LIGHT NUCLEUS EMISSION WITHIN A GENERALIZED LIQUID DROP MODEL AND QUASI-MOLECULAR SHAPES

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Light nucleus emission within a generalized liquid drop model and quasi-molecular shapes

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Abstract

The potential barrier governing the light nucleus emission has been determined within a generalized liquid drop model including the proximity effects between the light and daughter nuclei and adjusted to reproduce the experimental Q value. The partial decay half-lives have been calculated within the WKB barrier penetration probability, without introducing preformation factor. The agreement with the experimental data for the ^{14}C, ^{20}O, ^{23}F, $^{24-26}$Ne, $^{28-30}$Mg and ^{32}Si emission is correct. Predictions for other possible decays are presented meeting two criteria : partial half-life $\leq 10^{30}s$ and branching ratio relative to α emission $\geq 10^{-24}$. An analytic formula is proposed for the half-life of the light nucleus decay.

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1 Introduction

In 1980 [1], the possibility of light nucleus emission (often called cluster radioactivity) by heavy nuclei beyond alpha emission was pointed out within the fragmentation theory [2–4]. Previously, this theory which takes into account the shell closure effects of one or both the reaction partners and the parent nucleus had already allowed to successfully explain the cold fusion process and the different fission channels. In 1984 the emission of a ^{14}C nucleus by ^{223}Ra was observed [5,6]. Presently, the spontaneous emission of ^{14}C, ^{20}O, ^{23}F, $^{24-26}$Ne, ^{28,30}Mg and ^{32}Si by radioactive isotopes of Fr, Ra, Ac, Pa, Th, U and Pu has been observed with partial half-lives varying from 10^{11} up to $10^{28}s$ and a branching ratio relative to α emission from 10^{-9} down to 10^{-16} [7–9]. The daughter nucleus is an almost closed shell spherical nucleus, more precisely ^{211}Bi, $^{207-212}$Pb,$^{206-208}$Hg or ^{207}Tl. This confirms that the Q value and particularly its microscopic part due to shell and pairing effects plays a main role to select the possible emitted light nuclei.
New possible islands of light fragment emitters around the doubly magic nucleus ^{100}Sn and in the proton and neutron range $Z = 56 - 64$ and $N = 58 - 72$ have been predicted [10–13]. A first experiment has concluded to the nonobservation of ^{12}C emission by ^{114}Ba [14].
This very rare spontaneous emission from an initial almost spherical nucleus is a tunneling process through a potential barrier leading finally to two separated light and daughter nuclei. A good estimate of the partial half-life requires a good combination of the shape sequence, the deformation energy, the inertia parameter and the reproduction of the experimental Q value. Different asymmetric fission models have been developed [15,16]. In such approaches, the decay constant λ is simply the product of the barrier penetrability P and a constant assault frequency ν_0. More flexible preformed cluster models have been also proposed [17,18]. Then, the assault frequency ν_0 may vary with the size of the emitted light nucleus and a third factor, the cluster preformation probability, allows to empirically follow the experimental data.
In two preceding works [19,20], it has been shown that the partial half-lives of the α decay and the light nucleus emission might be reproduced within a generalized liquid drop model (GLDM) taking into account both the nuclear proximity energy, an accurate nuclear radius, the decay asymmetry and assuming that the decay path is the fusion-like second fission valley where the rupture of the neck between the fragments occurs before negotiating of the barrier.
The purpose of the present work is to determine from this GLDM complete tables given, for the most probable light nucleus emissions, the main characteristics of their potential barriers and, above all, their partial half-lives. In addition to the mass region where light fragment emissions have already been observed, the possible island of emitters around $A = 120$ and the heaviest mass region ($A \geq 250$) have also been investigated. A simple analytic formula

given the partial half-life of light nucleus emission is also finally proposed.

2 Generalized Liquid Drop Model

The macroscopic total energy is determined within the generalized liquid drop model which has already been used to describe the fission [21,22] and fusion [23,24] processes and the α emission [20].

$$E = E_V + E_S + E_C + E_N. \tag{1}$$

For one-body shapes, the volume E_V, surface E_S and Coulomb E_C energies are given by:

$$E_V = -15.494(1 - 1.8I^2)A \ MeV, \tag{2}$$

$$E_S = 17.9439(1 - 2.6I^2)A^{2/3}(S/4\pi R_0^2) \ MeV, \tag{3}$$

$$E_C = 0.6e^2(Z^2/R_0) \times 0.5 \int (V(\theta)/V_0)(R(\theta)/R_0)^3 \sin\theta d\theta. \tag{4}$$

I is the relative neutron excess and S the surface of the deformed nucleus. $V(\theta)$ is the electrostatic potential at the surface and V_0 the surface potential of the sphere.
The effective sharp radius R_0 has been chosen as:

$$R_0 = 1.28A^{1/3} - 0.76 + 0.8A^{-1/3} \ fm. \tag{5}$$

This later formula allows to take into account the increase of the ratio $r_0 = R_0/A^{1/3}$ with the mass; for example, $r_0 = 1.11fm$ for ^{20}Ne and $r_0 = 1.18fm$ for ^{240}Pu.
When the fragments are separated:

$$E_v = -15.494\left[(1 - 1.8I_1^2)A_1 + (1 - 1.8I_2^2)A_2\right] \ MeV, \tag{6}$$

$$E_S = 17.9439\left[(1 - 2.6I_1^2)A_1^{2/3} + (1 - 2.6I_2^2)A_2^{2/3}\right] \ MeV, \tag{7}$$

$$E_C = 0.6e^2Z_1^2/R_1 + 0.6e^2Z_2^2/R_2 + e^2Z_1Z_2/r, \tag{8}$$

where A_i,Z_i,R_i and I_i are the masses, charges, radii and relative neutron excesses of the fragments. r is the distance between the mass centres.

