Studies on Alpha Decay of Superheavy Elements with a Surface Area and Isospin Dependent Preformation Factor

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Introduction

A fascinating age in nuclear physics is currently underway as successive discoveries of new superheavy elements (SHE) take place. Typically, a superheavy nucleus is highly unstable and experiences sequential α-decays followed by spontaneous fission. Many significant details of nuclear structure, including the characteristics of the ground state, nuclear deformation, coexistence of nuclear shapes, energy levels, and more, have been observed via a study on α-decay. During the last five decades, many theoretical and empirical models have been developed to study the alpha decay characteristics of superheavy nuclei. Superheavy elements do not occur naturally. Synthesis of superheavy elements with Z = 107-112 were accomplished through cold fusion reactions at GSI, Darmstadt in Germany and the isotopes of elements with Z = 113 – 118 were synthesized at Joint Institute for Nuclear Research-Flerov Laboratory of Nuclear Reactions (JINR-FLNR), Dubna through hot fusion reactions [1].

Methodology

Gamow's theory describes the decay process as a preformed particle tunneling across the Coulomb barrier. Thus, an α-particle preformation factor $\left(S_\alpha\right)$ is usually defined and can be extracted from the experimental decay half-lives using various theoretical models like the Generalized Liquid Drop Model (GLDM) [2]. To predict the α-particle preformation in heavy and superheavy elements, many empirical and analytical equations were also developed. Recently, our group has proposed four empirical formulae for alpha and cluster preformation factors based on the dependence of preformation on various factors like the structure of the nuclei involved, Q-value, the surface area of the cluster, and the isospin [3]. In the present study, we use the surface area, isospin, and structure-dependent formula to estimate the α-particle preformation factor of superheavy nuclei whose experimental alpha decay half-lives are known. The formula is given as;

$$\log_{10} S_\alpha = a\sqrt{\mu}\left(Z_c Z_d\right) + bA_c^{2/3} + cI + d \qquad (1)$$

with $a = -0.002658$, $b = -0.4458$, $c = 87.916$ and $d = -16.6128$

To determine the efficiency of our empirical formula, we investigate the function of the formation probability S_α in α-decay half-life calculation. We employ the widely accepted semi-empirical Viola-Seaborg formula (VSF) which is given as [4];

$$\log_{10} T_{1/2} = \left(aZ + b\right)Q^{-1/2} + cZ + d - \log_{10} S_\alpha \qquad (2)$$

The coefficients are taken from ref. 4 without any modification. We calculate the decay half-lives of some superheavy nuclei using eq. 2 with $S_\alpha = 1$ and $S_\alpha \neq 0$ separately and the results are then compared with the experimental values of decay half-lives.

Results and Discussion

In the first step, we have calculated the preformation probabilities of various superheavy nuclei from Z = 110 – 118 using the eq. 1. The elements with known experimental alpha decay half-lives are selected from ref. [2]. Then the alpha decay half-lives of these elements were calculated using the Viola-Seaborg formula, with $S_\alpha = 1$ and then by including the S_α values calculated using the eq. 1. The Q-values are taken from ref. 2. Some of the results of our calculations are given in table 1.

Table 1: Comparison of alpha decay half-lives of superheavy nuclei calculated using the Viola-Seaborg formula with $S_\alpha = 1$ and $S_\alpha \neq 1$ with the experimental values

