Calculation of cluster decays half-lives for nuclei between $56 < Z_p < 120$ by using temperature dependent proximity model

V. Zanganeh$^1$\,*

$^1$Department of Physics, Sciences Faculty, Golestan University, P. O. Box 49138-15759, Gorgan, Iran

submitted at: Chinese Physics C

Abstract

Cluster decays half-lives of elements with proton numbers between $56 < Z_p < 120$ are calculated by applying temperature dependent proximity potential approach. For showing the influence of temperature on cluster decays, we compared the results among temperature dependent and independent case with experimental values. The obtained results of the present investigation reveal that we have more accurate results for temperature dependent proximity potential in comparison to ignoring one. In the present work, we find that results provided with temperature dependent proximity model are reasonable estimates for cluster decays half-lives and provide reliable predictions for other super heavies cluster decays.

Key words: Cluster decays, half-lives, temperature dependent, proximity model.

PACS: 23.70.+j

\*Electronic address: zanganeh_yahid@yahoo.com ; v.zanganeh@gu.ac.ir
I. INTRODUCTION

Spontaneous cluster decays, heavier than alpha particles but lighter than a fission fragment, of super heavy nuclei is one of most dominant decay chains which happens before spontaneous fission. However, the cluster decays and half-lives of the super heavy nuclei gives us information about the island of stability regions and hence help us to understand the nuclear structure of the daughter as well as parents nuclei[1, 2]. experimentally and theoretically, emitted clusters from heavy nuclei has greatly attracted researchers attention which theoretical mechanism of cluster decay is regarded as quantum mechanical tunneling through the potential barrier between cluster emitter and the residual daughter nucleus. At this study, calculation of potential barrier is critical part. At present, many theoretical approaches have been used to describe the cluster-decay, such as the macroscopic-microscopic model[3], Density-dependent cluster model[4–6] relativistic mean field theory [7, 8]. in these models, various nuclear potential is used for calculation of half-lives and spectroscopic properties. The liquid drop model , double-folding model and proximity are example of most potential that are applied recently [9–16]. One of the successful and applicable models is by using the proximity potential which is a function of separation between the surfaces of the two nuclei. Many versions of proximity potential are proposed by different groups in order to improve the model [17–22]. Interestingly, the temperature dependence of proximity model has been modified by some authors to study fusion reactions and barrier characteristic[22].

At previous work, we studied the influence of the temperature of the parent nucleus on the alpha-decay process by applying the temperature dependence of the proximity potential and transfer matrix approach to calculate the penetration probability[23]. In this work, we attempt to study the cluster-decay half-lives of parent nuclei by considering the temperature dependence of the proximity potential and using WKB approach for calculating the penetration probability across the potential barrier. The structure of this paper is as follows: In sec. II, modified proximity model with temperature dependence is briefly introduced. In sec. III, half-lives of emitted $^{14}$C, $^{18}$O, $^{23}$F, $^{22,24,25,26}$Ne, $^{28,30}$Mg and $^{34}$Si cluster are compared with existing experimental values. In addition, half-lives of heavy nuclei are calculated theoretically and compared with analytical relation based on the ASAF model [2]. Finally the conclusion is given in Sec. IV.
II. MODEL

In the cluster model the parent nucleus is assumed to be the interaction between the cluster particle an daughter nucleus where the total potential is equal to the sum of the nuclear potential, the coulomb potential and centrifugal barrier. Thus,

\[ V(R) = V_N(R) + V_C(R) + \frac{\hbar^2 l(l+1)}{2\mu R^2} \]  

(1)

Where \( \mu \) is the reduced mass and \( V_c(R) \), the Coulomb interaction potential is given by,

\[ V_c(R) = \begin{cases} 
\frac{Z_e Z_d e^2}{R} & \text{for } R \geq R_c \\
\left(\frac{Z_e Z_d e^2}{2R}(3 - \left(R/R_c\right)^2)\right) & \text{for } R \leq R_c 
\end{cases} \]  

(2)

in above equation, \( R_c \) is expressed by, \( R_c = 1.24(R_e + R_d) \), \( R_e \) and \( R_d \) are respectively the radii of emitted cluster and daughter nuclei. However, \( Z_e \) and \( Z_d \) represents the charge number of emitted cluster and daughter nuclei respectively.

Using the proximity theorem we can obtain a simple formula for nuclear potential between emitted clusters and residual daughter nuclei as a function of the separation distance between the surfaces of them [17].

\[ V_N(r) = 4\pi \gamma b \overline{R} \Phi(\xi) \text{ MeV.} \]  

(3)

Here \( \overline{R} \) is the reduced radius and is written as:

\[ \overline{R} = \frac{C_1 C_2}{C_1 + C_2} \]  

(4)

and

\[ C_i = R_i[1 - (\frac{b}{R_i})^2 + ...]. \]  

(5)

where \( b \) is the surface width and \( R_i \) is the effective sharp radius, and given by:

\[ R_i = 1.28 A_i^{1/3} - 0.76 + 0.8 A_i^{-1/3} \text{ fm} \quad (i = 1, 2). \]  

(6)

In Eq. (1), \( \Phi(\xi) \) is the universal function which has been derived by several authors in different forms [20, 21] and in original proximity version was defined as:

\[ \Phi(\xi) = \begin{cases} 
-\frac{1}{2}(\xi - 2.54)^2 - 0.0852(\xi - 2.54)^3 & \xi \leq 1.2511 \\
-3.437e^{-\xi/0.75} & \xi > 1.2511
\end{cases} \]  