The radii of the two emitted fragments have been calculated from the radius of the decaying nucleus to ensure volume conservation and final asymmetry.

$$R_1 = R_0(1+\beta^3)^{-1/3}, \tag{9}$$

$$R_2 = R_0\beta(1+\beta^3)^{-1/3}, \tag{10}$$

where

$$\beta = \frac{1.28A_2^{1/3} - 0.76 + 0.8A_2^{-1/3}}{1.28A_1^{1/3} - 0.76 + 0.8A_1^{-1/3}}. \tag{11}$$

The discontinuity of a few MeV appearing at the contact point between the nascent spherical fragments when Z_1/A_1 and Z_2/A_2 are very different has been substracted linearly from the contact point to the sphere to follow the progressive rearrangement of the nuclear matter before separation.
The surface energy E_S takes only into account the effects of the surface tension forces in a half space and does not include the contribution due to the attractive nuclear forces between the surfaces in regard in the neck or the gap between the fragments. The nuclear proximity energy term E_N allows to take into account these additional surface effects when a neck or a gap appears.

$$E_N(r) = 2\gamma \int_{h_{min}}^{h_{max}} \Phi\left[D(r,h)/b\right] 2\pi h dh, \tag{12}$$

where h is the transverse distance varying from the neck radius or zero to the height of the neck border. D is the distance between the opposite infinitesimal surfaces in regard and b the surface width fixed at 0.99 fm. Φ is the proximity function of Feldmeier [25]. The surface parameter γ is the geometric mean between the surface parameters of the two fragments:

$$\gamma = 0.9517\sqrt{(1-2.6I_1^2)(1-2.6I_2^2)}\ MeV fm^{-2}. \tag{13}$$

In this model the surface diffuseness is not considered and the proximity energy vanishes when there is no neck as for ellipsoids for example.
This additional term in the usual development of the liquid drop model is not a small correction ; for example, at the contact point between a ^{14}C nucleus and a ^{209}Pb one, the proximity energy reaches $-24MeV$. The different terms of this GLDM and the selected parameter set have allowed to reproduce accurately the fusion barrier heights and radii [23,24] and the symmetric and asymmetric fission barrier heights [21,26].
Finally, the microscopic corrections such as shell effects and pairing have been

empirically taken into account in adding at the macroscopic energy of the initial decaying nucleus the difference between the experimental and theoretical Q values with a linear attenuation vanishing at the rupture point between the nascent fragments.

3 Quasi-molecular shapes

The shape sequence already used to describe the asymmetric fusion [23] and fission [26] and the alpha emission [20] has been retained since it leads rapidly to the formation of a deep neck while keeping almost spherical ends (see Fig. 1) and, later on, to tangent spherical fragments. Indeed, it is very unlikely that the light nucleus emission leads to elongated fragments contracting after separation. Similar compact shapes have been also assumed to calculate the deformation energy of superheavy nuclei synthesized by fusion reactions [27] and of rotating superdeformed and hyperdeformed nuclei [28,29].
Within this quasi-molecular shape sequence, the future emitted particle and daughter nucleus are portions of elliptic lemniscatoids joined on a plane perpendicular to the elongation axis. This implicitly supposes that the light particle is rather formed at the surface of the mother nucleus.

4 Potential barriers and half-lives of light nucleus emission

As an example, the potential barrier governing the ^{14}C emission from ^{223}Ra is displayed in Fig. 2. The top of the high and sharp peak of the so-called pure Coulomb barrier corresponds to two tangent spherical fragments. The proximity energy lowers the Coulomb barrier by 15.5 MeV and shifts of 1.7 fm the peak towards a more external position. Consequently, the approaches using still this pure Coulomb barrier seem very rough and naturally necessitate artificial compensation to obtain reasonable half-lives. When the proximity forces are considered, the decay barrier is a barrier standing against scission of the one-body shape. The contact point between the spherical nascent fragments is attained before reaching the barrier top which corresponds to two separated fragments maintained in an unstable equilibrium between the attractive nuclear proximity forces and the repulsive Coulomb forces. The one-body shapes appear at the beginning of the decay process and the two-body configurations compose the main part of the path leading to the exit point where the Coulomb energy corresponds to the released energy Q.
In an unified fission model, the decay constant of the light nucleus emission is simply defined as

$$\lambda = \nu_0 P, \tag{14}$$

without preformation factor. The assault frequency ν_0 has been taken as

$$\nu_0 = 10^{20}\ s^{-1}. \tag{15}$$

The barrier penetrability P is calculated within the action integral

$$P = exp[-\frac{2}{\hbar}\int_{R_{in}}^{R_{out}}\sqrt{2B(r)(E(r) - E(sphere))}dr], \tag{16}$$

where R_{in} is the distance between the mass centres of the portions of the initial sphere separated by a plane perpendicular to the deformation axis to assume volume conservation of the future fragments. R_{out} is simply $e^2 Z_c Z_d/Q$.
The inertia B(r) has been chosen as

$$B(r) = \mu(1 + 1.5f(r)) \tag{17}$$

where

$$f(r) = \begin{cases} \sqrt{\frac{R_{cont}-r}{R_{cont}-R_{in}}}, r \leq R_{cont} \\ 0, r \geq R_{cont} \end{cases} \tag{18}$$