Parent	Q_α^{exp} MeV [2]	$\log_{10} S_\alpha$	$\log_{10} T_{1/2}$ Expt. [2]	VSF $S_\alpha = 1$	VSF $S_\alpha \neq 1$
^{294}Og	11.82	-1.22	-3.16	-4.70	-3.48
^{294}Ts	11.18	-0.61	-1.29	-3.29	-2.68
^{292}Lv	10.78	-0.47	-1.89	-2.46	-1.98
^{291}Lv	10.89	-0.71	-1.72	-2.76	-2.04
^{290}Lv	11.00	-0.96	-2.08	-3.06	-2.10
^{290}Mc	10.41	-0.34	-0.19	-1.67	-1.33
^{289}Mc	10.49	-0.58	-0.48	-1.90	-1.32
^{287}Mc	10.76	-1.07	-1.43	-2.65	-1.59
^{289}Fl	9.98	0.23	-0.28	-0.67	-0.30
^{285}Fl	10.35	-0.94	-0.89	-1.76	-0.83
^{286}Nh	9.79	-0.25	-0.98	-0.36	-0.61
^{285}Nh	10.01	-0.31	-0.62	-1.03	-0.73
^{283}Nh	10.38	-0.80	-1.13	-2.11	-1.31
^{282}Cn	9.16	-0.42	2.00	1.38	1.79
^{280}Rg	9.91	-0.28	0.66	-1.29	-1.02
^{278}Rg	10.85	-0.78	-2.38	-3.91	-3.13
^{278}Mt	9.58	0.51	0.65	-0.87	-1.38
^{275}Hs	9.45	0.41	-0.70	-0.77	-1.18
^{273}Hs	9.73	-0.10	-0.70	-1.62	-1.52
^{270}Bh	9.06	-0.61	1.79	0.16	0.87

From the table, it is clear that the calculated half-lives are closer to the experimental values when the preformation is included in the Viola-Seaborg formula than that with $S_\alpha = 1$. We have calculated the standard deviation of α-decay half-lives of 39 superheavy nuclei. For calculations with $S_\alpha = 1$, it is obtained as 0.823 and with $S_\alpha \neq 1$ it reduced to 0.586. This shows that the predictions of the Viola-Seaborg formula are improved considerably when the α-particle preformation factor is included in the calculation.

In the next part of our study, we have calculated the α-decay half-lives of various other superheavy nuclei whose α-decay half-lives are predicted by Chowdhury et al. [5] by using the DDM3Y effective interaction with microscopic nuclear potentials obtained by the double-folding procedure. In ref. 5, the authors have selected 76 even-even superheavy nuclei with Z = 104 – 120 and calculated results are compared with the predictions of VSF. We have recalculated the α-decay half-lives of these nuclei by including the preformation factor in VSF. The results are then compared with the predictions of the DDM3Y model and the errors are ploted in fig. 1. From the plot it is evident that the error is less when S_α is incorpoated in Viola-Seaborg formula.

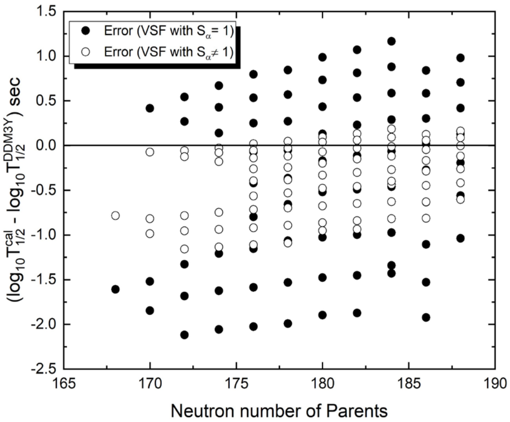

Fig. 1 Plot of error in the calculation of alpha decay half-lives of Z = 104 – 120 SHE using the Viola-Seaborg formula with $S_\alpha = 1$ (black circle) and $S_\alpha \neq 1$ (hollow circle) relative to the predictions of DDM3Y model.

It is interesting to notice that the inclusion of S_α in VSF brings the results closer to the prediction of the DDM3Y model. For example, for ^{274}104, VSF with $S_\alpha = 1$ predicts $\log_{10} T_{1/2}$ value as 9.21 s, and VSF with $S_\alpha \neq 1$ predicts a value of 8.68 s which is closer to the value of 8.75 s predicted by the DDM3Y model in ref. 5. Thus, the inclusion of the α-preformation factor predicted by our formula in VSF improves its predictive power considerably and the predicted alpha decay half-lives of superheavy elements are in close agreement with experimental and other theoretical predictions.

References

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