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α-particle preformation of heavy nuclei using proximity potential

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ABSTRACT

The half lives for α decay have been calculated using four different versions of the proximity potential for the even even isotopes of all known α-emitters. Using the experimental half lives, the preformation probability (P_0) of α particle before emission is calculated. Also the assault frequency (ν_0) is calculated through a modified formula. Half-lives obtained from the potential Prox 76 are minimum, and these values are used for calculating the preformation probability (P_0). Use of the potential Prox 76 in calculating P_0 is justified as it can best reproduce experimental Coulomb barriers among the four potentials. The trend of the values of P_0 versus the neutron number, N, and the proton number, Z, are in agreement with the shell model. The values of P_0 are also fitted using a four-parameter formula.

1. Introduction

Heavy nuclei tend to be unstable because of the Coulomb repulsion of the large number of protons carried by it. As the α-particle is highly stable and tightly bound structure, hence, it becomes the natural choice of these heavy nuclei to get rid of some of its extra positive charges through α decay. α decay was first observed by Becquerel in 1896, and then it was first isolated by Rutherford at McGill University in 1899. In 1908, Rutherford performed spectroscopic studies on α particles and found that it consists of helium (^{4}He) nuclei. In 1911, Geiger and Nuttal provided an empirical relationship connecting the half life and the energy of the α particles. α decay studies have been reliably used for providing valuable information about the ground state half life, ground state energy, nuclear spin and parity, shell effects and also the nuclear interaction [1–4]. On the experimental side, studies on α decay chains have been successfully used for the prediction of unknown superheavy nuclei (SHE) [5–8].

The explanation of α decay remained a puzzle for many years until the development of quantum mechanics during the late 1920s. In 1928, α decay was independently explained by Gamow [9], and by Condon and Gurney [10] as a quantum tunnelling process. The α decay constant (λ) is expressed as the product of three terms [11],

$$\lambda = P_0 \nu_0 P \tag{1}$$

Here, P_0 is the preformation probability of the α-particle inside the nucleus, ν_0 is the assault frequency of the α-particle at the barrier, and P is the probability of penetration of the α particle through the potential barrier. Technically speaking, the

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preformation probability of the α particle is defined as the probability of formation of the α particle as a separate cluster inside the nucleus before the emission process. Hence, the range of values should be, $0 < P_0 \leq 1$, and some authors even prefer to take the value of unity for explanation of α decay. It turns out that the exact calculation of P_0 within a microscopic model is extremely difficult because of complexities involved in treating a nuclear many body problem. In the early eighties, the phenomenon of cluster radioactivity was discovered in which nuclei heavier than the α particle are emitted during the decay process [12]. Emission of ^{14}C from $^{222,\,223,\,224,\,226}$Ra and ^{24}Ne from ^{231}Pa and ^{232}U are well known [12–17]. The explanation of cluster radioactivity can be done in a similar manner as α decay. However, it turns out that the preformation probability of the cluster should be several orders of magnitude smaller than unity [18–20]. Blendowske and Wallister had studied the mass dependence of the cluster preformation probability (P_c) and had even proposed a phenomenological formula, $P_c = [P_\alpha]^{(A-1)/3}$, for $A \leq 28$, where, P_α is the α preformation probability and A is the mass number of the cluster [21]. Hence, after the successful explanation of cluster radioactivity, it became clear that the explanation of α decay cannot be complete without the introduction of realistic values of the preformation probability, P_0.

Gupta and collaborators have employed their preformed cluster model (PCM) for direct calculation of P_0 for clusters by directly solving the Schrodinger equation for dynamical flow of mass and charge [18–20]. The method can also be employed for determination of P_0 for α particles. Varga et al. [22,23] developed a cluster configuration shell model or hybrid model and carried out a detailed calculation of P_0 for α particle inside the nucleus, ^{212}Po, and found its value to be 0.23. Ahmed et al. have developed a cluster formation model (CFM) in which the clusterization of an α particle inside the parent nucleus is considered to be a quantum mechanical cluster formation state [24]. Using this model the preformation probability for a number of even-even isotopes have been calculated, and later Deng et al. extended the model for the calculation of preformation probability of odd-odd and odd-A isotopes as well [25,26]. Zhang *et al.* have also provided a phenomenological formula for the α preformation probability [27]. Another alternate approach is to make an indirect calculation of P_0 by using the experimental values of the half-life of α decay. In this method the barrier penetrability (P) and the assault frequency (ν_0) are theoretically determined using appropriate models. By application of the above method, Zhang and Royer have determined the preformation probabilities for a number of even-even isotopes by using the generalized liquid drop model (GLDM) for direct calculation of the penetrability, P [11]. All the above results show that the preformation probability of the α particle is most likely to be of the order of 0.1, with slight variation from nuclei to nuclei. However, accuracy and consistency of results are lacking. The variation of preformation probability (P_0) and half-life (T_α) around the magic numbers, $Z = 82$ and $N = 126$, have also been studied by a few authors [25,28].

In this work we consider the alternate approach and present indirect calculations of the preformation probability of the α particle inside heavy nuclei. The nuclei considered are the even-even isotopes of all known α-emitters, starting from ^{144}Nd upto the super-heavy element ^{292}116. The penetration probability (P) is determined using four different versions of the proximity potential (Prox 81, Prox 77, Prox 88 and Prox 76), and the assault frequency (ν_0) is calculated using an improved formula. Various versions of the proximity potential have been used by a number of authors for the study of fusion barriers and fusion cross section [29–31]. K. P. Santosh *et al.* had used the potential Prox 81 for the study of α-decay of nuclei in the range $67 \leq Z \leq 91$ [32], as well as in the super-heavy region ($^{271-294}$115, $^{293,\,294}$117, and $^{272-319}$120) [33–35].

2. Formalism

The half-life for α decay is given by,

$$T_\alpha^{expt} = \frac{ln(2)}{\lambda} = \frac{ln(2)}{P_0 \nu_0 P} \tag{2}$$

Hence, the preformation probability (P_0) is given by,

$$P_0 = \frac{T_\alpha^{theo}}{T_\alpha^{expt}} \tag{3}$$

where,

$$T_\alpha^{theo} = \frac{ln(2)}{\nu_0 P} \tag{4}$$

For calculating the barrier penetrability (P) the WKB approximation is used and is given by,

$$P = exp\left(-\frac{2}{\hbar} \int_a^b \sqrt{2\mu(V-Q)}dr \right) \tag{5}$$

Here, μ and V are the reduced mass and the interacting potential between the α-particle and the residual nucleus, respectively, and Q is the Q value of the disintegration process. The turning points a and b are determined from the equation, $V(a) = V(b) = Q$. The interaction potential between the two nuclei can be written as the sum of nuclear, Coulomb and centrifugal potentials. Hence,

$$V = V_C(r) + V_N(r) + \frac{\hbar^2 l(l+1)}{2\mu r^2} \tag{6}$$