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Exotic decay in Ba isotopes via ^{12}C emission

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Abstract. Considering Coulomb and proximity potentials as barriers, we have calculated the half lives for ^{12}C emission from various Ba isotopes using different mass tables. The half life for ^{112}Ba isotope calculated by us is 6.020×10^3 s which is comparable with the experimental value 5.620×10^3 s. From our study it is found that ^{114}Ba is the good parent for ^{12}C emission whose emission rate is favorable for measurement. The half lives predicted by us lie very close to those reported by Shanmugam *et al* using their cubic plus Yukawa plus exponential model. It is observed that inclusion of proximity potential does not produce significant deviation from the linear nature of the Geiger–Nuttall plots. Also it is found that the neutron excess in the parent nuclei slows down the exotic decay process.

Keyword. Exotic decay.

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1. Introduction

The spontaneous emission of fragments heavier than alpha particle termed as exotic decay was first predicted by Sandulescu, Poenaru and Greiner in 1980 [1] and the first experimental observation of this phenomenon was made by Rose and Jones in 1984 [2]. Based on analytical super asymmetric fission model, Poenaru *et al* [3] predicted a new region of proton rich parent nuclei with $Z = 56$–64 and $N = 56$–72 which decay exotically. This region is very interesting because the daughter nuclei in such decays are formed around doubly magic ^{100}Sn and the estimated half life time for such decays are favorable for measurement.

The exotic decay of Ba isotope $(Z = 56)$ was first experimentally observed by Oganessian *et al* [4] at Dubna, Russia and later by Guglielmetti *et al* [5,6] at GSI, Darmstadt, Germany. The experimental half life time for ^{12}C decay from ^{112}Ba is 5.620×10^3 s and that from ^{114}Ba is 1.70×10^4 s, but ^{114}Ba is the best parent for exotic decay with highest emission rate since ^{112}Ba is short lived and decays by two proton emission.

In this paper we studied the exotic decay of various Ba isotopes via ^{12}C emission. We have made our calculations considering the potential energy barrier as the sum of Coulomb and proximity potential of Blocki *et al* [7,8] (described in §2). The half life values presented in this paper are well within the present experimental limit of measurements. The results, discussion and conclusion are given in §3.

2. Calculations

The interacting potential barrier for a parent nucleus exhibiting exotic decay is given by

$$V = Z_1 Z_2 \mathrm{e}^2/r + V_p(z) \quad \text{for} \quad z > 0. \tag{1}$$

Here Z_1 and Z_2 are atomic numbers of daughter and emitted cluster, r is the distance between the fragment centers and z is the distance between the near surface of the fragments and V_p is the proximity potential given by [7]

$$V_p(z) = 4\pi\gamma b[C_1 C_2/(C_1 + C_2)]\phi(z/b), \tag{2}$$

with nuclear surface tension coefficient,

$$\gamma = 0.9517[1 - 1.7826(N - Z)^2/A^2]\,\mathrm{MeV/fm}^2. \tag{3}$$

ϕ, the universal proximity potential is given as [8]

$$\phi(\varepsilon) = -4.41\mathrm{e}^{-\varepsilon/0.7176} \quad \text{for} \quad \varepsilon \geq 1.9475, \tag{4}$$

$$\begin{aligned}\phi(\varepsilon) = {} & -1.7817 + 0.9270\varepsilon + 0.01696\varepsilon^2 \\ & -0.05148\varepsilon^3 \quad \text{for} \quad 0 \leq \varepsilon \leq 1.9475,\end{aligned} \tag{5}$$

with $\varepsilon = z/b$ where the width (diffuseness) of the nuclear surface $b \approx 1$ and Siissmann central radii C_i of fragments related to sharp radii R_i is $C_i \approx R_i - b/R_i$. For R_i we use semi-empirical formula in terms of mass number A_i as [7]

$$R_i = 1.28 A_i^{1/3} - 0.76 + 0.8 A_i^{-1/3}. \tag{6}$$

For the touching configuration $\phi(0) = -1.7817$.

The Gamow factor G is given by

$$G = (2\pi/h)\int_{\varepsilon_0}^{\varepsilon_f} \sqrt{2\mu(V - Q)}\mathrm{d}z. \tag{7}$$

Here h stands for the Planck's constant. The mass parameter is replaced by reduced mass $\mu = mA_1A_2/A$ where m is the nucleon mass. Here $\varepsilon_0 = 2(C - C_1 - C_2)$ and ε_f is defined as $V(\varepsilon_f) = Q$, where Q is the energy released. The above integral can be evaluated numerically or analytically [9].

