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Effect of parent and daughter deformation on half-life time in exotic decay

K P SANTHOSH[1] and ANTONY JOSEPH[2,*]
[1]Department of Physics, Payyanur College, Payyanur 670 327, India
[2]Department of Physics, Calicut University, Calicut 673 635, India
*Corresponding author: Email: ajvar@rediffmail.com

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Abstract. Taking Coulomb and proximity potential as interacting barrier for post-scission region we calculated half-life time for different modes of exotic decay treating parent and fragments as spheres and these values are compared with experimental data. We studied the effect of deformation of parent and daughter on half-life time treating emitted cluster as spherical. When deformations are included half-life time values are found to decrease, though slightly. It is found that parent deformation alone will not produce appreciable change in half-life time since it affects relatively small pre-scission part of the barrier.

Keywords. Exotic decay; deformation.

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1. Introduction

Exotic decay, the spontaneous emission of particle heavier than alpha particle was first predicted by Sandulescu *et al* [1] in 1980 on the basis of quantum mechanical fragmentation theory (QMFT) [2]. Experimental observation of exotic decay has first reported by Rose and Jones [3] in ^{14}C emission from ^{223}Ra. This phenomenon can be treated as a strong asymmetric fission [4] or an exotic process of cluster formation and tunneling through the barrier making many assaults on the barrier similar to alpha decay [5].

Shi and Swiatecki [6] put forward a model for exotic decay studies that uses Coulomb and proximity potential as interacting barrier for post-scission region and uses simple power law for overlap region. These authors [7] studied the effect of deformation of parent, daughter and shell attenuation on half-life time treating emitted cluster as spherical. Pik Pichak [8] studied the effect of ground state deformation of parent and daughter on life time treating emitted cluster as spherical. In their model finite range effect or proximity effect were not considered.

Malik and Gupta [9] put forward preformed cluster model (PCM), which uses Coulomb and proximity potential as interacting barrier for separated fragments. These authors use ‘pocket formula’ of Blocki *et al* [10] for proximity potential. Kumar and Gupta [11] studied the effect of deformation of cluster and daughter nuclei and also the role of neck formation in overlap region.

Shanmugam and Kamalaharan [12] put forward cubic plus Yukawa plus exponential model (CYEM) which uses Coulomb and Yukawa plus exponential potential as interacting barrier for separated fragments and cubic potential for the overlap region. These authors studied [13] the role of deformation of parent and daughter nuclei on half-life time.

Taking interacting potential as the sum of Coulomb and proximity potential of Blocki and Swiatecki [14] we calculated half-life time for ^{12}C emission from various Ba isotopes [15] treating parent and fragments as spheres. In the present paper we improved our model incorporating ground state deformation of both parent and daughter treating emitted cluster as sphere.

2. Details of the model

In the present model the emitted cluster is assumed to be spherical but the parent and daughter nuclei may have axially symmetric deformation. The potential energy barrier will depend on the polar angle θ between the axis of symmetry of the parent or daughter and the direction of emitted cluster.

The potential energy barrier for touching and separated configuration is given by

$$V = V_{\mathrm{C}}(r) + V_{\mathrm{p}}(z), \quad z > 0. \tag{1}$$

Here V_{C} is the Coulomb potential between the spheroidal daughter and spherical emitted cluster, V_{p} the proximity potential, r the distance between the fragment centers and z the distance between the near surface of the fragments.

The empirical formula for effective sharp radii R_i in terms of mass number A_i is given as [10]

$$R_i = 1.28A_i^{1/3} - 0.76 + 0.8A_i^{-1/3}. \tag{2}$$

If the nuclei have spheroidal shape, the radius vector $R_i(\theta)$ making an angle θ with the axis of symmetry locating sharp surface of deformed nuclei is given by [16]

$$R_i(\theta) = R_i\left[1 + \sum_{n=0}^{\infty}\sum_{m=-n}^{n}\beta_{nm}Y_{nm}(\theta)\right]. \tag{3}$$

If we consider spheroidal deformation β_2 then

$$R_i(\theta) = R_i\left[1 + \beta_2\left(\frac{5}{4\pi}\right)^{1/2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right)\right] \tag{4}$$

and if Nilssion hexadecapole deformation β_4 is also included in the deformation then eq. (4) becomes

$$R_i(\theta) = R_i\left[1 + \beta_2\left(\frac{5}{4\pi}\right)^{1/2}\left(\frac{3}{2}\cos^2\theta - \frac{1}{2}\right) + \beta_4\left(\frac{9}{4\pi}\right)^{1/2}\frac{1}{8}(35\cos^4\theta - 30\cos^2\theta + 3)\right]. \tag{5}$$