(7)
and the surface energy coefficient defines as a function of the neutron/proton excess as:

\[ \gamma = \gamma_0 [1 - k_s A_s^2] \] (8)

where \( A_s = \left( \frac{N - Z}{N + Z} \right) \) and \( \gamma_0 \) and \( K_s \) are the surface energy and surface asymmetry constants respectively. These constants have different values in different proximity potential versions and they revised to \( K_s = 4 \) and \( \gamma_0 = 1.460734 \text{MeV/fm}^2 \) for to the proximity-2010 [21] that we used in this work. In order to achieve an exact form of proximity potential where be able to reproduce the experimental data more accurately, many researches have been done which led to different versions for proximity potentials [24–26]. In one of these attempts, proximity-2010 is modified with a temperature dependence of surface energy coefficient and it has been successful in expecting the fusion barrier data and the experimental fusion cross section [22].

\[ \gamma(T) = \gamma(T = 0)[1 - \frac{T - T_B}{T_B}]^{3/2} \] (9)

where \( T_B \) is the temperature associated with the energies near the Coulomb barrier.

Temperature dependency, also followed in some other parts of the proximity potential as:

\[ R_i(T) = R_i(T = 0)[1 + 0.0005T^2] \text{fm}(i = 1, 2) \] (10)

and,

\[ b(T) = b(T = 0)[1 + 0.009T^2] \] (11)

The temperature \( T \) in Eqs. (9-11) can be expressed as [27, 28],

\[ E_{CN}^* = E_{c.m.} + Q_{in} = \frac{1}{9}AT^2 - T. \] (12)

Here, \( E_{CN}^* \) denotes the excitation energy of parent nucleus with mass number \( A \). \( Q_{in} \) denote the entrance channel Q-value of the system and \( E_{c.m.} \) is the center-of-mass incident energy which according to Refs. [22, 29], one can use the following definition

\[ E_{c.m.} = \frac{e^2Z_cZ_d}{R_1 + R_2 + 2} \] (13)

where the radius \( R_{1,2} \) is obtained by Eq. (6). In order to explore the temperature effects of parents nucleus in this study, we have employed all three above relations simultaneously in proximity-2010 potential, and we have calculated the interaction potential in this way. With the shape of total cluster-nucleus potential, one can calculate the penetration probability
as well as half-life $T_{1/2}$ of the parent nucleus. According to the WKB approximation the
penetration probability is calculated by,

$$P = \exp \left[ -\frac{2}{\hbar} \int_{R_{\text{in}}}^{R_{\text{out}}} \sqrt{2\mu(R)[V(R) - Q]} \, dR \right]$$

(14)

Where $\mu(R)$ is the effective mass of the cluster particle and the daughter nucleus which is
set as the reduced mass. $Q$ is released energy for which experimental values are used in the
present calculations. $R_{\text{in}}$ and $R_{\text{out}}$ denote the classical turning points inside and outside of
the barrier which are determined from the equation $V(R_{\text{in}}) = V(R_{\text{out}}) = Q$.

The cluster-decay half-life $T_{1/2}$ is then calculated with the penetration probability [30],

$$T_{1/2} = \frac{\hbar \ln 2}{2E_{\nu}P}.$$  

(15)

Where $E_{\nu}$ denotes the zero point the empirical vibration energy is given by [31],

$$E_{\nu} = Q[0.056 + 0.039e^{\frac{4-A_{e}}{2.5}}]$$

(16)

where $A_{e}$ is the mass number of emitted cluster nuclei

### III. RESULTS

In this section at first we test our calculation for the existing measured values of half-lives.
after investigate the role of temperature dependence on cluster decay half-lives, then we will
apply this formalism for calculation of cluster decay half-lives.

### III-A. compare to experimental data

In order to test the precision of our calculation, we compare the calculated results with the
existing experimental data[32] of the half-lives. We gets the 28 parents nuclei which cluster
decays includes $^{14}\text{C}$, $^{18,20}\text{O}$, $^{23}\text{F}$, $^{22,24,25,26}\text{Ne}$, $^{28,30}\text{Mg}$ and $^{34}\text{Si}$. It is relevant to mention here
that the selected cluster nuclei were discovered from the experiments[33, 34]. In Table-I, we compared measured experimental data and the calculated half-lives of cluster decay
with including the temperature effect of parent nucleus(TD.) and without the temperature
effect(IND.). also the minimum angular momentum $l_{\text{min}}$ carried away by the emitted cluster
is determined by the principle of spin-parity conservation when the nuclei are decayed and
the values are from [35]. In order to give some indication of the quality of the results, the last line of table-I also shows the relative error,

\[ \chi^2_R = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{Y_{Exp.} - Y^{Th.}}{Y_{Exp.} + Y^{Th.}} \right)^2, \]  

(17)

where Y=log_{10}T_{1/2}. This quantity show the deviation of the calculated half-lives from the experimental values. It is clear that corresponding values of \( \chi^2_R \) for temperature dependent is less than ignoring the temperature effects one.

In order to show better the ability of our method on calculations of cluster decay half-lives, we define hindrance factor as follow:

\[ HF = \frac{T_{1/2}^{Exp.}}{T_{1/2}^{Cal}} \]  

(18)

Figure-1 depicts the comparison of HF between temperature dependence of proximity potential (TD.) and temperature independent (IND.). as the definition of HF clear that closer to unity is more accurate results we have. This figure reveals that TD. results are motivating. therefore it seems we can apply this method for calculation of cluster decay for heavy nuclei.