The partial half-life is related to the decay constant λ by

$$T_{1/2} = \frac{ln2}{\lambda}. \tag{19}$$

This procedure is now adopted to determine in an unified way the half-lives for the light nucleus and alpha emissions. The small changes relatively to the two preceding works [19,20] must be explained. Within this GLDM, the whole set of α decay half-lives is better reproduced when $\nu_0 = 10^{20}\ s^{-1}$ than $2.5.10^{20}\ s^{-1}$ previously adopted in Ref. [19]. Then the inertia selected before was obliged to change. The present inertia, illustrated on an example in Fig. 3, simulates a rapid variation of the friction force effects only at the moment of the neck rupture between the nascent fragments. It has been shown recently [29] that states corresponding to two spheres joined by a small neck might be stable during a relatively long time. In Ref. [20] the inner point was taken as the contact point between the α particle and the daughter nucleus. Now the tunneling process starts from the sphere configuration as in Ref. [19]. This does not affect the α decay half-lives since the deformation energy is small or even negative till the rupture point between the fragments.
The half-lives and potential barrier characteristics for decays meeting the two criteria: partial half-life $\leq 10^{30}s$ and branching ratio relative to α emission

$\geq 10^{-24}$ are given in tables 1, 2 and 3. The predicted half-lives agree with the still sparse experimental data obtained for trans-radium parents. It is interesting to observe that the successful experiments correspond to a subtle combination of a favorable branching ratio relative to α emission and a not too long half-life. In this first mass region other light nucleus emissions have about the same favourable characteristics and should be, perhaps, observable; for example : ^{14}C from ^{222,223}Fr, ^{225}Ra, ^{223,224,226}Ac and ^{224}Th, ^{20}O from ^{227,228}Ac, ^{22}O from ^{229}Ac,^{230}Th, ^{23}F from ^{229}Ac, ^{232}Pa, ^{24}Ne from ^{230}Pa, ^{25}Ne from ^{231}Th, ^{28}Mg from ^{234,235,236}Np, ^{235}Pu, ^{29}Mg from ^{235}U, ^{236}Np and ^{30}Mg from ^{236}Np.
The GLDM and the selection criteria leads also to a possible island of light nucleus emission around $A = 120$. Only the emission of ^{12}C and ^{16}O seems possible (see table 2). The branching ratio relative to α decay is very favourable and the light nucleus emission is even more probable than the α decay for some nuclei. Unfortunately, most of these possible emitters must be formed in heavy-ion collisions or have short total half-lives. The possibility of the emission of ^{12}C by ^{114}Ba has been intensively investigated experimentally but has not been observed till today [14]. Other decays from these neutron deficient isotopes seem possible.
In the heaviest mass region (see table 3) the very light nucleus decay mode seems very unlikeky. Only emission of medium nuclei around ^{48}Ca meets the selection criteria ; the emission of ^{48}Ca by ^{255,256}No and ^{50}Ca by ^{259}No being perhaps the most probable.

5 Analytic formula for the half-life of the light nucleus emission

Recently [20], new accurate analytic formulas have been proposed for the α decay half-lives. The input data are only the mass and charge of the α emitter and the experimental Q_α. For the half-lives of the light nucleus emission, different expressions have been advanced [31,32]. A fitting procedure applied on a set of 144 cluster decay half-lives predicted by the GLDM leads to the following formula with a rms deviation of 0.42.

$$Log_{10}T_{1/2}(s) = -11.035 + R_{cont}\sqrt{A_{12}Q_{exp}}[-4.311 - \frac{1.17277}{\sqrt{Q_{exp}}}$$
$$-0.054618\sqrt{\frac{Q_{exp}}{A_{12}R_{cont}}} + \frac{1.62744}{\sqrt{x}} + 4.4956\sqrt{x} - 1.7526x], \qquad (20)$$

where

$$x = \frac{R_{cont}Q_{exp}}{e^2 Z_c Z_d} \qquad (21)$$

and

$$A_{12} = \frac{A_1 A_2}{A_1 + A_2}. \tag{22}$$

The input data are the charge product $Z_c Z_d$, the experimental Q value and the mass numbers A_1 and A_2 which allow to determine the dimensionless reduced mass A_{12} and R_{cont} via the formulas (5, 9-11).

6 Summary and conclusion

The potential barrier governing the light nucleus emission has been determined within a generalized liquid drop model previously defined and used to study the fusion, fission and α emission. No parameter has been changed. The effects of the proximity forces between the light and daughter nuclei are included and the potential energy is adjusted to reproduce the experimental Q value.
The selected shape sequence leads rapidly to two tangent spherical nuclei. The light nucleus decay half-lives have been calculated within the WKB barrier penetration probability without preformation factor. The experimental data for ^{14}C, ^{20}O, ^{23}F, ^{24,26}Ne, ^{28,30}Mg and ^{32}Si are correctly reproduced. Therefore, within the GLDM and the experimental Q value, the emission of the light nuclei can be described in an unified way as a spontaneous tunneling process via quasi-molecular shapes like the α emission and the asymmetric fission.
Predictions are presented for other possible light nucleus emission meeting two criteria : partial half-life $\leq 10^{30} s$ and branching ratio relative to α emission $\geq 10^{-24}$. About thirty new decays corresponding to emission of ^{14}C, ^{20,22}O, ^{23}F, ^{24,25}Ne, $^{28-30}$Mg seem actually observable. A possible island of ^{12}C and ^{16}O emitters exists around $A = 120$ but most of these nuclei must be formed in heavy-ion reactions or have short total half-lives. For the heaviest nuclei, only the observation of the ^{48,50}Ca and ^{46}Ar emission seems to be possible. An analytic formula is proposed for the half-life of the light nucleus emission.

