Araştırma Makalesi / Research Article

Calculations of Spontaneous Fission (SF) half-lives of superheavy nuclei in different models

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Abstract
The spontaneous fission (SF) is a decay mode for heavy and superheavy nuclei (Z≥90) and it is an important confining factor explaning the stability of synthesized superheavy nuclei. Since the fission decay is complex, it is difficult to explain such a multi-dimensional system in a complete microscopic manner. In this study, SF half-lives of ^{284}Cn and ^{284}Fl superheavy nuclei are investigated using the direct method, the Universal Decay Law (UDL). The fission decay constant for each possible case is computed by using the UDL and then the SF half-life for ^{284}Cn and ^{284}Fl superheavy nuclei are predicted. The calculated SF half-lives are compared with the results of other semi-empirical models and the experimental data. Furthermore, the results are compared with ones of the model in which they proposed this direct method for the SF by using CPPM potentials. Good agreement has been obtained between the results of present approach and the others. This study shows that UDL would also be used in the half-lives calculations of Spontaneous Fission of superheavy nuclei in a direct way.

Keywords: Superheavy, Half-lives, Spontaneus Fission.

Süper-ağır çekirdeklerin kendiliğinden fisyon yarı ömürlerinin farklı modellerdeki hesaplamaları

Öz
Kendiliğinden Fisyon (SF) Z≥90 olan ağır ve süper-ağır çekirdekler için bir bozunma modudur ve süper-ağır çekirdeğin sentezinin kararlılığını tanımlayan önemli bir sınırlandırma faktörüdür. Fisyon bozunması karmaşık olduğu için, böyle çok boyutlu bir sistemin açıklamasını yapmak zordur. Bu çalışmada, ^{284}Cn ve ^{284}Fl süper-ağır çekirdeklerinin kendiliğinden fisyon yarı-ömürleri doğrudan bir metot olan evrensel bozunma yasası (UDL) kullanılarak araştırıldı. Her bir mümkün bozunma durumu için fisyon bozunma sabitleri UDL ile hesaplandı ve sonrasında ^{284}Cn ve ^{284}Fl için SF yarı-ömürleri tahmin edildi. Elde edilen SF yarı-ömürleri diğer yarı-ampirilk formüller ve deneysel değerleriyle kıyaslandı. Ayrıca sonuçlar diğer doğrudan model olan CPPM potansiyeli modeli sonuçlarıyla karşılaştırıldı. Bu yaklaşımların sonuçları arasında iyi bir uyum elde edildi. Bu çalışma UDL metodunun da doğrudan metot olarak kendiliğinden fisyon yarı ömürlerinin hesaplamalarında kullanılabileceğini gösterdi.

Anahtar kelimeler: Süper-ağır, Yarı-ömürler, Kendiliğinden Fisyon.

1. Introduction

More recently, investigation of α decay (AD) of superheavy nuclei has been popular for both the experimental and theoretically in nuclear area. When superheavy nuclei are produced in an experiment, they go to the ground state via α decays. Counting these α particles give important information on the synthesis of nuclei. Therefore, it is very important to make theoretical studies on the α decay of superheavy nuclei [1-7]. On the other hand, these decays can sometimes be in the form of the

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spontaneous fission (SF) [8]. Although these phenomena are studied through the quantum mechanical tunneling [9,10], the SF is more complex. Since there are many uncertainties and complexity in the fission process, it is very difficult to describe it in a complete microscopic manner of such a multidimensional system. Xu and others have studied the half-lives of the AD and SF for heavy and super-heavy nuclei with $Z \geq 90$ protons systematically [11]. In recent years, Santhosh et al. predicted half-life and decay modes of all $104 \leq Z \leq 136$ isotopes of superheavy nuclei and compared results with the AD half-lives [12].