The barrier penetrability P is expressed as

$$P = \exp(-2G). \tag{8}$$

The half life time is given by

$$T_{1/2} = \ln 2/\lambda = \ln 2/\nu P, \tag{9}$$

where $\nu = \omega/2\pi = 2E_v/h$, represents number of assaults on the barrier per second and λ, the decay constant. E_v, the empirical zero point vibration energy is given as [10]

$$E_v = Q[0.056 + 0.039\exp[(4 - A_2)/2.5]] \quad \text{for} \quad A_2 \geq 4. \tag{10}$$

3. Results, discussion and conclusion

We have made our calculations taking potential energy barrier as the sum of the Coulomb and proximity potential of Blocki *et al* [7,8] from touching configuration onwards. From touching configuration and down to the parent central radius we use simple power law interpolation as done by Shi and Swiatecki [9]. Inclusion of proximity potential reduces the height of the potential barrier which closely agrees with the experimental values. We have not taken into consideration the contribution of potential barrier between touching configuration and parent central radius, which will not affect the barrier penetrability since major part of the barrier corresponds to configuration of separated fragments. Figures 1 and 2 represent the potential energy barrier for alpha particle and ^{12}C emission from ^{120}Ba. For

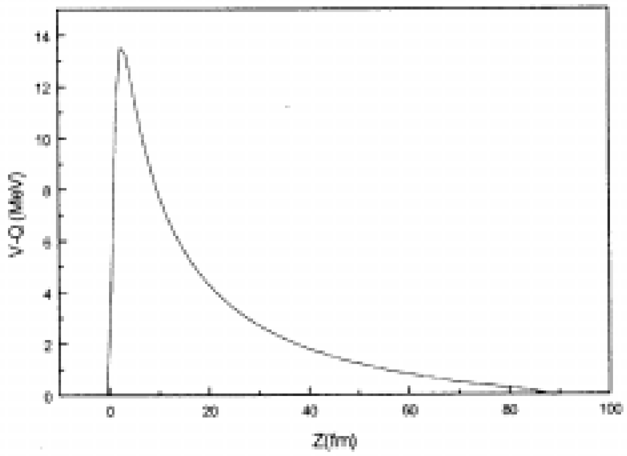

Figure 1. Potential energy barrier for the emission of ^{4}He from ^{120}Ba isotope.

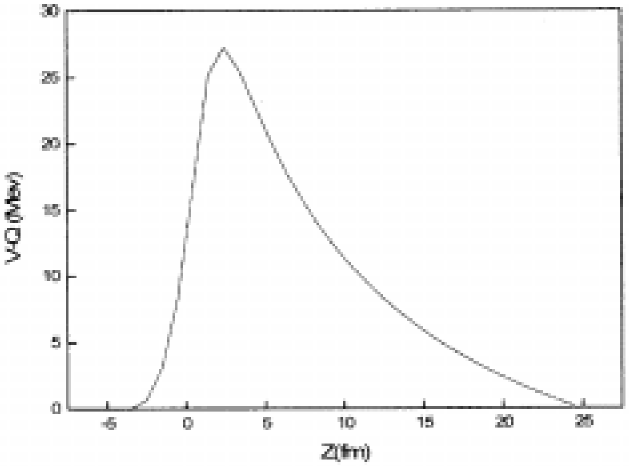

Figure 2. Potential energy barrier for the emission of ^{12}C from ^{120}Ba isotope.

the calculation of the decay constant we simply ignore the contribution of pre-formation probability of emitted cluster since we also agree with Poenaru *et al* [11] that the main contribution to decay constant would come from the barrier penetrability.

Table 1 gives the logarithm of predicted half life time for ^{12}C and ^{4}He emission from various Ba isotopes using different mass tables. For ^{112}Ba, our calculated half life time

Table 1. Logarithm of the predicted half life time and other characteristics of ^{12}C and ^{4}He emission from various Ba isotopes using different mass tables. Q values are taken from ref. [15].

