays the same role as the rotational frequency as in the cranking term ω. J_Z. The pair breaking term γ-m_j is temperature dependent and will generate the required angular momentum. The temperature effect creates particle hole excitation. The total excitation energy $E^*(M, T)$ is obtained using,

$$E^*(M, T) = E(M, T) - E_0 \quad (3)$$

Where, $E(M, T)$ is the total energy and E_0 is the ground state energy.

Under the Statistical assumption, by relating E^* and the entropy 'S', nuclear level density parameter (LDP) 'a', can be determined as a function of M and T [9-11] as,

$$a(M,T) = S^2(M,T)/4E^*(M,T) \quad (4)$$

The NLD for different E^*, and M, can be written as,

$$\rho(E^*, M) = \frac{1}{12\sqrt{2\sigma}} \frac{\exp\left(2\sqrt{aE^*}\right)}{a^{1/4} E^{*5/4}} \quad (5)$$

Where the spin cut-off parameter 'σ' can be written as [23],

$$\sigma = 0.0888 \text{ at } A^{2/3} \quad (6)$$

Accurate knowledge of the properties of first excited states and associated quadrupole deformation parameter are necessary for continuing development of nuclear model calculations and theoretical understanding of many interesting phenomena in nuclear physics. Since the nuclei in excited state will be hot rotating due to higher agitation of nucleons (higher internal excitation), the temperature effects are included in the suitable statistical model and the excited levels are calculated for T=0.5MeV, which is taken as the optimum temperature.

The mean life time for a γ-transition is calculated by following the equation of Bohr & Mottelson[30], incorporating E_γ and the nucleon numbers, as,

$$\tau_\gamma = (1.59 \pm 0.28) * 10^{14} E_\gamma^{-4} Z^{-2} A^{2/3} \quad (7)$$

The nucleus is assumed to be spheroidal shape and the corresponding quadrupole deformation β is obtained from the equation by Raman *et al*. [31] as,

$$\beta = 466\, E_\gamma^{-0.5} A^{-1} \quad (8)$$

The E_γ values are obtained from the excitation energy E* calculated at different angular momentum. Thus obtained E_γ values are used to calculate τ_γ and β for the isotopes of Cobalt.

3. Results and Discussion

From the droplet model formula [32, 33], the binding energy can be written as,

$$E(A, Z) = \left(-\alpha_1 + J\bar{\delta}^2 - \frac{1}{2}K\bar{\epsilon}^2 + \frac{1}{2}M\bar{\delta}^4\right)A$$

$$+(\alpha_2 + \frac{9}{4}\frac{J^2}{Q}\bar{\delta}^2)A^{\frac{2}{3}}B_s + \alpha_3 A^{\frac{1}{3}}B_k + c_1 Z^2 A^{-\frac{1}{3}}B_c - c_2 Z^2 A^{\frac{1}{3}}B_{red} - c_3 Z^2 A^{-1} - c_4 Z^{\frac{4}{3}}A^{-\frac{1}{3}} - c_5 Z^2 B_2 + E_{shell} + E_{pair} \quad (9)$$

The mean binding energies are calculated using the parameter values of Moller *et al.*, [34] with r_o = 1.6 fm, α_1 = 16.279 MeV, α_2 = 23 MeV, Q = 29.4 MeV, and J = 32.5 MeV. The binding energy for Co isotopes shows ^{61}Co (Figure 1) are having maximum BE/Aand which supports the claim of stable neutron number N=34. The BE/A of the neighbouring isotopes of ^{61}Co is comparatively less and the isotopes with neutron number N±1 are low, which supports the claim of exotic magic neutron number N=34 [8, 35].