### III-B. Calculation of cluster decay for heavy nuclei

In Table-II we list the theoretical cluster decay half-lives of temperature dependent proximity potential and prediction of ASAF model [2] ones for nuclei with Z parent between 56 and 120. The first column of Table-II denotes nuclide. The experimental Q cluster-decay energy (\( Q_c \)) is given in column 2. When the \( Q_c \) is not known, we use a theoretical value from ref. [36]. The logarithmic cluster decay half-lives with TD. and ASAF model [2] ones are listed in columns 3 and 4, respectively. The last column is the reference the error between calculation of our work and ASAF model. It is seen from Table-II that TD. half-lives are reasonable estimates.
IV. CONCLUSION

By using the temperature dependent proximity potential, we calculated cluster decay half-lives of parent nuclei whose proton numbers are from $Z_p = 56$ to $Z_p = 120$. Before the calculation, we test the accuracy of the our calculation for some nuclei in compare with experimental data. The results of present calculation made with T.D. model are in good agreement with experimental data (see Table-I and Figure-1). at next, T.D. model calculation are provided in Table-II for cluster decay half-lives of heavy nuclei and compared with the values based on the ASAF model \[2\] estimation using the same $Q$ – values. this formalism has been found to be quit reliable.

ACKNOWLEDGMENTS

The authors would like to give special thanks to Dr. F. Zanganeh for helpful discussions.
and encouragements.

[1] S. Kumar, Phys. Rev. C 85, 024320 (2012).
[2] D. N. Poenaru and et al. Phys. Rev. C 65, 054308 (2002).
[3] M. Mirea, A. Sandulescu and D. S. Delion, Nucl. Phys. A 870, 23 (2011).
[4] D. Ni and Z. Ren, Phys. Rev. C 83, 014310 (2011).
[5] D. Ni and Z. Ren, Phys. Rev. C 81, 024315 (2010).
[6] F. R. Xu and J. C. Pei, nucl-th/0603064 (2006).
[7] M. Bhuyan, S. K. Patra and R. K. Gupta, Phys. Rev. C 84, 014317 (2011).
[8] P. Roy. Choudhury, G. Gangopadhyay and A. Bhattacharyya, Phys. Rev. C 83, 027601 (2011).
[9] B. Buck, A. C. Merchant and S. M. Perez, Phys. Rev. C 45, 2247 (1992).
[10] B. Buck, A. C. Merchant and S. M. Perez, Data Nucl. Data Tables 54, 53 (1993).
[11] C. Xu and Z. Ren, Phys. Rev. C 69, 024614 (2004).
[12] P. Mohr Phys. Rev. C 61, 045802 (2000).
[13] U. Atzrott, P. Mohr, H. Abele, C. Hillenmayer and G. Staudt, Phys. Rev. C 53, 1336 (1996).
[14] C. Xu and Z. Ren, Nucl. Phys. A 760, 303 (2005).
[15] Z. Ren, C. Xu and Z. Wang, Phys. Rev. C 70, 034304 (2004).
[16] P. R. Chowdhury, C. Samanta and D. N. Basu, Phys. Rev. C 73, 014612 (2006).
[17] J. Blocki, J. Randrup, W. J. Swiastecki, and C.F.Tsang, Ann. Phys. (NY) 105, 427 (1977).
[18] G. Royer and J. Mignen, J. Phys. G: Nucl. Part. Phys. 18, 1781 (1992).
[19] S. Shlomo and J. B. Natowitz, Phys. Rev. C 44, 2878 (1991).
[20] W. D. Myers, Phys. Rev. C 62, 17 (2000).
[21] I. Dutt and R. K. Puri, Phys. Rev. C 81, 047601 (2010).
[22] M. Salehi and O. N. Ghodsi, Chin. Phys. Lett. 30, No.4, 042502 (2013).
[23] V. Zanganeh and N. Wang, Nucl. Phys. A 929, 94 (2014).
[24] A. Winther, Nucl. Phys. A 594,203 (1995).
[25] H. Ngo and C. Ngo, Nucl. Phys. A 348, 140 (1980).
[26] V. Y. Denisov, Phys. Lett. B 526, 315 (2002).
[27] R. K. Puri and R. K. Gupta, J. Phys. G: Nucl. Part. Phys. 18, 903 (1992).
[28] R. K. Gupta, S. Singh, R. K. Puri, A. Sandulescu, W. Greiner and W. Scheid, J. Phys. G: Nucl.
[29] M. Golshanian, O. N. Ghodsi, and R. Gharaei, Mod. Phys. Lett. A, vol. 28, no. 36, pp. 113, (2013).

[30] S. A. Gurvitz, G. Kalbermann, Phys. Rev. Lett. 59, 262 (1987).

[31] D.N. Poenaru, M. Ivascu, A. Sandulescu, W. Greiner, Phys. Rev. C 32, 572 (1985).

[32] G. Royer, R. Moustabchir, Nucl. Phys. A 683, 182 (2001).

[33] H. J. Rose, G. A. Jones, Nature 307, 245 (1984).

[34] D. V. Aleksandrov, et al., JETP. Lett. 40, 909 (1984).

[35] D. N. Basu, Phys. Lett. B 566, 90 (2003).

[36] G. Audi and et al., Chin. Phys. C 36, 1157 (2012).
### Table-I: Comparison of logarithmic half-lives of cluster decays between temperature independent proximity (IND.), temperature dependent proximity (TD.) and experiment data