In Ref. [13], isotopic yields and half-lives of ^{284}Cn and ^{284}Fl superheavy nuclei have been investigated by using CPPM as a direct way. Decay constant for each combination has been computed and then the total decay constant and fission half-life for ^{284}Cn and ^{284}Fl superheavy nuclei have been predicted. Good agreement has been obtained between the results of present study and the experimental data. Furthermore, some predictions have been made on heavier cluster decays from superheavy nuclei [14] by using different models. It has been found in Ref. [15] that the UDL formula [16] could predict the lighter and heavier cluster decay owing to the inclusion of the preformation and fission-like mechanisms. In this study, using UDL approach [16] that works well for cluster decay as a direct way, the SF half-lives of ^{284}Cn and ^{284}Fl superheavy nuclei have been investigated. The SF half-lives have also been computed with the formulas of Bao [17] and Soylu [18]. The obtained half-lives are compared with the results of other models and present experimental data.

2. Models

2.1. Universal Decay Law (UDL)

Qi et al. proposed a universal decay law (UDL) for the decays (α and cluster) by helping R-Matrix theory and the microscopic mechanism [16] as follows

$$\log_{10} T_{1/2} = aZ_c Z_d \sqrt{\frac{A}{Q_c}} + b\sqrt{AZ_c Z_d (A_d^{1/3} + A_c^{1/3})} + c \quad (1)$$

where $A=A_cA_d/(A_c+A_d)$ and the constants a=0.4314, b=-0.4087, c=-25.7725 by fitting above equation to α and cluster decays experimental data [16].

2.2. The formula of Bao et al.

Bao et al. [17] derived a formula for the SF half-lives considering of the shell and isospin effect, this formula is given by

$$\log_{10} T_{1/2}(yr) = c_1 + c_2\left(\frac{Z^2}{\left(1-kI^2\right)A}\right) + c_3\left(\frac{Z^2}{\left(1-kI^2\right)A}\right)^2 + c_4 E_{sh} + h_i \quad (2)$$

The using parameters in this formula can be found in Ref. [17].

2.3. Formula of Soylu

A new function that was proposed for the SF half-lives [18] is given by

$$T_{SF} = e^{2\pi[aA+bA^{2/3}+cZ(Z-1)/A^{1/3}+d(N-Z)^2/A+eZ^4+f]} \quad (3)$$

where Z, N and A are the proton, neutron and mass numbers of the parent nuclei and a, b, c, d, e, f are the adjustable parameters obtained by fitting it to present experimental data and this equation is in terms of years. The parameters are given by a=-10.0987592959, b=119.319858732, c=-0.516609881059, d=-9.52538327068, e=1.92155604207.10-6, f=-1496.05967574 [18].

3. Results

UDL approach was applied to ^{284}F1 nucleus and λ values for each case were obtained. The results obtained are given in Table 1 for different cases. Using these λ values, SF half-lives were obtained for ^{284}F1. This value,-4.8750, is given in the Table 3. On the other hand, the same process was applied for ^{284}Cn and results were obtained. The obtained λ values and half-life value,-3.884, are given in the Tables 2 and 3. By using semiempirical formulas given in Eqs.2 and 3, the SF half-lives have been calculated for related nuclei. These values are presented in Table 3. It should be noted that the MES code [19] in Python language has been used for the calculations in this study.

Table 1. Spontaneous fission constant for each individual fragmentation of ^{284}F1superheavy nucleus.

