Studies on alpha and cluster radioactivity using improved universal (UNIV) curve

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Introduction

There are many effective relationships available which allow us to estimate the α and cluster radioactivity half-lives if kinetic energy (KE) of the ejected particle or Q value of the reaction are known. Poenaru et al. [1, 2] introduced the universal (UNIV) curves derived by extending a fission theory to larger mass asymmetry for studying alpha and cluster radioactivity. The universal (UNIV) curve is obtained by plotting the sum of logarithmic half-life and preformation probability against negative logarithm of penetrability of external barrier. In this article we improved the universal (UNIV) curves by introducing a disintegration energy dependent cluster preformation probability and applied to alpha radioactivity of heavy and superheavy nuclei; and cluster radioactivity of heavy nuclei.

Improved universal (UNIV) curve

In spontaneous α and cluster radioactivity a parent nucleus in its ground state splits into daughter nucleus and emitted cluster, with the release of energy, Q value of the reaction. In both fission like and α-like theories the decay (disintegration) constant λ is given as

$$\lambda = \ln 2 / T_{1/2} = \nu S P_s \qquad (1)$$

By using the decimal logarithm, we have

$$\log_{10} T_{1/2} = -\log_{10} P_s - \log_{10} S - 22.16917 \qquad (2)$$

The penetrability of external barrier is given as

$$P_s = \exp\left[\int_{R_{in}}^{R_{out}} -\frac{2}{\hbar}\sqrt{2B(R)E(R)}\,dR\right] \qquad (3)$$

The preformation probability S depends on the size (mass number) of the cluster [3] and it is expressed as

$$\log_{10} S = -0.598(A_e - 1) \qquad (4)$$

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The plot connecting $\log_{10} T_{1/2} + \log_{10} S$ versus $-\log_{10} P_s$ for all decay modes (α and cluster radioactivity) results in a single universal curve [4] and the formalism explained to compute partial half-life is denoted as the universal (UNIV) formula.

The preformation probability S also depends on disintegration energy, Q value of the reaction [5] and is given as

$$\log_{10} S = a_0 + a_1 Q + a_2 Q^2 \qquad (5)$$

The constants a_0, a_1 and a_2 of preformation probability for α and cluster radioactivity are obtained by least square fitting to experimental α and cluster radioactivity data. The formalism with Q dependent preformation probability is denoted as the improved universal (Imp UNIV) formula.

Results and discussion

We have computed half-lives of α radioactivity of 309 nuclei in the region Z=74-93 and cluster radioactivity of 27 nuclei in heavy region using universal (UNIV) formula and improved universal (Imp UNIV) formula. The computed alpha and cluster radioactivity half-lives for few nuclei are tabulated in Table 1. In Table 1 the first three columns indicate the parent nuclei, emitted cluster and experimental Q values respectively. The calculated half-lives using UNIV, Imp UNIV and experimental values are listed in columns 4, 5 and 6 respectively. The experimental Q values and α half-lives are taken from [6]. The predicted half-life values are in agreement with the experimental data. In order to check the agreement of both formalisms with experiment we have calculated standard deviation σ of logarithmic half-life using,

$$\sigma = \sqrt{\frac{1}{N}\sum(\log_{10} T_{1/2}^{Theory} - \log_{10} T_{1/2}^{Expt.})^2} \qquad (6)$$

It is found that in the case of α decay of heavy

nuclei the standard deviation σ of decimal logarithmic half-life decreased from 0.64312 (UNIV) to 0.56467 (Imp UNIV). It is also observed that σ value decreased from 0.70502 (UNIV) to 0.68189 (Imp UNIV) in the case of cluster radioactivity showing improvement of present formalism Imp UNIV over UNIV in reproducing experimental half-lives of α and cluster radioactivity of heavy nuclei.

The plot (Fig. 1) connecting the sum of decimal logarithm of half-life and preformation factor, $\log_{10} T_{1/2}(s) + \log_{10} S$ versus decimal logarithm of external penetrability, $-\log_{10} P_s$ for Imp UNIV is found linear for both α and cluster radioactivity with the same slope and intercept showing the universal nature of the curve. In this plot blue circle and red star represent the α and cluster decay data respectively.