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Table captions

Table 1. Half-lives and potential barrier characteristics for light nucleus emission from parent nuclei with mass $215 \leq A \leq 249$. R_{in} and R_{out} are the inner and outer turning points. R_{cont} is the distance between the centres of the spherical light and daughter nuclei at the contact point. R_{bar} gives the position of the barrier top. E_{bar} is the decay barrier height while the Q value is extracted from [30]. The predicted half-life and the logarithm of the ratio between the α and light nucleus half-lives are given in the two last columns. The experimental cluster decay half-lives are also given [7–9].

Table 2. Same as table 1 but for $A \leq 130$. There is no experimental data.

Table 3. Same as table 2 but for $250 \leq A$.

Figure captions

Fig. 1. Shape evolution in the deformation path through compact quasi-molecular configurations. The nuclei are spherical when they are separated.

Fig. 2. Potential barrier including empirical microscopic corrections against emission of ^{14}C from the ^{223}Ra mother nucleus. The dashed and solid lines correspond respectively to the energy relatively to the sphere without and with a nuclear proximity energy term. r is the centre-of-mass distance.

Fig. 3. Relative inertia B(r) during the ^{14}C emission from the ^{223}Ra mother nucleus.

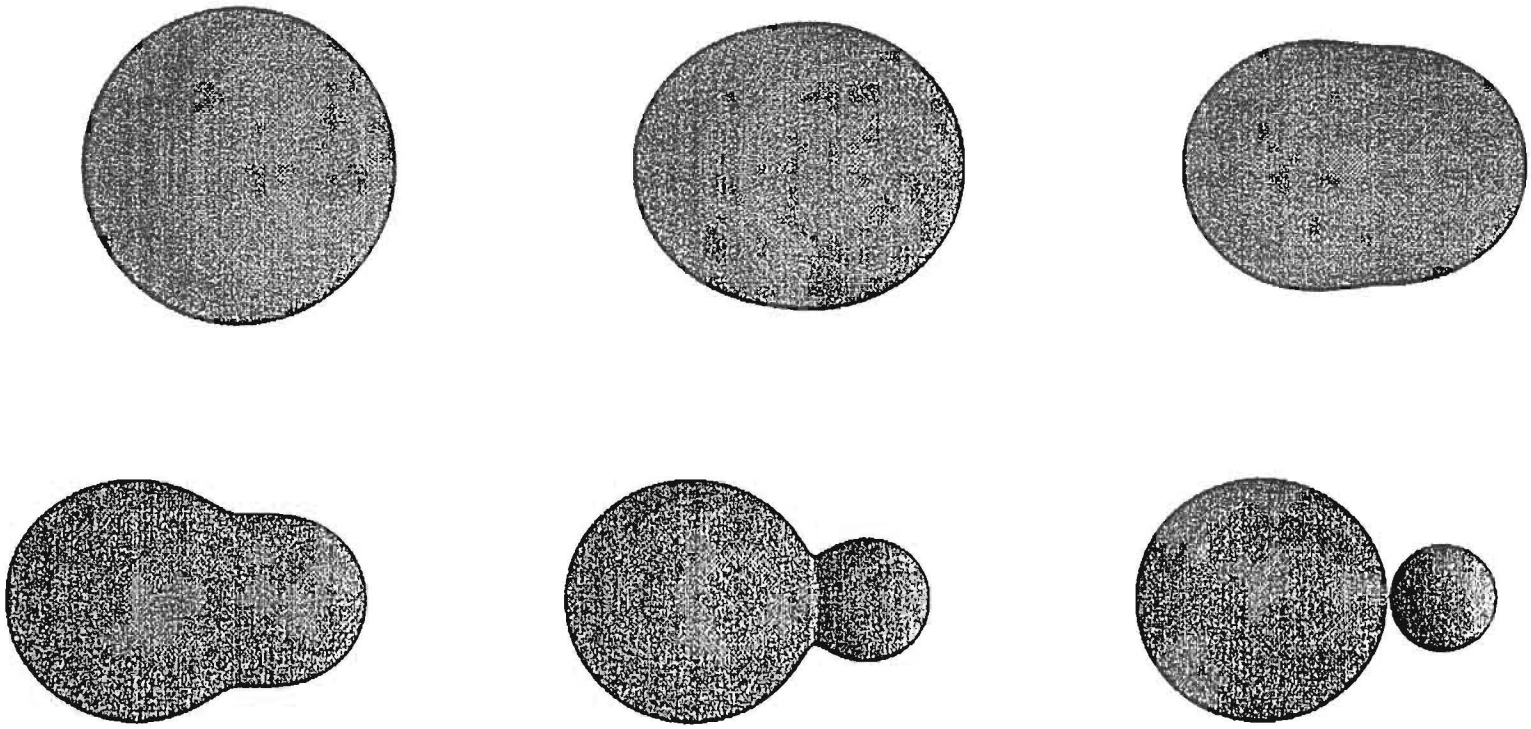

Figure 1

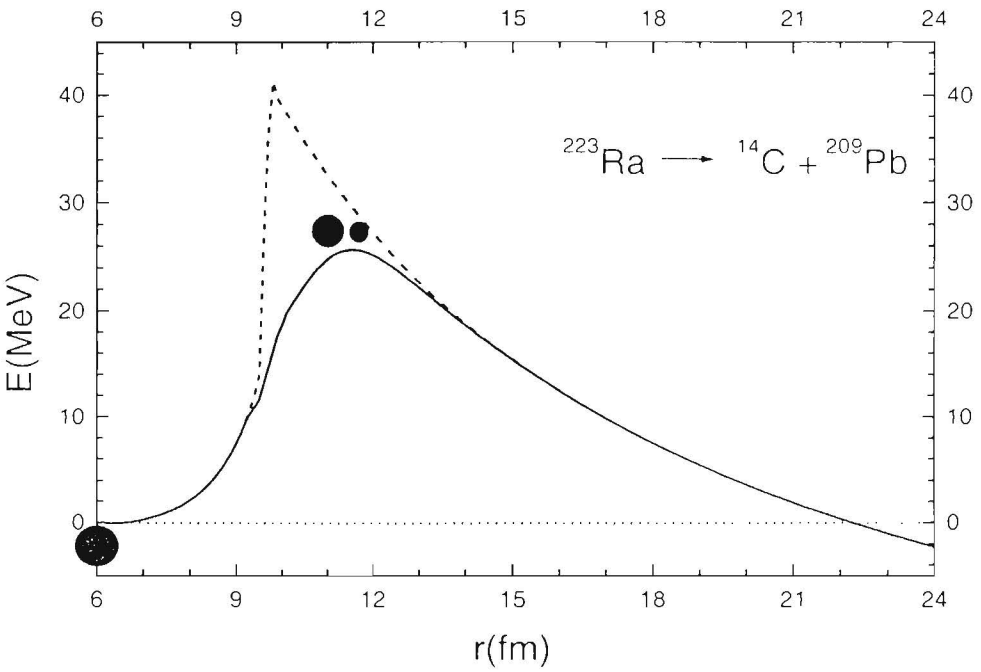

Figure 2

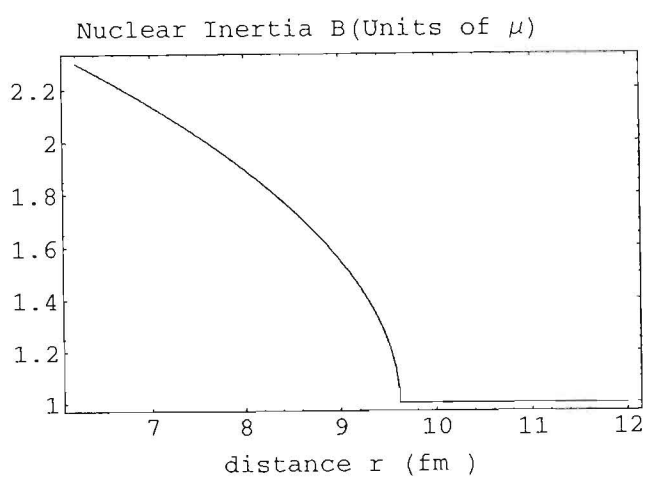

Figure 3

Table 1

Emitter and cluster	R_{in} (fm)	$R_{cont} = R_1 + R_2$ (fm)	R_{bar} (fm)	R_{out} (fm)	E_{bar} (MeV)	Q_{exp} (MeV)	Theoretical $T_{1/2}$(s)	Experimental $T_{1/2}$(s)	$Log_{10}(T_\alpha/T_{cl})$
$^{215}At \rightarrow {}^{8}Be + {}^{207}Tl$	6.3	9.2 = 2.2 + 7.0	11.1	31.4	24.4	14.84	1.3×10^{17}	--	-21.59
$^{215}Rn \rightarrow {}^{8}Be + {}^{207}Pb$	6.3	9.2 = 2.2 + 7.0	11.1	28.9	23.4	16.34	1.3×10^{13}	--	-19.03
$^{216}At \rightarrow {}^{8}Be + {}^{208}Tl$	6.3	9.2 = 2.2 + 7.0	11.1	33.2	25.1	14.06	7.5×10^{19}	--	-23.69
$^{216}Rn \rightarrow {}^{8}Be + {}^{208}Pb$	6.3	9.2 = 2.2 + 7.0	11.1	27.7	22.6	17.06	8.8×10^{10}	--	-15.15
$^{216}Fr \rightarrow {}^{8}Be + {}^{208}Bi$	6.3	9.2 = 2.2 + 7.0	11.1	28.3	23.3	16.91	1.5×10^{12}	--	-18.62