The central Siissmann radius vector $C_i(\theta)$ specifying the parent and daughter surfaces related to $R_i(\theta)$ as [7]

$$C_i(\theta) = R_i(\theta) - \frac{1}{2}kb^2 \tag{6}$$

where k is the total curvature of the surface at the point in consideration and $b \approx 1$ is the width (diffuseness) of the nuclear surface. The Siissmann central radius C_2 of the emitted cluster is

$$C_2 = R_2 - \frac{b^2}{R_2}. \tag{7}$$

The Coulomb potential between spherical emitted cluster and spheroidal daughter nucleus is given by $V_\mathrm{C} = \frac{Z_1 Z_2 e^2}{r}$. Here Z_1 and Z_2 are the atomic numbers of daughter and emitted cluster and $r = z + C_1(\theta) + C_2$ is the distance between the fragment centers. The proximity potential V_p is given by [10]

$$V_\mathrm{p}(z) = 4\pi\gamma b \frac{C_1(\theta)C_2}{C_1(\theta)+C_2}\phi\left(\frac{z}{b}\right). \tag{8}$$

With nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N-Z)^2/A^2] \quad \mathrm{MeV/fm^2} \tag{9}$$

and ϕ, the universal proximity potential is given as [14]

$$\phi(\varepsilon) = -4.41\mathrm{e}^{-\varepsilon/0.7176}, \quad \text{for } \varepsilon \geq 1.9475 \tag{10}$$

$$\phi(\varepsilon) = -1.7817 + 0.9270\varepsilon + 0.1696\varepsilon^2 - 0.05148\varepsilon^3, \quad \text{for } 0 \leq \varepsilon \leq 1.9475. \tag{11}$$

For touching configuration $\phi(0) = -1.7817$ where $\varepsilon = z/b$ and the barrier penetrability is given as

$$P = \exp\left(-\frac{2}{\hbar}\int_{\varepsilon_i}^{\varepsilon_f}\sqrt{2\mu(V-Q)}\,\mathrm{d}z\right). \tag{12}$$

Here ε_i and ε_f are defined as $V(\varepsilon_i) = V(\varepsilon_f) = Q$, where Q is the energy released. The mass parameter is replaced by reduced mass $\mu = mA_1A_2/A$, where m is the nucleon mass. The half-life time is given by

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{\ln 2}{\nu P} \tag{13}$$

where $\nu = \varpi/2\pi = 2E_\mathrm{v}/h$ represents the number of assaults on the barrier per second and λ the decay constant. E_v, the empirical zero point vibration energy is given as [4]

$$E_\mathrm{v} = Q\{0.056 + 0.039\exp[(4-A_2)/2.5]\} \quad \text{for } A_2 \geq 4. \tag{14}$$

3. Result and discussion

We have done our calculation taking potential barrier consisting of Coulomb and proximity potential for the post-scission region. For the pre-scission (overlap) region we use simple power law interpolation as done by Shi and Swiatecki [6]. We studied the effect of deformation of parent and daughter on half-life time treating emitted cluster as spherical. In table 1 (a) gives half-life time treating parent and fragments as spherical, i.e., without considering deformation, (b) gives that when considering both parent and daughter deformation, (c) gives that when daughter deformation alone is considered and (d) gives that when parent deformation alone is considered. The calculated half-life time values are compared with experimental data [17].

When deformation effects are included half-life time value is found to decrease even though it is very small. When logarithm of predicted half-life time treating parent and fragments as spherical are compared with that for deformed parent and daughter it is found that deviation (change) in half-life time value increases with increase in mass of the parent and the cluster. When deformation of parent alone is taken, there is appreciably no deviation in half-life time value. This is because parent deformation affect relatively small

Table 1. Comparison of calculated values of logarithm of half-life time for the case with out deformation (a), with parent and daughter deformation (b), with daughter deformation (c) and with parent deformation (d) with experimental values. The deformation β_2 and β_4 are taken from [18].