| Cluster Decay | $l_{\text{min}}$ | $Q_{\text{exp.}}$ | IND. | TD. | Exp. | $\Delta^{\text{IND.}}$ | $\Delta^{\text{TD.}}$ |
|---------------|------------------|-------------------|------|-----|------|--------------------------|--------------------------|
| $^{221}$Fr $\rightarrow ^{14}$C | 3 | 31.29 | 15.86 | 14.94 | 14.5 | -1.36 | -0.44 |
| $^{221}$Ra $\rightarrow ^{14}$C | 3 | 32.40 | 14.56 | 13.66 | 13.4 | -1.16 | -0.26 |
| $^{222}$Ra $\rightarrow ^{14}$C | 0 | 33.05 | 13.15 | 12.28 | 11.0 | -2.15 | -1.28 |
| $^{223}$Ra $\rightarrow ^{14}$C | 4 | 31.83 | 15.75 | 14.82 | 15.2 | -0.55 | 0.37 |
| $^{224}$Ra $\rightarrow ^{14}$C | 0 | 30.54 | 18.19 | 17.22 | 15.7 | -2.49 | -1.52 |
| $^{226}$Ra $\rightarrow ^{14}$C | 0 | 28.19 | 23.61 | 22.51 | 21.2 | -2.41 | -1.31 |
| $^{225}$Ac $\rightarrow ^{14}$C | 4 | 30.47 | 19.52 | 18.52 | 17.2 | -2.32 | -1.32 |
| $^{226}$Th $\rightarrow ^{14}$C | 0 | 30.55 | 20.04 | 19.04 | 15.3 | -4.74 | -3.74 |
| $^{226}$Th $\rightarrow ^{18}$O | 0 | 45.73 | 20.50 | 19.05 | 16.8 | -3.70 | -2.25 |
| $^{224}$Th $\rightarrow ^{14}$C | 0 | 32.93 | 15.11 | 14.20 | 15.7 | 0.58 | 1.49 |
| $^{228}$Th $\rightarrow ^{20}$O | 0 | 44.73 | 23.97 | 22.53 | 20.7 | -3.27 | -1.83 |
| $^{231}$Pa $\rightarrow ^{23}$F | 1 | 51.85 | 26.90 | 25.16 | 26.0 | -0.90 | 0.83 |
| $^{230}$U $\rightarrow ^{22}$Ne | 0 | 61.39 | 23.27 | 21.11 | 19.6 | -3.67 | -1.51 |
| $^{230}$Th $\rightarrow ^{24}$Ne | 0 | 57.76 | 27.92 | 25.72 | 24.6 | -3.32 | -1.12 |
| $^{233}$Pa $\rightarrow ^{24}$Ne | 1 | 60.41 | 24.71 | 22.73 | 22.9 | -1.81 | 0.16 |
| $^{230}$U $\rightarrow ^{24}$Ne | 0 | 61.35 | 24.51 | 22.56 | 18.2 | -6.31 | -4.36 |
| $^{232}$U $\rightarrow ^{24}$Ne | 0 | 62.31 | 22.94 | 21.05 | 20.4 | -2.54 | -0.65 |
| $^{233}$U $\rightarrow ^{24}$Ne | 2 | 60.49 | 25.97 | 23.89 | 24.8 | -1.17 | 0.90 |
| $^{234}$U $\rightarrow ^{24}$Ne | 0 | 58.83 | 28.91 | 26.55 | 26.0 | -2.91 | -0.55 |
| $^{233}$U $\rightarrow ^{25}$Ne | 2 | 60.73 | 26.17 | 24.19 | 24.8 | -1.37 | 0.60 |
| $^{232}$Th $\rightarrow ^{26}$Ne | 0 | 55.97 | 32.56 | 30.32 | 29.0 | -3.56 | -1.32 |
| $^{234}$U $\rightarrow ^{26}$Ne | 0 | 59.47 | 28.94 | 26.91 | 26.0 | -2.94 | -0.91 |
| $^{236}$U $\rightarrow ^{26}$Ne | 0 | 56.75 | 34.10 | 31.67 | 26.0 | -8.10 | -5.67 |
| cluster decay | lmin | $Q_{exp}$ | $IND.$ | $TD.$ | Exp. | $\Delta^{IND.}$ | $\Delta^{TD.}$ |
|---------------|------|----------|--------|-------|-----|----------------|----------------|
| $^{236}\text{Pu} \rightarrow ^{28}\text{Mg}$ | 0    | 79.67    | 23.55  | 21.10 | 21.7| -1.85         | 0.59           |
| $^{237}\text{Np} \rightarrow ^{30}\text{Mg}$ | 2    | 74.79    | 30.53  | 27.74 | 27.6| -2.93         | -0.14          |
| $^{238}\text{Pu} \rightarrow ^{30}\text{Mg}$ | 0    | 76.80    | 28.81  | 26.19 | 25.7| -3.11         | -0.49          |
| $^{241}\text{Am} \rightarrow ^{34}\text{Si}$ | 3    | 93.93    | 28.13  | 24.97 | 25.3| -2.83         | 0.32           |
| $^{242}\text{Cm} \rightarrow ^{34}\text{Si}$ | 0    | 96.52    | 26.13  | 23.17 | 23.2| -2.93         | 0.02           |
| $\chi^2_R \times 10^{-3}$ | —— | —— | 4.96 | 1.91 | —— | —— | —— |
Table-II: Comparison of the calculated logarithmic half-lives between temperature dependent proximity (TD.) with results based on ASAF model [2].