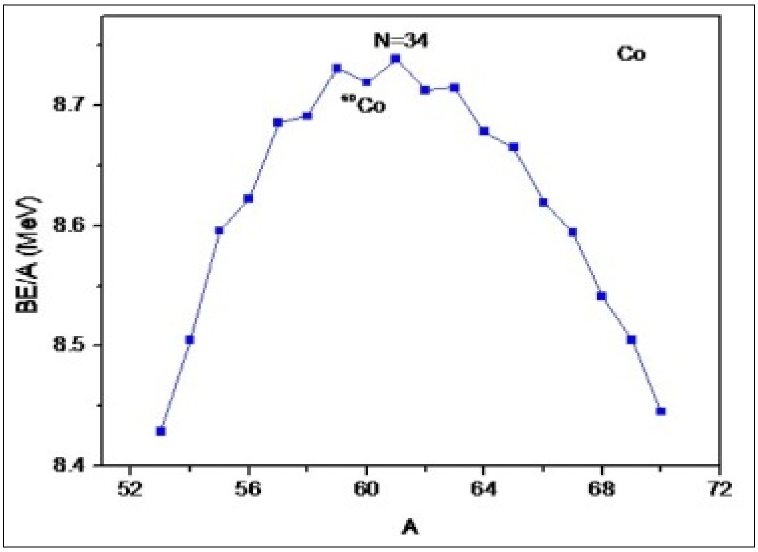

Fig 1: Binding energy per nucleon (BE/A) of Cobalt isotope

The lowest value of Eγ obtained at A=61 (Figure 2) shows a strong shell gap at N=34, which resembles new exotic neutron magic number N= 34 [35], as what reported for Ca nucleus [8]. Usually the neighboring isotope to a magic nuclei will be more radioactive since it is less than or more by only one neutron and hence the isotope with N=33 will be highly radioactive and hence ^{60}Co will be used as radioisotope, which is a neighbor to the exotic magic neutron number isotope ^{61}Co. Since the life time is closely associated with the shape degrees of freedom, i.e., larger the half-life, shape of the nucleus would be nearly spherical. The quadrupole deformation 'β' calculated from the Eγ value (eqn-8) shows the isotopes of Co are having a spheroidal shape with the deformation of 0.1 to 0.2, (Figure 3), which lies within the limit of normal deformation of the nucleus (δ=0.2). A very small deformation, close to spherical shape, is obtained for ^{61}Co(N=34) compared to other isotopes of Cobalt, which indicates the stable nature of ^{61}Co, than the other isotopes. In determining the quadrupole deformation parameter using the formula of Raman *et al.*, [31], it is observed from Figure 3 that the deformation of the N=34 system (^{61}Co) is δ≈0.09, and the N=33 system(^{60}Co) is highly deformed (δ≈0.12).

Fig.4 shows the τ_γ plot obtained from the eqn.7 [30], and is found that at the neutron magic number N=34, the lifetime of ^{61}Co(N=34) is very high compared to the neighboring isotopes and which has the least E_γ value (Figure 2).

Such an effect is obtained since the isotope very close to magic number are more unstable, because, the excess or less neutron tries to either exit or change to one proton by emitting a β-particle. This is what exactly being happened in decay of ^{60}Co, that it decays a β-particle and emitting gamma ray. Since the isotope which is neighbor to a magic or quasi-magic neutron number will be radioactive, the neutron number, N ± 1 to ^{61}Co will be a radioactive one, and so, ^{60}Co or ^{62}Co may be the radioactive nuclei. It is known that ^{60}Co is an important isotope in the field of oncology.