A_1	**A_2**	**Q (MeV)**	**λ (s^{-1})**	**A_1**	**A_2**	**Q (MeV)**	**λ (s^{-1})**
^{4}He	^{280}Cn	10.80	2.71e+01	^{118}Pd	^{166}Er	309.23	2.68e-07
^{8}Be	^{276}Ds	21.44	9.52e-19	^{119}Ag	^{165}Ho	312.46	2.80e-06
^{9}Be	^{275}Ds	16.00	2.34e-38	^{120}Cd	^{164}Dy	318.85	3.56e-02
^{10}Be	^{274}Ds	17.11	7.95e-37	^{121}Cd	^{163}Dy	316.38	2.08e-04
^{11}Be	^{273}Ds	10.38	3.99e-78	^{122}Cd	^{162}Dy	317.71	3.90e-03
^{12}Be	^{272}Ds	7.82	5.65e-110	^{123}Cd	^{161}Dy	314.39	3.44e-06
^{13}B	^{271}Mt	21.26	2.45e-51	^{124}Sn	^{160}Gd	325.10	2.12e+01
^{14}C	^{270}Hs	40.79	3.91e-21	^{125}Sn	^{159}Gd	323.38	6.39e-01
^{15}C	^{269}Hs	34.49	1.57e-35	^{126}Sn	^{158}Gd	325.62	7.43e+01
^{16}C	^{268}Hs	32.40	1.96e-42	^{127}Sn	^{157}Gd	323.21	5.24e-01
^{72}Ni	^{212}Rn	231.81	2.63e-12	^{128}Sn	^{156}Gd	324.82	1.60e+01
^{78}Zn	^{206}Po	244.59	7.38e-11	^{129}Sb	^{155}Eu	325.37	3.08e+00
^{82}Ge	^{202}Pb	260.28	5.75e-06	^{130}Te	^{154}Sm	328.73	3.16e+02
^{83}Ge	^{201}Pb	255.17	8.54e-11	^{131}Te	^{153}Sm	326.69	4.86e+00
^{84}Ge	^{200}Pb	253.32	1.49e-12	^{132}Te	^{152}Sm	328.87	4.71e+02
^{86}Se	^{198}Hg	270.38	1.21e-05	^{133}Te	^{151}Sm	326.43	3.12e+00
^{87}Se	^{197}Hg	265.89	7.77e-10	^{134}Te	^{150}Sm	328.50	2.41e+02
^{88}Se	^{196}Hg	264.63	5.43e-11	^{135}I	^{149}Pm	291.51	1.13e-35
^{92}Kr	^{192}Pt	273.98	1.51e-10	^{136}Xe	^{148}Nd	332.76	5.01e+04
^{96}Sr	^{188}Os	282.98	1.21e-09	^{137}Xe	^{147}Nd	329.45	5.69e+01
^{102}Zr	^{182}W	288.75	6.14e-11	^{138}Xe	^{146}Nd	329.82	1.25e+02
^{108}Mo	^{176}Hf	294.25	9.84e-12	^{139}Xe	^{145}Nd	326.00	4.31e-02
^{112}Ru	^{172}Yb	303.81	5.79e-08	^{140}Xe	^{144}Nd	325.65	2.12e-02
^{113}Ru	^{171}Yb	300.10	1.82e-11	^{141}Ba	^{143}Ce	330.26	5.61e+01
^{114}Ru	^{170}Yb	299.91	1.30e-11	^{142}Ba	^{142}Ce	331.30	4.79e+02
^{115}Rh	^{169}Tm	304.43	1.03e-09				
^{116}Pd	^{168}Er	311.74	4.95e-05				
^{117}Pd	^{167}Er	308.64	6.66e-08				

Table 2. Spontaneous fission constant for each individual fragmentation of ^{284}Cn superheavy nucleus.