Parent nuclei	Daughter nuclei	Emitted cluster	Q value (MeV)	Deformation: Parent β_2	Deformation: Parent β_4	Deformation: Daughter β_2	$\log_{10}(T_{1/2})$ (a)	(b)	(c)	(d)	Expt.
^{221}Fr	^{207}Tl	^{14}C	31.28	0.098	−0.060	0.003	13.90	13.73	13.79	13.85	14.52
^{221}Ra	^{207}Pb		32.39	0.098	−0.060	0.003	12.58	12.41	12.46	12.52	13.39
^{222}Ra	^{208}Pb		33.05	0.104	−0.060	0.003	11.07	10.90	10.96	11.01	11.01
^{223}Ra	^{209}Pb		31.85	0.138	−0.075	0.003	13.69	13.45	13.58	13.56	15.04
^{224}Ra	^{210}Pb		30.53	0.144	−0.075	0.003	16.74	16.45	16.62	16.55	15.68
^{225}Ac	^{211}Bi		30.48	0.151	−0.080	0.003	18.03	17.72	17.92	17.83	17.16
^{226}Ra	^{212}Pb		28.21	0.151	−0.080	0.003	22.55	22.21	22.44	22.31	21.34
^{230}Th	^{206}Hg	^{24}Ne	57.78	0.185	−0.075	−0.003	26.00	25.34	26.19	25.17	24.61
^{231}Pa	^{207}Tl		60.42	0.185	−0.080	0.003	22.56	21.70	22.36	21.87	22.88
^{232}U	^{208}Pb		62.31	0.192	−0.080	0.003	20.72	19.83	20.52	20.01	20.40
^{233}U	^{209}Pb		60.50	0.192	−0.080	0.003	24.15	23.16	23.95	23.34	24.84
^{234}U	^{210}Pb		58.84	0.198	−0.075	0.003	27.39	26.16	27.20	26.33	25.92
^{232}Th	^{206}Hg	^{26}Ne	55.97	0.192	−0.070	−0.003	29.54	28.81	29.74	28.63	>29.20
^{234}U	^{208}Pb		59.47	0.196	−0.075	0.003	25.88	24.87	25.67	25.05	25.88
^{234}U	^{206}Hg	^{28}Mg	74.13	0.198	−0.075	−0.003	27.55	26.47	27.78	26.27	27.54
^{238}Pu	^{210}Pb		75.93	0.205	−0.060	0.003	28.31	26.32	28.07	26.58	25.70
^{237}Np	^{207}Tl	^{30}Mg	75.02	0.198	−0.070	0.003	27.34	25.92	27.09	26.14	>26.90
^{238}Pu	^{208}Pb		77.03	0.025	−0.060	0.003	25.70	24.07	25.45	24.29	25.70
^{238}Pu	^{206}Hg	^{32}Si	91.21	0.205	−0.060	−0.003	28.65	26.82	28.94	26.58	25.27
^{241}Am	^{207}Tl	^{34}Si	93.84	0.212	−0.050	0.003	25.40	23.16	25.10	23.41	>25.30

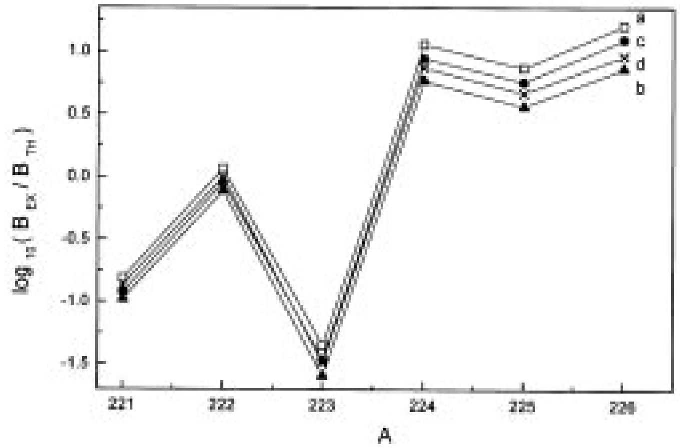

Figure 1. Plot of $\log_{10}(B_{ex}/B_{th})$ vs. A for ^{14}C emission from various parents.

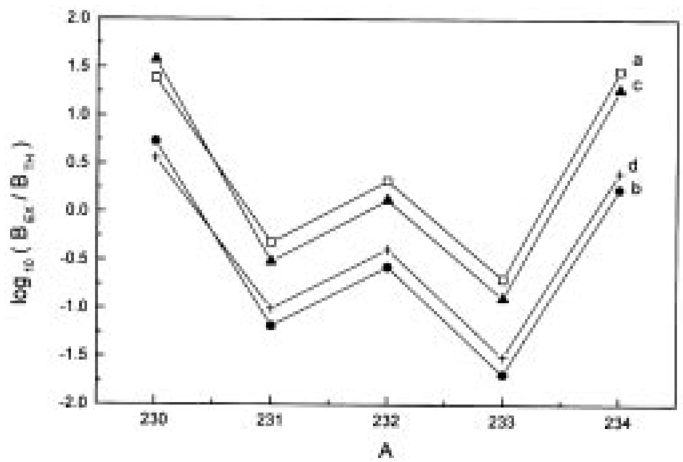

Figure 2. Plot of $\log_{10}(B_{ex}/B_{th})$ vs. A for ^{24}Ne emission from various parents.

pre-scission part of the barrier but it will not effect the barrier corresponding to separated fragments. In asymmetric disintegration most of the barrier corresponds to separated fragments.

The branching ratio of exotic decay with respect to alpha decay is given by

$$B = \frac{\lambda_{\text{cluster}}}{\lambda_{\text{alpha}}} = \frac{T_{1/2}^{\text{alpha}}}{T_{1/2}^{\text{cluster}}}. \tag{15}$$

The experimental half-life time for respective alpha decay $T_{1/2}^{\text{alpha}}$ are taken from [19].

Figures 1 and 2 give plot for the logarithm of the ratio of experimental branching ratio to calculated (theoretical) branching ratio, $\log_{10}(B_{ex}/B_{th})$ vs. A, the mass number of the parent for ^{14}C emission and ^{24}Ne emission respectively. Here (a) represents plot for the case without considering deformation, (b) for the case of parent and daughter deformation, (c) for the case of daughter deformation and (d) for the case of parent deformation respectively.

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