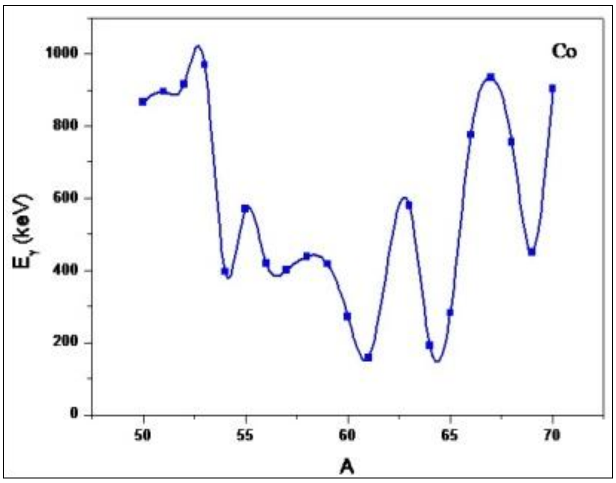

Fig 2: E_γ values of isotopes of 'Co', A=50-70

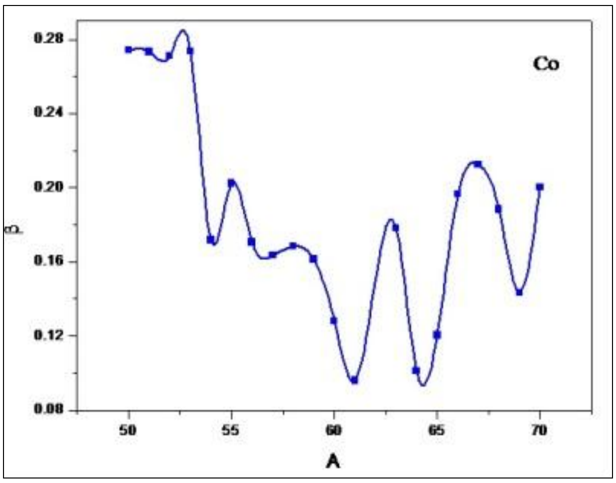

Fig 3: Quadrupole deformation of Cobalt

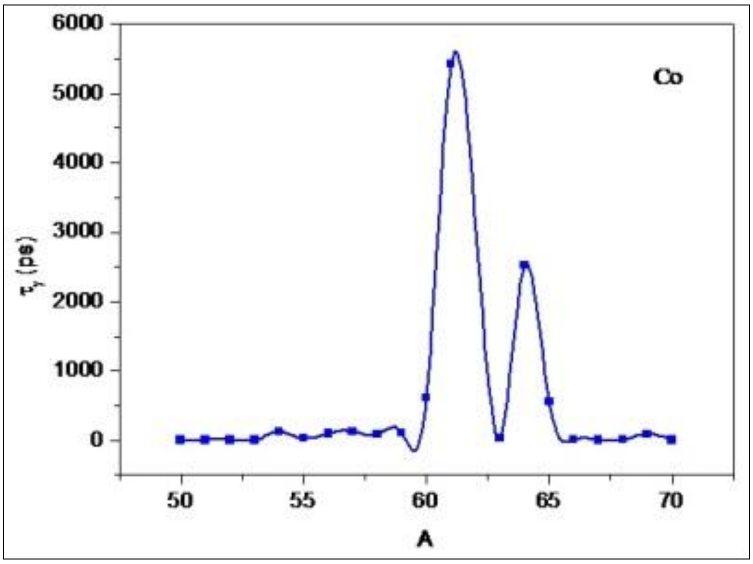

Fig 4: γ-transition energy of Co-isotopes

For better understanding of the interplay between different parameters, ie., Eγ, β and LDP, obtained from our statistical model calculations through the formula [9-11], $a=S^2/4E^*$, which is obtained from the nuclear level density (eqn.5), the figures of E_γ and τ_γ (Figure 5), E_γ and 'a' (Fig.6), and E_γ and β (Figure 7) are plotted.