Parent nuclei	Emitted cluster	Daughter nucleus	Q value (MeV)	Penetrability P	Decay constant λ	Calculated $\log_{10}(T_{1/2})$			
						Present	CYEM ref. [12]	ASAFM ref. [3]	PCM ref. [13]
^{112}Ba	^{12}C	^{100}Sn	21.46[f]	1.92605E-25	1.1512E-04	3.78			3.75
^{114}Ba	^{12}C	^{102}Sn	20.20[d]	3.65981E-28	2.0590E-07	6.53			5.12
			18.34[e]	4.17843E-33	2.1343E-12	11.51			9.67
			20.75[a]	8.04016E-27	4.6465E-06	5.17			
			19.97[b]	9.70947E-29	5.4003E-08	7.11			
			18.16[c]	1.27581E-33	6.4527E-13	12.01			
			19.46	4.74124E-30	2.5697E-09	8.43	8.71	9.4	
			18.91	1.61129E-31	8.4861E-11	9.91	10.12	l0.6	
			19.33	2.15768E-30	1.1616E-09	8.78	9.04	9.7	
			19.40	3.29978E-30	1.7829E-09	8.59	8.86	9.5	
			20.12	2.31237E-28	1.2958E-07	6.73	7.09	7.9	
^{115}Ba	^{12}C	^{103}Sn	18.25	3.13608E-33	1.5940E-12	11.64	11.81	13.6	
			17.83	1.88045E-34	9.3380E-14	12.87	12.99	14.7	
			18.27	3.55769E-33	1.8205E-12	11.58	11.75	13.6	
			17.42	1.10089E-35	5.3411E-15	14.11	14.18	15.8	
			18.78	9.63156E-32	5.0377E-11	10.14	10.37	12.3	
^{116}Ba	^{12}C	^{104}Sn	17.63[f]	6.37407E-35	3.1298E-14	13.35			11.31
			17.40	1.27870E-35	6.1967E-15	14.05	14.15	14.4	
			17.00	7.27910E-37	3.4464E-16	15.30	15.35	15.5	
			16.64	5.08267E-38	2.3555E-17	16.47	16.47	16.6	
			17.43	1.57942E-35	7.6672E-15	13.96	14.06	14.3	
			18.95	3.76275E-31	1.9859E-10	9.54	9.84	10.4	
			16.83	2.09188E-37	9.8053E-17	15.85	15.88	16.0	
			17.44	1.69444E-35	8.2302E-15	12.93	14.03	14.3	
^{117}Ba	^{12}C	^{105}Sn	16.08	9.03230E-40	4.0451E-19	18.23	18.21	19.6	
^{118}Ba	^{12}C	^{106}Sn	15.44[f]	6.54238E-42	2.81334E-21	20.39			18.13
			15.10	3.65471E-43	1.5370E-22	21.65	21.54	21.3	
^{119}Ba	^{12}C	^{107}Sn	14.01	2.32280E-47	9.0634E-27	25.88	25.67	26.7	
^{120}Ba	^{12}C	^{108}Sn	13.40[f]	6.95994E-50	2.5975E-29	28.43			32.23
			13.03	1.45772E-51	5.2900E-31	30.18	29.81	29.1	
^{115}Ba	^{4}He	^{111}Xe	2.45	4.66280E-34	5.2485E-14	13.12	12.98	12.6	
^{116}Ba	^{4}He	^{112}Xe	2.32[f]	1.22770E-35	1.3086E-15	14.72			12.83
^{118}Ba	^{4}He	^{114}Xe	1.90[f]	7.14627E-42	6.2381E-22	21.05			18.59
^{119}Ba	^{4}He	^{115}Xe	1.78	4.87877E-44	3.9898E-24	23.24	23.04	22.6	
^{120}Ba	^{4}He	^{116}Xe	1.54[f]	3.75803E-49	2.6589E-29	28.46			26.17
			1.60	9.3112E-48	6.8445E-28	27.01	26.78	26.0	

[a] Masses are taken from refs [a][16], [b][17], [c][18], [d][19], [e][20], [f][21].

$T_{1/2}$ is 6.020 × 10^3 s and $\log_{10}(T_{12})$ is 3.7796 s which are in close agreement with the experimental $T_{1/2} = 5.620 \times 10^3$ s and experimental $\log_{10}(T_{1/2}) = 3.750$ s. In the case of ^{114}Ba the experimental $\log_{10}(T_{1/2}) = 4.23$ s [6] which is also comparable with our value 5.1736 s for $Q = 20.75$ MeV. We have compared our predicted half life times with those reported by Poenaru *et al* [3] using their analytical super asymmetric fission model (ASAFM), Shanmugam *et al* [12] using their cubic plus Yukawa plus exponential model (CYEM) and Satish Kumar *et al* [13] using pre-formed cluster model (PCM) of Malik and Gupta [14]. It is very interesting to point out that our calculated values lie very close to those reported by Shanmugam *et al* [12].