$^{216}Ra \rightarrow {}^{8}Be + {}^{208}Po$	6.3	9.2 = 2.2 + 7.0	11.1	30.6	24.9	15.82	2.2×10^{16}	--	-23.27
$^{216}Ac \rightarrow {}^{8}Be + {}^{208}At$	6.3	9.2 = 2.2 + 7.0	11.1	31.2	25.5	15.68	4.2×10^{17}	--	-23.58
$^{217}Rn \rightarrow {}^{8}Be + {}^{209}Pb$	6.3	9.2 = 2.2 + 7.0	11.1	28.9	23.3	16.33	1.2×10^{13}	--	-16.38
$^{217}Fr \rightarrow {}^{8}Be + {}^{209}Bi$	6.3	9.2 = 2.2 + 7.0	11.1	27.1	22.5	17.63	1.2×10^{10}	--	-14.70
$^{217}Ra \rightarrow {}^{8}Be + {}^{209}Po$	6.3	9.2 = 2.2 + 7.0	11.1	27.9	23.3	17.31	5.8×10^{11}	--	-17.84
$^{217}Ac \rightarrow {}^{8}Be + {}^{209}At$	6.3	9.2 = 2.2 + 7.0	11.1	29.4	24.5	16.64	3.5×10^{14}	--	-21.85
$^{217}Pa \rightarrow {}^{8}Be + {}^{209}Fr$	6.3	9.2 = 2.2 + 7.0	11.1	31.5	26.2	15.9	3.4×10^{18}	--	-21.74
$^{218}Rn \rightarrow {}^{8}Be + {}^{210}Pb$	6.4	9.2 = 2.2 + 7.0	11.2	31.5	24.6	15.00	2.4×10^{17}	--	-18.64
$^{218}Rn \rightarrow {}^{10}Be + {}^{208}Pb$	6.3	9.4 = 2.4 + 7.0	11.4	32.9	24.5	14.36	3.3×10^{22}	--	-23.78
$^{218}Fr \rightarrow {}^{8}Be + {}^{210}Bi$	6.4	9.2 = 2.2 + 7.0	11.2	28.3	23.2	16.91	1.5×10^{12}	--	-15.48
$^{218}Ra \rightarrow {}^{8}Be + {}^{210}Po$	6.4	9.2 = 2.2 + 7.0	11.2	27.4	22.9	17.66	6.2×10^{10}	--	-15.28
$^{218}Ra \rightarrow {}^{12}C + {}^{206}Pb$	6.2	9.5 = 2.5 + 7.0	11.3	23.3	28.2	30.44	7.8×10^{15}	--	-20.38
$^{218}Ac \rightarrow {}^{8}Be + {}^{210}At$	6.4	9.2 = 2.2 + 7.0	11.2	27.4	23.2	17.87	9.3×10^{10}	--	-17.29
$^{218}Ac \rightarrow {}^{12}C + {}^{206}Bi$	6.2	9.5 = 2.5 + 7.0	11.3	23.2	28.5	30.87	9.9×10^{15}	--	-22.32
$^{218}Pa \rightarrow {}^{8}Be + {}^{210}Fr$	6.4	9.2 = 2.2 + 7.0	11.2	29.4	25.0	17.05	8.2×10^{14}	--	-21.56
$^{219}Rn \rightarrow {}^{8}Be + {}^{211}Pb$	6.4	9.2 = 2.2 + 7.0	11.2	32.8	25.2	14.38	3.3×10^{19}	--	-19.68
$^{219}Rn \rightarrow {}^{14}C + {}^{205}Hg$	6.2	9.6 = 2.7 + 6.9	11.5	24.6	28.2	28.11	4.3×10^{20}	--	-20.79
$^{219}Fr \rightarrow {}^{8}Be + {}^{211}Bi$	6.4	9.2 = 2.2 + 7.0	11.2	30.8	24.5	15.53	2.5×10^{16}	--	-17.92
$^{219}Fr \rightarrow {}^{14}C + {}^{205}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	23.8	27.6	29.42	2.6×10^{18}	--	-19.93
$^{219}Ra \rightarrow {}^{8}Be + {}^{211}Po$	6.4	9.2 = 2.2 + 7.0	11.2	28.7	23.7	16.88	9.8×10^{12}	--	-15.13
$^{219}Ra \rightarrow {}^{12}C + {}^{207}Pb$	6.2	9.5 = 2.5 + 7.0	11.3	22.2	26.7	31.85	6.5×10^{12}	--	-14.95