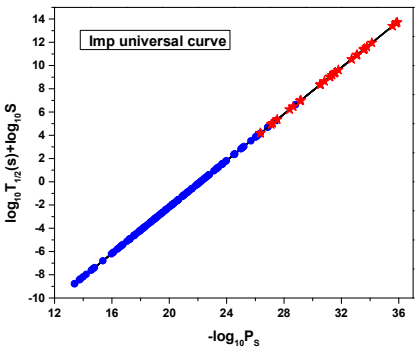

Fig. 1 Improved universal curve for α and cluster radioactivity

The α radioactivity half-lives of 80 superheavy nuclei with $Z \geq 104$ have also been calculated using UNIV and Imp UNIV formalism by inputting the experimental Q values [6]. The detailed results of some known superheavy nuclei are listed in Table 1. The value of standard deviation σ obtained for UNIV and Imp UNIV is 1.10681 and 0.69399 respectively, which clearly indicate the improvement of the Imp UNIV formula over the UNIV formula. As a result, α radioactivity half-life of superheavy nuclei can be reproduced well by using Imp UNIV formula. We have also studied the deviation of logarithmic half-life, $\log_{10} T_{1/2}^{Expt.} - \log_{10} T_{1/2}^{Theory}$ against the neutron number of parent nuclei and it is found that most of the data points of Imp UNIV are within -0.5 and 1.0 and it is clear that Imp UNIV formula can predict α radioactivity half-life values of nuclei in superheavy regions well.

Table 1: The comparison of predicted alpha and cluster decay half-lives with experimental data.

Parent nuclei	Emitted cluster	Q value (MeV)	$\log_{10}T_{1/2}$(s)		
			UNIV	Imp UNIV	Expt
^{198}Po	^{4}He	6.310	1.95	2.27	2.27
^{220}At	^{4}He	6.077	3.01	3.35	3.44
^{203}Ra	^{4}He	7.736	-1.63	-1.36	-1.44
^{208}Ac	^{4}He	7.720	-1.28	-1.01	-1.01
^{214}Th	^{4}He	7.827	-1.34	-1.07	-1.06
^{226}Pa	^{4}He	6.987	1.80	2.07	2.03
^{223}U	^{4}He	9.158	-4.54	-4.17	-4.19
^{224}Np	^{4}He	9.329	-4.65	-4.25	-4.32
^{221}Fr	^{14}C	31.28	14.24	14.21	14.5
^{221}Ra	^{14}C	32.39	13.13	13.42	13.4
^{230}Th	^{24}Ne	57.78	24.65	24.99	24.6
^{234}U	^{28}Mg	74.13	25.16	25.76	25.9
^{238}Pu	^{30}Mg	77.03	25.68	25.45	25.7
^{242}Cm	^{34}Si	96.53	23.93	23.01	23.2
^{277}Cn	^{4}He	11.62	-4.77	-3.85	-3.16
^{283}Nh	^{4}He	10.26	-1.33	-0.77	-0.99
^{287}Fl	^{4}He	10.16	-0.79	-0.26	-0.28
^{289}Mc	^{4}He	10.49	-1.38	-0.77	-0.70
^{291}Lv	^{4}He	10.89	-2.10	-1.39	-1.55
^{293}Ts	^{4}He	11.18	-2.53	-1.74	-1.84
^{294}Og	^{4}He	11.81	-3.68	-2.70	-2.85

Acknowledgements

The author K.P.S. would like to thank the Council of Scientific and Industrial Research, Government of India, for the financial support under the scheme “Emeritus Scientist, CSIR”, No. 21(1154)/22/EMR-II dated 20-05-2022.

References

[1] D. N. Poenaru and W. Greiner, J. Phys. G: Nucl. Part. Phys. 17, 443 (1991).
[2] D. N. Poenaru, I. H. Polonski and W. Greiner, Phys Rev. C 74, 014312 (2006).
[3] M. Irindo, D. Jerrestam and R. J. Liotta, Nucl. Phys. A 454, 252 (1986).
[4] D. N. Poenaru, R. A. Gherghescu and W. Greiner, Phys. Rev. C 83, 014601 (2011).
[5] K. P. Santhosh, Tinu Ann Jose and N. K. Deepak, Phys. Rev. C 105, 054605 (2022).
[6] https://www.nndc.bnl.gov/nudat3/