Figures 3 and 4 give Geiger–Nuttall (GN) plots of calculated $\log_{10}(T_{1/2})$ vs $Q^{-1/2}$ for ^{4}He and ^{12}C emission from Ba isotopes. Both plots are straight lines with different slopes

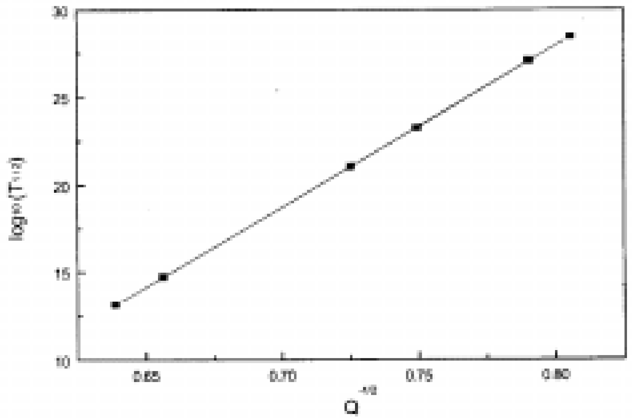

Figure 3. Gieger–Nuttall plot for $\log_{10}(T_{1/2})$ vs $Q^{-1/2}$ for ^{4}He emission from various Ba isotopes.

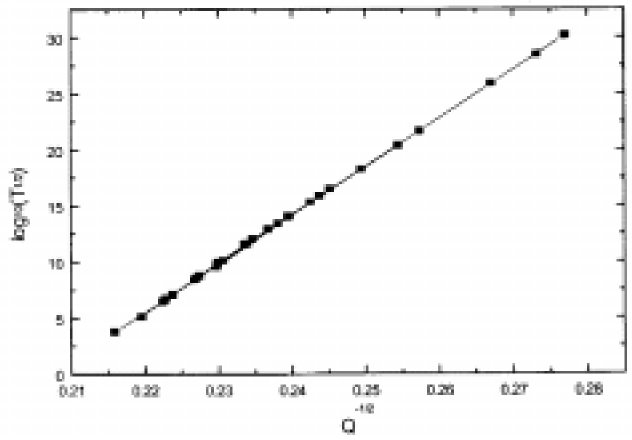

Figure 4. Gieger–Nuttall plot for $\log_{10}(T_{1/2})$ vs $Q^{-1/2}$ for ^{12}C emission from various Ba isotopes.

and intercepts. Figures 5 and 6 give Geiger–Nuttall (GN) plots of calculated $\log_{10}(T_{1/2})$ vs $-\ln P$ for ^{4}He and ^{12}C respectively. These plots are also straight lines with different slopes and intercepts. From GN plots we conclude that the inclusion of proximity potential will not produce much deviation to linear nature of the GN plots. From the observed linear nature of the GN plots, we arrived at an equation for logarithm of half life time as

$$\log_{10}(T_{1/2}) = (X/\sqrt{Q}) + Y. \tag{11}$$

For ^{12}C emission $X = 431.93$, $Y = -89.49$ and for ^{4}He emission $X = 91.62$, $Y = -45.42$.

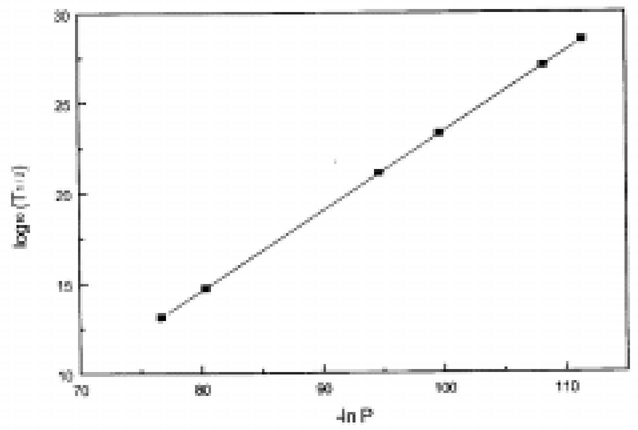

Figure 5. Gieger–Nuttall plot for $\log_{10}(T_{1/2})$ vs $-\ln P$ for ^{4}He emission from various Ba isotopes.

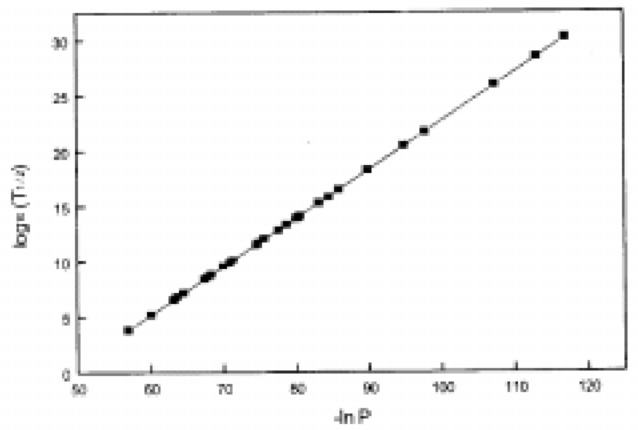

Figure 6. Gieger–Nuttall plot for $\log_{10}(T_{1/2})$ vs $-\ln P$ for ^{12}C emission from various Ba isotopes.