$^{219}Ac \rightarrow {}^{8}Be + {}^{211}At$	6.4	9.2 = 2.2 + 7.0	11.2	26.8	22.8	18.28	5.9×10^{9}	--	-14.68
$^{219}Ac \rightarrow {}^{12}C + {}^{207}Bi$	6.2	9.5 = 2.5 + 7.0	11.3	22.7	27.7	31.63	2.0×10^{14}	--	-19.21
$^{219}Th \rightarrow {}^{12}C + {}^{207}Po$	6.2	9.5 = 2.5 + 7.0	11.3	22.9	28.4	31.62	2.2×10^{15}	--	-21.63
$^{219}Pa \rightarrow {}^{8}Be + {}^{211}Fr$	6.4	9.2 = 2.2 + 7.0	11.2	28.2	24.3	17.74	6.6×10^{12}	--	-20.14
$^{220}Rn \rightarrow {}^{8}Be + {}^{212}Pb$	6.4	9.2 = 2.2 + 7.0	11.2	35.7	26.3	13.22	8.7×10^{23}	--	-21.92
$^{220}Rn \rightarrow {}^{14}C + {}^{206}Hg$	6.2	9.7 = 2.7 + 7.0	11.5	24.2	27.7	28.54	2.9×10^{19}	--	-17.44
$^{220}Fr \rightarrow {}^{8}Be + {}^{212}Bi$	6.4	9.2 = 2.2 + 7.0	11.2	32.6	25.3	14.66	2.2×10^{19}	--	-18.51
$^{220}Fr \rightarrow {}^{14}C + {}^{206}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	22.8	26.2	30.72	1.3×10^{15}	--	-14.28
$^{220}Fr \rightarrow {}^{15}N + {}^{205}Hg$	6.2	9.7 = 2.7 + 7.0	11.5	23.9	32.0	33.67	5.6×10^{24}	--	-23.92
$^{220}Ra \rightarrow {}^{8}Be + {}^{212}Po$	6.4	9.2 = 2.2 + 7.0	11.2	30.8	24.8	15.70	4.3×10^{16}	--	-18.26
$^{220}Ra \rightarrow {}^{12}C + {}^{208}Pb$	6.2	9.5 = 2.5 + 7.0	11.3	22.1	26.5	32.02	2.7×10^{12}	--	-14.06
$^{220}Ra \rightarrow {}^{14}C + {}^{206}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	22.8	26.6	31.04	3.1×10^{15}	--	-17.12
$^{220}Ac \rightarrow {}^{8}Be + {}^{212}At$	6.4	9.2 = 2.2 + 7.0	11.2	28.1	23.6	17.43	1.4×10^{12}	--	-15.70
$^{220}Ac \rightarrow {}^{12}C + {}^{208}Bi$	6.2	9.5 = 2.5 + 7.0	11.3	22.0	26.6	32.62	1.6×10^{12}	--	-15.75
$^{220}Ac \rightarrow {}^{14}C + {}^{206}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	23.3	27.6	30.76	2.2×10^{17}	--	-20.89
$^{220}Th \rightarrow {}^{12}C + {}^{208}Po$	6.2	9.5 = 2.5 + 7.0	11.3	22.6	27.8	32.14	1.6×10^{14}	--	-19.09
$^{220}Pa \rightarrow {}^{8}Be + {}^{212}Fr$	6.4	9.2 = 2.2 + 7.0	11.2	26.4	23.0	18.98	2.3×10^{9}	--	-16.12
$^{221}Fr \rightarrow {}^{14}C + {}^{207}Tl$	6. 2	9.7 = 2.7 + 7.0	11.5	22.4	25.6	31.29	4.8×10^{13}	3.3×10^{14}	-11.48
$^{221}Fr \rightarrow {}^{15}N + {}^{206}Hg$	6.2	9.7 = 2.7 + 7.0	11.5	23.6	31.5	34.13	4.0×10^{23}	--	-21.40
$^{221}Ra \rightarrow {}^{8}Be + {}^{213}Po$	6.4	9.2 = 2.2 + 7.0	11.2	33.0	25.8	14.68	1.3×10^{20}	--	-18.58
$^{221}Ra \rightarrow {}^{12}C + {}^{209}Pb$	6.3	9.5 = 2.5 + 7.0	11.3	23.2	27.9	30.58	2.8×10^{15}	--	-13.92
$^{221}Ra \rightarrow {}^{14}C + {}^{207}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	21.9	25.2	32.40	1.5×10^{12}	2.4×10^{13}	-10.65
$^{221}Ra \rightarrow {}^{15}N + {}^{206}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	23.2	31.3	35.12	4.0×10^{22}	--	-21.07
$^{221}Ac \rightarrow {}^{8}Be + {}^{213}At$	6.4	9.2 = 2.2 + 7.0	11.2	30.3	24.8	16.16	8.8×10^{15}	--	-17.78
$^{221}Ac \rightarrow {}^{12}C + {}^{209}Bi$	6.3	9.5 = 2.5 + 7.0	11.3	21.9	26.4	32.78	6.9×10^{11}	--	-13.68
$^{221}Ac \rightarrow {}^{14}C + {}^{207}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	22.7	26.0	31.56	2.2×10^{15}	--	-17.18
$^{221}Ac \rightarrow {}^{15}N + {}^{206}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	21.6	29.1	38.21	1.4×10^{17}	--	-18.99
$^{221}Th \rightarrow {}^{12}C + {}^{209}Po$	6.3	9.5 = 2.5 + 7.0	11.3	21.8	26.6	33.31	5.8×10^{11}	--	-14.84