| cluster decay | ASAF | TD. | Δ  | cluster decay | ASAF | TD. | Δ  |
|---------------|------|-----|----|---------------|------|-----|----|
| $^{114}$Ba $\rightarrow ^{12}$C | 10.760 | 10.714 | -0.046 | $^{232}$Pa $\rightarrow ^{23}$F | 27.041 | 28.081 | 1.040 |
| $^{117}$Ba $\rightarrow ^{12}$C | 21.159 | 21.623 | 0.464 | $^{232}$U $\rightarrow ^{26}$Ne | 28.735 | 29.535 | 0.800 |
| $^{119}$Ba $\rightarrow ^{12}$C | 24.044 | 24.624 | 0.580 | $^{232}$Pu $\rightarrow ^{22}$Ne | 21.116 | 22.124 | 1.008 |
| $^{120}$La $\rightarrow ^{12}$C | 23.668 | 24.256 | 0.587 | $^{233}$U $\rightarrow ^{25}$Ne | 23.707 | 24.162 | 0.455 |
| $^{121}$La $\rightarrow ^{12}$C | 27.208 | 27.940 | 0.732 | $^{233}$U $\rightarrow ^{28}$Mg | 25.106 | 25.918 | 0.813 |
| $^{122}$Ce $\rightarrow ^{12}$C | 26.027 | 26.741 | 0.714 | $^{233}$Np $\rightarrow ^{24}$Ne | 22.049 | 22.519 | 0.470 |
| $^{124}$Ce $\rightarrow ^{12}$C | 34.286 | 35.304 | 1.018 | $^{233}$Pu $\rightarrow ^{22}$Ne | 23.483 | 24.967 | 1.484 |
| $^{215}$At $\rightarrow ^{8}$Be | 15.358 | 16.694 | 1.336 | $^{234}$U $\rightarrow ^{24}$Ne | 25.367 | 26.550 | 1.183 |
| $^{218}$Ra $\rightarrow ^{12}$C | 14.007 | 15.194 | 1.186 | $^{234}$U $\rightarrow ^{28}$Mg | 25.176 | 26.074 | 0.898 |
| $^{222}$Ac $\rightarrow ^{12}$C | 12.934 | 14.093 | 1.159 | $^{234}$Np $\rightarrow ^{28}$Mg | 22.795 | 23.059 | 0.264 |
| $^{223}$Th $\rightarrow ^{15}$N | 16.878 | 17.940 | 1.062 | $^{234}$Pu $\rightarrow ^{28}$Mg | 21.889 | 21.856 | -0.033 |
| $^{225}$Np $\rightarrow ^{12}$C | 9.911 | 10.645 | 0.734 | $^{235}$U $\rightarrow ^{25}$Ne | 27.945 | 29.198 | 1.254 |
| $^{225}$U $\rightarrow ^{15}$N | 16.845 | 17.857 | 1.012 | $^{235}$U $\rightarrow ^{28}$Mg | 27.560 | 29.050 | 1.490 |
| $^{227}$Th $\rightarrow ^{22}$Ne | 25.220 | 27.049 | 1.829 | $^{235}$Np $\rightarrow ^{28}$Mg | 22.879 | 23.228 | 0.349 |
| $^{228}$Pu $\rightarrow ^{15}$N | 18.105 | 19.258 | 1.152 | $^{235}$Pu $\rightarrow ^{25}$Ne | 26.781 | 27.633 | 0.852 |
| $^{228}$Th $\rightarrow ^{24}$Ne | 25.307 | 26.338 | 1.031 | $^{235}$Pu $\rightarrow ^{29}$Mg | 25.538 | 25.911 | 0.373 |
| $^{229}$Ac $\rightarrow ^{22}$O | 26.916 | 27.595 | 0.679 | $^{236}$U $\rightarrow ^{26}$Ne | 30.376 | 31.677 | 1.301 |
| $^{229}$Th $\rightarrow ^{24}$Ne | 24.642 | 25.623 | 0.981 | $^{114}$Ba $\rightarrow ^{16}$O | 15.192 | 14.988 | -0.204 |
| $^{229}$Pa $\rightarrow ^{23}$F | 27.024 | 27.898 | 0.875 | $^{117}$Ba $\rightarrow ^{16}$O | 24.113 | 24.468 | 0.355 |
| $^{229}$Pa $\rightarrow ^{24}$Ne | 23.278 | 23.935 | 0.656 | $^{119}$Ba $\rightarrow ^{16}$O | 27.517 | 28.064 | 0.548 |
| $^{230}$Th $\rightarrow ^{23}$F | 28.734 | 29.995 | 1.261 | $^{120}$Ce $\rightarrow ^{16}$O | 17.415 | 17.388 | -0.027 |
| $^{230}$Pa $\rightarrow ^{23}$F | 25.436 | 26.150 | 0.714 | $^{121}$Ce $\rightarrow ^{16}$O | 19.671 | 19.799 | 0.129 |
| $^{230}$Pa $\rightarrow ^{22}$Ne | 25.066 | 26.958 | 1.892 | $^{123}$Ce $\rightarrow ^{16}$O | 24.949 | 25.413 | 0.464 |
| $^{230}$U $\rightarrow ^{24}$Ne | 22.139 | 22.566 | 0.428 | $^{124}$Pr $\rightarrow ^{16}$O | 24.196 | 24.645 | 0.449 |
| $^{231}$U $\rightarrow ^{22}$Ne | 22.688 | 24.111 | 1.423 | $^{218}$Fr $\rightarrow ^{8}$Be | 10.856 | 11.924 | 1.067 |
| $^{221}$Pa $\rightarrow ^{8}$Be | 8.441 | 9.279 | 0.838 |
| Reaction                  | ASAF | TD.  | Δ    | Reaction                  | ASAF | TD.  | Δ    |
|--------------------------|------|------|------|--------------------------|------|------|------|