Table 2. Logarithm of predicted half life time for ^{12}C and ^{4}He emission for various Ba isotopes using our equation (11) and their comparison with values from other models. Q values are taken from ref. [15].

Parent nuclei	Emitted cluster	Daughter nuclei	Q value (MeV)	Calculated $\log_{10}(T_{1/2})$				
				Present	Ref. [12]	Ref. [3]	Ref. [13]	Ref. [11]
^{112}Ba	^{12}C	^{100}Sn	21.46[f]	3.75			3.75	
^{114}Ba	^{12}C	^{102}Sn	20.20[d]	6.16			5.12	
			18.34[e]	11.37	11.65	12.10	9.67	
^{115}Ba	^{12}C	^{103}Sn	18.25	11.62	11.81	13.60		
			18.78	10.18	10.37	12.30		
^{116}Ba	^{12}C	^{104}Sn	17.40	14.00	14.15	14.40		
			17.00	15.27	15.35	15.50		
^{117}Ba	^{12}C	^{105}Sn	16.08	18.22	18.21	19.60		
^{118}Ba	^{12}C	^{106}Sn	15.10	21.66	21.54	21.30		
			17.63[f]	13.38			11.31	
^{119}Ba	^{12}C	^{107}Sn	14.01	25.91	25.67	26.70		
^{120}Ba	^{12}C	^{108}Sn	13.03	30.17	29.81	29.10		
			13.40[f]	28.50			32.23	
^{112}Ba	^{4}He	^{108}Xe	4.33[f]	−1.39			−2.91	
^{114}Ba	^{4}He	^{110}Xe	3.13[f]	6.37			4.96	
			3.99	0.44	0.29	0.00		
			3.43	4.04	3.91	3.40		
			3.85	1.27	1.12	0.80		
			3.93	0.79	0.64	0.40		
			2.87	8.66	8.54	8.00		
			4.65	−2.93	−3.11	−3.10		
			3.035[b]	7.16				6.52
			3.125[d]	6.41				5.78
			3.155[e]	6.16				5.54
			3.465[a]	3.79				3.26
			3.475[c]	3.73				3.19
^{115}Ba	^{4}He	^{111}Xe	3.28	5.16	5.00	4.80		
			2.86	8.75	8.60	8.30		
			2.67	10.65	10.51	10.10		
			3.30	5.01	4.84	4.60		
			2.45	13.11	12.98	12.60		
			3.81	1.52	1.33	1.20		
^{116}Ba	^{4}He	^{112}Xe	2.32[f]	14.73			12.83	
			3.35	4.64	4.43	4.00		
			2.96	7.83	7.64	7.20		
			2.60	11.39	11.23	10.60		
			3.38	4.41	4.21	3.80		
			4.90	−4.03	−4.28	−4.20		
			2.78	9.53	9.35	8.70		
			3.39	4.34	4.13	3.70		
^{117}Ba	^{4}He	^{113}Xe	2.50	12.52	12.33	11.9		
^{118}Ba	^{4}He	^{114}Xe	1.90[f]	21.05			18.59	
			2.40	13.72	13.50	12.80		
^{119}Ba	^{4}He	^{115}Xe	1.78	23.25	23.04	22.60		
^{120}Ba	^{4}He	^{116}Xe	1.54[f]	28.41			26.17	
			1.60	27.00	26.78	26.00		

[a] Masses are taken from refs [a][16], [b][17], [c][18], [d][19], [e][20], [f][21].

Using the above equation we have calculated the logarithm of half life time for various Ba isotopes which are given in table 2 and our predictions are compared with the values obtained from other models. In this case also our predictions lie very close to those values reported by Shanmugam *et al* [12].

When decay of ^{12}C from ^{112}Ba is compared with that from the heavier isotopes up to ^{120}Ba, it is found that $\log_{10}(T_{1/2})$ value increased from 3.7796 s (for ^{112}Ba, $Q = 21.46$ MeV) to 28.4262 s (for ^{120}Ba, $Q = 13.4$ MeV). All these cases refer to doubly magic or nearly doubly magic daughter Sn nuclei. This points to the fact that the presence of neutron excess in parent nuclei slows down the exotic decay process.

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