$^{221}Pa \rightarrow {}^{8}Be + {}^{213}Fr$	6.4	9.2 = 2.2 + 7.0	11.2	26.4	23.0	18.99	2.0×10^{9}	--	-14.67
$^{221}Pa \rightarrow {}^{12}C + {}^{209}At$	6.3	9.5 = 2.5 + 7.0	11.3	22.1	27.4	33.26	7.4×10^{12}	--	-18.24
$^{222}Fr \rightarrow {}^{14}C + {}^{208}Tl$	6.2	9.7 = 2.7 + 7.0	11.6	23.3	26.7	30.08	4.4×10^{16}	--	-11.09
$^{222}Fr \rightarrow {}^{15}N + {}^{207}Hg$	6.2	9.7 = 2.7 + 7.0	11.5	24.8	33.1	32.47	3.5×10^{27}	--	-21.99
$^{222}Ra \rightarrow {}^{8}Be + {}^{214}Po$	6.4	9.2 = 2.2 + 7.0	11.2	34.9	26.6	13.85	1.5×10^{23}	--	-21.46
$^{222}Ra \rightarrow {}^{12}C + {}^{210}Pb$	6.3	9.5 = 2.5 + 7.0	11.4	24.4	29.3	29.05	7.1×10^{18}	--	-17.13
$^{222}Ra \rightarrow {}^{14}C + {}^{208}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	21.4	24.5	33.05	3.9×10^{10}	1.0×10^{11}	-8.87
$^{222}Ra \rightarrow {}^{15}N + {}^{207}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	23.2	31.2	35.25	1.8×10^{22}	--	-20.53
$^{222}Ac \rightarrow {}^{8}Be + {}^{214}At$	6.4	9.2 = 2.2 + 7.0	11.2	32.5	25.9	15.06	3.8×10^{19}	--	-19.22
$^{222}Ac \rightarrow {}^{12}C + {}^{210}Bi$	6.3	9.5 = 2.5 + 7.0	11.4	22.8	27.7	31.41	4.5×10^{14}	--	-14.29
$^{222}Ac \rightarrow {}^{14}C + {}^{208}Bi$	6.2	9.7 = 2.7 + 7.0	11.6	22.1	25.8	32.47	1.3×10^{13}	--	-12.75
$^{222}Ac \rightarrow {}^{15}N + {}^{207}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	21.21	28.3	38.97	3.5×10^{15}	--	-15.18
$^{222}Ac \rightarrow {}^{16}O + {}^{206}Tl$	6.2	9.8 = 2.8 + 7.0	11.4	21.4	32.4	43.61	1.1×10^{21}	--	-20.68
$^{222}Th \rightarrow {}^{12}C + {}^{210}Po$	6.3	9.5 = 2.5 + 7.0	11.4	21.9	26.7	33.15	1.1×10^{12}	--	-14.62
$^{222}Th \rightarrow {}^{14}C + {}^{208}Po$	6.2	9.7 = 2.7 + 7.0	11.6	22.9	27.4	31.65	1.8×10^{16}	--	-18.83
$^{222}Th \rightarrow {}^{15}N + {}^{208}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	22.5	30.9	37.16	3.5×10^{20}	--	-23.12
$^{222}Th \rightarrow {}^{16}O + {}^{206}Pb$	6.2	9.8 = 2.8 + 7.0	11.4	20.7	31.3	45.73	2.3×10^{18}	--	-20.94
$^{223}Fr \rightarrow {}^{14}C + {}^{209}Tl$	6.2	9.7 = 2.7 + 7.0	11.6	24.1	27.8	29.01	2.1×10^{19}	--	-12.16
$^{223}Ra \rightarrow {}^{12}C + {}^{211}Pb$	6.3	9.6 = 2.53 + 7.03	11.4	25.5	30.6	27.73	9.4×10^{21}	--	-16.62
$^{223}Ra \rightarrow {}^{14}C + {}^{209}Pb$	6.2	9.7 = 2.7 + 7.0	11.4	22.2	25.7	31.84	2.8×10^{13}	1.4×10^{15}	-8.10
$^{223}Ra \rightarrow {}^{15}N + {}^{208}Tl$	6.2	9.7 = 2.7 + 7.0	11.5	24.1	32.4	33.89	2.3×10^{25}	--	-20.01
$^{223}Ra \rightarrow {}^{18}O + {}^{205}Hg$	6.1	9.9 = 2.9 + 7.0	11.6	22.9	33.8	40.32	6.3×10^{27}	--	-22.45
$^{223}Ac \rightarrow {}^{12}C + {}^{211}Bi$	6.3	9.6 = 2.53 + 7.03	11.4	24.2	29.4	29.68	2.6×10^{18}	--	-16.63
$^{223}Ac \rightarrow {}^{14}C + {}^{209}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	21.7	25.2	33.07	4.5×10^{11}	--	-9.87
$^{223}Ac \rightarrow {}^{15}N + {}^{208}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	20.9	27.7	39.48	2.9×10^{14}	--	-12.68
$^{223}Ac \rightarrow {}^{16}O + {}^{207}Tl$	6.2	9.8 = 2.8 + 7.0	11.4	21.4	32.4	43.6	1.0×10^{21}	--	-19.22
$^{223}Th \rightarrow {}^{12}C + {}^{211}Po$	6.3	9.6 = 2.53 + 7.03	11.4	22.8	28.0	31.82	5.8×10^{14}	--	-15.01
$^{223}Th \rightarrow {}^{14}C + {}^{209}Po$	6.2	9.7 = 2.7 + 7.0	11.5	22.2	26.2	32.73	4.0×10^{13}	--	-13.85