| $^{231}\text{Th} \rightarrow ^{25}\text{Ne}$ | 26.970 | 28.056 | 1.086 | $^{222}\text{Ac} \rightarrow ^{15}\text{N}$ | 14.665 | 15.497 | 0.832 |
| $^{231}\text{Pa} \rightarrow ^{23}\text{F}$ | 24.509 | 25.152 | 0.643 | $^{233}\text{Th} \rightarrow ^{17}\text{O}$ | 19.915 | 21.289 | 1.374 |
| $^{231}\text{Np} \rightarrow ^{22}\text{Ne}$ | 20.605 | 21.555 | 0.950 | $^{225}\text{Pa} \rightarrow ^{15}\text{N}$ | 14.445 | 15.235 | 0.789 |
| $^{227}\text{U} \rightarrow ^{17}\text{O}$ | 18.959 | 20.233 | 1.274 | $^{235}\text{U} \rightarrow ^{29}\text{Mg}$ | 27.959 | 29.076 | 1.117 |
| $^{227}\text{Pa} \rightarrow ^{22}\text{Ne}$ | 22.813 | 24.119 | 1.306 | $^{235}\text{Np} \rightarrow ^{29}\text{Mg}$ | 27.498 | 28.386 | 0.887 |
| $^{228}\text{Th} \rightarrow ^{22}\text{Ne}$ | 25.723 | 27.714 | 1.991 | $^{235}\text{Pu} \rightarrow ^{28}\text{Mg}$ | 21.263 | 21.151 | -0.112 |
| $^{228}\text{Ac} \rightarrow ^{23}\text{F}$ | 28.811 | 30.074 | 1.263 | $^{236}\text{U} \rightarrow ^{24}\text{Ne}$ | 29.604 | 31.640 | 2.036 |
| $^{228}\text{U} \rightarrow ^{22}\text{Ne}$ | 20.768 | 21.681 | 0.912 | $^{236}\text{U} \rightarrow ^{30}\text{Mg}$ | 29.083 | 30.084 | 1.001 |
| $^{229}\text{Ac} \rightarrow ^{23}\text{F}$ | 27.984 | 29.195 | 1.211 | $^{236}\text{Np} \rightarrow ^{28}\text{Mg}$ | 25.100 | 25.992 | 0.891 |
| $^{229}\text{U} \rightarrow ^{22}\text{Ne}$ | 19.874 | 20.682 | 0.809 | $^{236}\text{Np} \rightarrow ^{30}\text{Mg}$ | 27.581 | 28.140 | 0.559 |
| $^{229}\text{Pa} \rightarrow ^{22}\text{Ne}$ | 22.306 | 23.642 | 1.336 | $^{236}\text{Pu} \rightarrow ^{29}\text{Mg}$ | 26.214 | 26.785 | 0.572 |
| $^{230}\text{Th} \rightarrow ^{22}\text{O}$ | 26.388 | 26.962 | 0.575 | $^{237}\text{Np} \rightarrow ^{30}\text{Mg}$ | 27.163 | 27.708 | 0.545 |
| $^{230}\text{Th} \rightarrow ^{24}\text{Ne}$ | 24.674 | 25.724 | 1.050 | $^{237}\text{Pu} \rightarrow ^{29}\text{Mg}$ | 24.362 | 24.614 | 0.252 |
| $^{230}\text{Pa} \rightarrow ^{24}\text{Ne}$ | 22.249 | 22.793 | 0.544 | $^{237}\text{Pu} \rightarrow ^{32}\text{Si}$ | 25.273 | 25.624 | 0.351 |
| $^{230}\text{U} \rightarrow ^{20}\text{O}$ | 25.653 | 26.672 | 1.019 | $^{237}\text{Am} \rightarrow ^{29}\text{Mg}$ | 27.384 | 28.142 | 0.758 |
| $^{231}\text{Pa} \rightarrow ^{22}\text{O}$ | 29.269 | 30.111 | 0.842 | $^{238}\text{Pu} \rightarrow ^{28}\text{Mg}$ | 25.341 | 26.288 | 0.947 |
| $^{231}\text{Th} \rightarrow ^{24}\text{Ne}$ | 27.253 | 28.795 | 1.542 | $^{238}\text{Pu} \rightarrow ^{30}\text{Mg}$ | 25.954 | 26.195 | 0.240 |
| $^{231}\text{U} \rightarrow ^{22}\text{O}$ | 33.553 | 34.746 | 1.193 | $^{238}\text{Pu} \rightarrow ^{33}\text{Si}$ | 28.717 | 29.571 | 0.854 |
| $^{231}\text{Pa} \rightarrow ^{24}\text{Ne}$ | 22.144 | 22.722 | 0.579 | $^{238}\text{Am} \rightarrow ^{29}\text{Mg}$ | 25.778 | 26.267 | 0.490 |
| $^{232}\text{Th} \rightarrow ^{26}\text{Ne}$ | 29.211 | 30.325 | 1.114 | $^{238}\text{Am} \rightarrow ^{32}\text{Si}$ | 23.191 | 22.941 | -0.250 |
| $^{232}\text{U} \rightarrow ^{24}\text{Ne}$ | 20.755 | 21.050 | 0.295 | $^{238}\text{Cm} \rightarrow ^{28}\text{Mg}$ | 22.733 | 22.893 | 0.159 |
| $^{232}\text{U} \rightarrow ^{28}\text{Mg}$ | 25.065 | 25.804 | 0.739 | $^{239}\text{Pu} \rightarrow ^{30}\text{Mg}$ | 27.997 | 28.712 | 0.715 |
| $^{233}\text{U} \rightarrow ^{24}\text{Ne}$ | 23.106 | 23.847 | 0.741 | $^{239}\text{Pu} \rightarrow ^{34}\text{Si}$ | 27.318 | 27.455 | 0.137 |