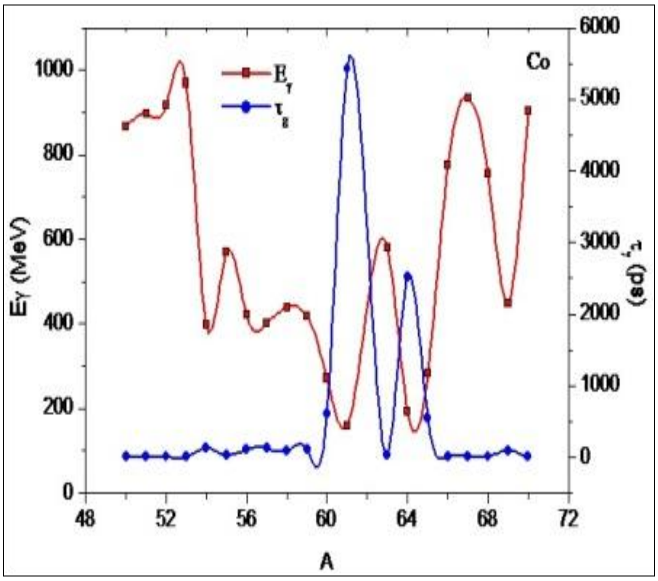

Fig 5: Lifetime of 'Co', and E_γ of Co isotopes

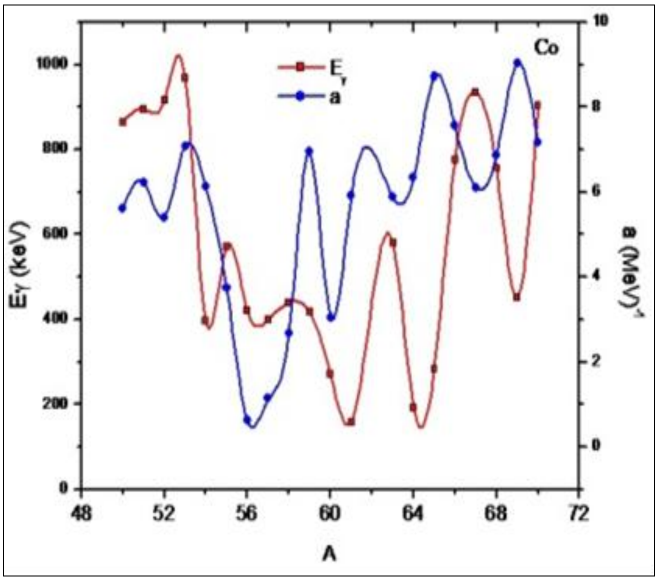

Fig 6: E_γ and LDP of Co isotopes

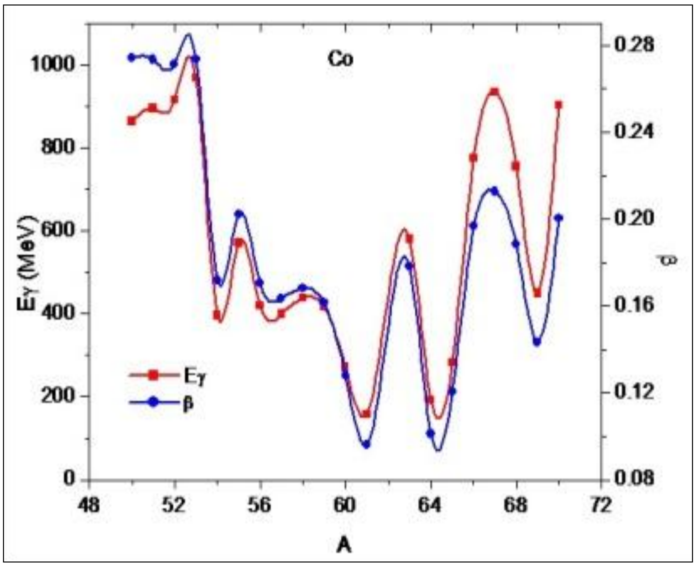

Fig 7: Quadrupole deformation and E_γ of Cobalt

From Figure 5, the τ_γ value for the isotopes $^{50-59}$Co and $^{66-70}$Co are very low and which may have a very short decay time and hence the feasibility of existence of these isotopes is very less. The isotopes $^{60-64}$Co are having considerable decay time except ^{63}Co, which is 2n excess than the N=34 isotope and ^{61}Co has the highest γ-decay time of ≈5400ps whereas ^{64}Co has τ_γ≈2500ps; while the E_γ value is low for ^{61}Co and ^{63}Co which can be understood that the energy of the γ-particle emitted is high if the decay time is low, ie., high energy particles decay very fast.

Interconnecting the LDP with the γ-particle energy the interplay between Eγ and LDP plotted in (Figure 6), shows a nearly similar trend of both Eγ and a, but with the effect of difference evolved is, ±1n^{o} to both the quantities.

But the β-value obtained for the isotopes of Co, ie., for $^{50-70}$Co, the E_γ value matches very well with the trend of quadrupole deformation 'β', which convolute the link between E_γ and β, since β is a function of inverse square root of E_γ, which needs to be explored in future studies.

4. Summary

In this work the statistical model is employed to study the isotopes of Cobalt. Emphasis is given to the medical radioisotope ^{60}Co., which is a γ-ray source and hence the γ-transition energy of the isotopes (A=50-70), are calculated by considering the ground state to the first excited state energies. A higher BE/A is obtained for N=34 isotope, which reflects the newly discovered exotic magic neutron number. The Eγ and τγ values reveal that the high energy particles decay at a faster rate. The level density parameter from the statistical model calculations closely coincides with the trend of E_γ values, and the low quadrupole deformation describes the low E_γ and vice versa. These studies threw light on the medical isotope ^{60}Co, which is used not only in medical oncology but also used as sterilizer. Further studies may explore the interplay between LDP and quadrupole transitions of isotopes of Cobalt.

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