A_1	A_2	Q (MeV)	λ (s^{-1})	A_1	A_2	Q (MeV)	λ (s^{-1})
^{4}He	^{280}Ds	9.61	8.89e-02	^{113}Ru	^{171}Er	292.14	2.28e-10
^{8}Be	^{276}Hs	19.32	6.54e-23	^{114}Ru	^{170}Er	292.88	1.32e-09
^{9}Be	^{275}Hs	14.58	1.26e-42	^{115}Rh	^{169}Ho	295.58	2.92e-09
^{10}Be	^{274}Hs	16.45	1.21e-37	^{116}Pd	^{168}Dy	300.94	3.65e-06
^{11}Be	^{273}Hs	10.48	8.58e-75	^{117}Pd	^{167}Dy	298.90	4.49e-08
^{12}Be	^{272}Hs	8.46	6.99e-99	^{118}Pd	^{166}Dy	300.52	1.75e-06
^{13}B	^{271}Bh	20.07	7.22e-54	^{119}Ag	^{165}Tb	301.77	3.79e-07
^{14}C	^{270}Sg	38.04	1.79e-24	^{120}Cd	^{164}Gd	306.28	1.65e-04
^{15}C	^{269}Sg	32.92	2.83e-37	^{121}Cd	^{163}Gd	304.94	9.68e-06
^{72}Ni	^{212}Po	227.15	3.63e-11	^{122}Cd	^{162}Gd	307.44	2.43e-03
^{73}Ni	^{211}Po	225.09	3.48e-13	^{123}Cd	^{161}Gd	305.47	3.61e-05
^{74}Ni	^{210}Po	226.96	2.97e-11	^{124}Sn	^{160}Sm	311.02	1.14e-02
^{77}Cu	^{207}Bi	231.22	1.47e-12	^{125}Sn	^{159}Sm	310.65	5.59e-03
^{78}Zn	^{206}Pb	243.82	1.57e-05	^{126}Sn	^{158}Sm	313.81	5.17e+00
^{79}Zn	^{205}Pb	239.75	2.01e-09	^{127}Sn	^{157}Sm	312.70	5.14e-01
^{80}Zn	^{204}Pb	239.31	8.32e-10	^{128}Sn	^{156}Sm	315.27	1.29e+02
^{82}Ge	^{202}Hg	255.31	2.67e-04	^{129}Sn	^{155}Sm	314.12	1.02e+00
^{83}Ge	^{201}Hg	251.19	3.50e-08	^{130}Te	^{154}Nd	315.72	4.38e+00
^{84}Ge	^{200}Hg	250.20	4.38e-09	^{131}Te	^{153}Nd	315.09	1.20e+00
^{86}Se	^{198}Pt	262.96	6.52e-06	^{132}Te	^{152}Nd	317.89	4.69e+02
^{87}Se	^{197}Pt	259.40	2.85e-09	^{133}Te	^{151}Nd	316.43	2.26e+01
^{88}Se	^{196}Pt	259.08	1.61e-09	^{134}Te	^{150}Nd	318.76	3.22e+03
^{90}Se	^{194}Pt	253.11	2.21e-15	^{135}I	^{149}Pr	280.12	9.90e-37
^{92}Kr	^{192}Os	267.20	7.14e-10	^{136}Xe	^{148}Ce	319.38	8.74e+02
^{96}Sr	^{188}W	274.14	1.45e-10	^{137}Xe	^{147}Ce	316.95	5.29e+00
^{98}Sr	^{186}W	271.48	4.38e-13	^{138}Xe	^{146}Ce	318.16	7.01e+01
^{102}Zr	^{182}Hf	280.19	3.18e-11	^{139}Xe	^{145}Ce	315.26	1.51e-01
^{103}Zr	^{181}Hf	277.77	1.44e-13	^{140}Xe	^{144}Ce	315.97	6.88e-01
^{108}Mo	^{176}Yb	286.80	1.52e-10	^{141}Ba	^{143}Ba	316.22	4.84e-01
^{110}Mo	^{174}Yb	284.04	3.46e-13	^{142}Ba	^{142}Ba	318.23	3.51e+01
^{111}Tc	^{173}Tm	287.83	3.83e-12				
^{112}Ru	^{172}Er	294.67	5.80e-08				

Table 3. Spontaneous fission half-lives for ^{284}Fl and ^{284}Cn superheavy nucleus in different models.

	UDL(direct way)	Soylu (Eq.3)	Bao (Eq.2)	CPPM (direct way) [13]	Exp. [20,21]
^{284}**Fl**	-4.8750	2.4688	0.3304	-3.83	-2.602
^{284}**Cn**	-3.8443	-4.0197	-2.1547	-3.48	1.001

4. Conclusion

In this study, the Spontaneous Fission (SF) half-lives of ^{284}Fl and ^{284}Cn superheavy nuclei are calculated using the direct method, the Universal Decay Law (UDL). The calculated SF half-lives are compared with the results of the model using the CPPM, other semi-empirical formulas and the present experimental data. Good agreement is obtained between the results of present approach and the others. It has been shown that UDL would also be used in the half-lives calculations of Spontaneous Fission of superheavy nuclei in a direct way. Present mechanism could be applied to obtain SF half-lives of new superheavy nuclei.

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