| $^{233}\text{U} \rightarrow ^{26}\text{Ne}$ | 27.197 | 27.825 | 0.628 | $^{239}\text{Am} \rightarrow ^{32}\text{Si}$ | 23.367 | 23.227 | -0.140 |
| $^{233}\text{Np} \rightarrow ^{22}\text{Ne}$ | 26.062 | 28.111 | 2.049 | $^{239}\text{Am} \rightarrow ^{34}\text{Si}$ | 26.224 | 25.957 | -0.267 |
| $^{233}\text{Np} \rightarrow ^{25}\text{Ne}$ | 27.596 | 28.557 | 0.961 | $^{240}\text{Pu} \rightarrow ^{34}\text{Si}$ | 27.029 | 27.170 | 0.141 |
| $^{233}\text{Pu} \rightarrow ^{24}\text{Ne}$ | 22.945 | 23.473 | 0.527 | $^{240}\text{Am} \rightarrow ^{34}\text{Si}$ | 25.576 | 25.215 | -0.361 |
| $^{234}\text{U} \rightarrow ^{26}\text{Ne}$ | 26.359 | 26.914 | 0.555 | $^{240}\text{Cm} \rightarrow ^{32}\text{Si}$ | 21.634 | 20.979 | -0.655 |
| $^{234}\text{Np} \rightarrow ^{25}\text{Ne}$ | 25.498 | 26.186 | 0.688 | $^{241}\text{Am} \rightarrow ^{33}\text{Si}$ | 28.547 | 29.451 | 0.904 |
| $^{234}\text{Pu} \rightarrow ^{24}\text{Ne}$ | 23.037 | 23.629 | 0.592 | $^{241}\text{Cm} \rightarrow ^{32}\text{Si}$ | 23.649 | 23.592 | -0.058 |
| Cluster Decay | ASAF | TD. | Δ    | Cluster Decay | ASAF | TD. | Δ    |
|---------------|------|-----|------|---------------|------|-----|------|
| $^{235}$U $\rightarrow$ $^{24}$Ne | 27.478 | 29.079 | 1.601 | $^{242}$Cm $\rightarrow$ $^{34}$Si | 23.938 | 23.174 | -0.764 |
| $^{235}$U $\rightarrow$ $^{26}$Ne | 28.323 | 29.244 | 0.921 | $^{242}$Cf $\rightarrow$ $^{33}$Si | 26.205 | 26.179 | -0.026 |
| $^{242}$Cf $\rightarrow$ $^{36}$S | 24.037 | 23.064 | -0.973 | $^{237}$Am $\rightarrow$ $^{28}$Mg | 22.160 | 22.243 | 0.083 |
| $^{244}$Cm $\rightarrow$ $^{34}$Si | 27.261 | 27.461 | 0.200 | $^{237}$Am $\rightarrow$ $^{32}$Si | 23.567 | 23.352 | -0.215 |
| $^{244}$Cf $\rightarrow$ $^{36}$S | 23.781 | 22.852 | -0.929 | $^{238}$Pu $\rightarrow$ $^{29}$Mg | 28.028 | 29.105 | 1.077 |
| $^{249}$No $\rightarrow$ $^{42}$S | 31.708 | 30.886 | -0.822 | $^{238}$Pu $\rightarrow$ $^{32}$Si | 25.484 | 25.966 | 0.482 |
| $^{249}$No $\rightarrow$ $^{48}$Ca | 27.237 | 23.322 | -3.915 | $^{238}$Am $\rightarrow$ $^{28}$Mg | 23.892 | 24.410 | 0.518 |
| $^{250}$No $\rightarrow$ $^{48}$Ca | 26.894 | 22.916 | -3.979 | $^{238}$Am $\rightarrow$ $^{30}$Mg | 28.052 | 28.592 | 0.540 |
| $^{251}$No $\rightarrow$ $^{48}$Ca | 26.646 | 22.633 | -4.013 | $^{238}$Am $\rightarrow$ $^{33}$Si | 26.006 | 26.035 | 0.029 |
| $^{252}$Cf $\rightarrow$ $^{50}$Ca | 32.209 | 30.055 | -2.154 | $^{238}$Cm $\rightarrow$ $^{32}$Si | 22.065 | 21.411 | -0.655 |
| $^{252}$No $\rightarrow$ $^{48}$Ca | 26.321 | 22.250 | -4.071 | $^{239}$Pu $\rightarrow$ $^{33}$Si | 27.436 | 27.461 | 0.029 |
| $^{253}$Fm $\rightarrow$ $^{48}$Ca | 27.932 | 24.796 | -3.137 | $^{239}$Am $\rightarrow$ $^{33}$Si | 26.563 | 26.798 | 0.236 |
| $^{254}$No $\rightarrow$ $^{46}$Ca | 26.810 | 23.880 | -2.930 | $^{239}$Cm $\rightarrow$ $^{32}$Si | 21.546 | 20.818 | -0.728 |
| $^{254}$No $\rightarrow$ $^{50}$Ca | 29.401 | 25.731 | -3.670 | $^{240}$Am $\rightarrow$ $^{33}$Si | 25.545 | 25.602 | 0.056 |
| $^{255}$No $\rightarrow$ $^{50}$Ca | 28.718 | 24.871 | -3.846 | $^{240}$Cm $\rightarrow$ $^{30}$Mg | 28.773 | 29.466 | 0.693 |
| $^{256}$No $\rightarrow$ $^{50}$Ca | 27.896 | 23.813 | -4.083 | $^{240}$Cm $\rightarrow$ $^{34}$Si | 25.142 | 24.544 | -0.598 |
| $^{257}$No $\rightarrow$ $^{50}$Ca | 27.034 | 22.714 | -4.320 | $^{241}$Am $\rightarrow$ $^{34}$Si | 25.285 | 24.923 | -0.362 |
| $^{258}$No $\rightarrow$ $^{48}$Ca | 27.071 | 23.640 | -3.431 | $^{242}$Cm $\rightarrow$ $^{32}$Si | 25.389 | 25.858 | 0.469 |
| $^{258}$Rf $\rightarrow$ $^{48}$Ca | 25.519 | 21.218 | -4.301 | $^{242}$Cf $\rightarrow$ $^{32}$Si | 22.321 | 21.737 | -0.584 |
| $^{258}$Rf $\rightarrow$ $^{50}$Ca | 28.953 | 25.076 | -3.876 | $^{242}$Cf $\rightarrow$ $^{34}$Si | 26.373 | 25.969 | -0.404 |
| $^{258}$Rf $\rightarrow$ $^{51}$Ti | 27.699 | 23.286 | -4.413 | $^{243}$Cm $\rightarrow$ $^{34}$Si | 25.638 | 25.360 | -0.278 |
| $^{258}$Rf $\rightarrow$ $^{53}$Ti | 29.963 | 25.593 | -4.370 | $^{244}$Cf $\rightarrow$ $^{34}$Si | 25.575 | 25.095 | -0.480 |
| $^{259}$No $\rightarrow$ $^{48}$Ca | 28.184 | 25.229 | -2.955 | $^{246}$Cf $\rightarrow$ $^{38}$S | 26.050 | 25.058 | -0.991 |
| $^{260}$No $\rightarrow$ $^{48}$Ca | 29.194 | 26.700 | -2.493 | $^{249}$Cf $\rightarrow$ $^{46}$Ar | 31.476 | 29.809 | -1.668 |
| $^{261}$No $\rightarrow$ $^{50}$Ca | 29.409 | 26.204 | -3.205 | $^{249}$Cf $\rightarrow$ $^{50}$Ca | 33.768 | 31.906 | -1.862 |
| $^{236}$Np $\rightarrow$ $^{29}$Mg | 26.044 | 26.701 | 0.657 | $^{251}$Cf $\rightarrow$ $^{46}$Ar | 30.023 | 28.044 | -1.979 |
| $^{236}$Pu $\rightarrow$ $^{28}$Mg | 21.180 | 21.107 | -0.073 | $^{252}$Cf $\rightarrow$ $^{46}$Ar | 29.450 | 27.371 | -2.079 |
| $^{236}$Pu $\rightarrow$ $^{30}$Mg | 27.608 | 28.051 | 0.444 | $^{252}$Md $\rightarrow$ $^{46}$Ca | 28.135 | 25.713 | -2.422 |
| Cluster Decay | ASAF | TD.  | Δ    | Cluster Decay | ASAF | TD.  | Δ    |
|---------------|------|------|------|---------------|------|------|------|
| $^{237}$Np → $^{33}$Si | 27.691 | 28.824 | 1.133 | $^{290}$Lv → $^{28}$Mg | 28.151 | 31.051 | 2.900 |
| $^{237}$Pu → $^{30}$Mg | 26.473 | 26.752 | 0.279 | $^{294}$118 → $^{50}$Ca | 30.932 | 28.049 | -2.883 |
| $^{254}$Md → $^{48}$Ca | 26.229 | 22.387 | -3.843 | $^{252}$No → $^{50}$Ca | 30.370 | 26.912 | -3.458 |
| $^{254}$No → $^{48}$Ca | 25.771 | 21.616 | -4.155 | $^{253}$No → $^{50}$Ca | 29.953 | 26.411 | -3.542 |
| $^{255}$No → $^{48}$Ca | 25.129 | 20.802 | -4.328 | $^{294}$118 → $^{48}$Ca | 28.298 | 25.294 | -3.004 |
| $^{256}$No → $^{48}$Ca | 24.856 | 20.481 | -4.374 | $^{294}$118 → $^{34}$Si | 28.340 | 29.541 | 1.202 |
| $^{257}$Md → $^{50}$Ca | 25.982 | 22.075 | -3.907 | $^{294}$118 → $^{28}$Mg | 26.362 | 28.647 | 2.285 |
| $^{258}$No → $^{50}$Ca | 28.580 | 25.039 | -3.540 | $^{296}$120 → $^{50}$Ca | 29.703 | 26.144 | -3.559 |
| $^{258}$Rf → $^{49}$Ca | 27.898 | 24.045 | -3.854 | $^{296}$120 → $^{48}$Ca | 26.588 | 22.688 | -3.900 |
| $^{258}$Rf → $^{52}$Ti | 26.451 | 21.964 | -4.488 | $^{296}$120 → $^{34}$Si | 26.225 | 26.588 | 0.362 |
| $^{258}$Rf → $^{54}$Ti | 27.570 | 22.681 | -4.889 | $^{296}$120 → $^{28}$Mg | 23.811 | 25.164 | 1.353 |
| $^{259}$No → $^{50}$Ca | 30.359 | 25.722 | -4.636 | $^{296}$120 → $^{22}$Ne | 21.380 | 23.695 | 2.315 |
| $^{261}$No → $^{48}$Ca | 27.544 | 23.526 | -4.019 | $^{271}$Sg → $^{50}$Ca | 35.508 | 34.739 | -0.769 |
| $^{262}$No → $^{50}$Ca | 30.204 | 28.182 | -2.022 | $^{271}$Sg → $^{48}$Ca | 35.301 | 35.561 | 0.260 |
| $^{271}$Sg → $^{50}$Ca | 34.793 | 33.712 | -1.081 | $^{275}$Hs → $^{50}$Ca | 33.969 | 33.627 | -0.342 |
| $^{275}$Hs → $^{48}$Ca | 32.585 | 35.222 | 2.637 | $^{275}$Hs → $^{34}$Si | 26.760 | 30.290 | -3.541 |
| $^{272}$Ds → $^{50}$Ca | 30.114 | 27.558 | -2.556 | $^{272}$Ds → $^{28}$Mg | 26.238 | 29.287 | 3.049 |
| $^{272}$Ds → $^{22}$Ne | 30.079 | 29.703 | -2.375 | $^{290}$Lv → $^{50}$Ca | 29.710 | 27.344 | -2.367 |
| $^{290}$Lv → $^{48}$Ca | 29.450 | 31.000 | 1.550 | $^{290}$Lv → $^{34}$Si | 29.450 | 31.000 | 1.550 |