$^{223}Th \rightarrow {}^{15}N + {}^{208}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	21.9	29.9	38.15	2.5×10^{18}	--	-18.65
$^{223}Th \rightarrow {}^{16}O + {}^{207}Pb$	6.2	9.8 = 2.8 + 7.0	11.4	20.3	30.4	46.58	5.5×10^{16}	--	-16.99
$^{223}Th \rightarrow {}^{17}O + {}^{206}Pb$	6.1	9.8 = 2.86 + 6.98	11.6	21.5	32.5	43.98	1.5×10^{22}	--	-22.43
$^{223}Pa \rightarrow {}^{8}Be + {}^{215}Fr$	6.4	9.3 = 2.2 + 7.1	11.2	29.4	24.8	17.07	4.7×10^{14}	--	-17.52
$^{223}Pa \rightarrow {}^{12}C + {}^{211}At$	6.3	9.6 = 2.53 + 7.03	11.4	21.6	26.6	33.98	2.2×10^{11}	--	-14.19
$^{223}Pa \rightarrow {}^{14}C + {}^{209}At$	6.2	9.7 = 2.7 + 7.0	11.5	22.8	27.5	32.19	1.1×10^{16}	--	-18.89
$^{223}Pa \rightarrow {}^{15}N + {}^{208}Po$	6.2	9.7 = 2.7 + 7.0	11.5	21.3	29.2	39.7	2.6×10^{16}	--	-19.26
$^{224}Ra \rightarrow {}^{12}C + {}^{212}Pb$	6.3	9.6 = 2.53 + 7.04	11.4	26.9	31.9	26.37	2.5×10^{25}	--	-19.66
$^{224}Ra \rightarrow {}^{14}C + {}^{210}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	23.2	26.9	30.54	3.9×10^{16}	5.9×10^{15}	-10.85
$^{224}Ac \rightarrow {}^{12}C + {}^{212}Bi$	6.3	9.6 = 2.53 + 7.04	11.4	25.3	30.7	28.35	3.2×10^{21}	--	-17.51
$^{224}Ac \rightarrow {}^{14}C + {}^{210}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	22.4	26.2	32.01	1.4×10^{14}	--	-10.16
$^{224}Ac \rightarrow {}^{15}N + {}^{209}Pb$	6.2	9.7 = 2.7 + 7.0	11.5	21.9	29.4	37.76	9.1×10^{17}	--	-13.97
$^{224}Ac \rightarrow {}^{16}O + {}^{208}Tl$	6.2	9.8 = 2.8 + 7.0	11.5	22.4	34.2	41.72	4.8×10^{24}	--	-20.69
$^{224}Ac \rightarrow {}^{17}O + {}^{207}Tl$	6.2	9.9 = 2.9 + 7.0	11.6	22.2	33.3	42.07	4.6×10^{24}	--	-20.67
$^{224}Ac \rightarrow {}^{18}O + {}^{206}Tl$	6.1	9.9 = 2.9 + 7.0	11.6	21.6	31.7	43.27	5.6×10^{22}	--	-18.76
$^{224}Th \rightarrow {}^{12}C + {}^{212}Po$	6.3	9.6 = 2.53 + 7.04	11.4	23.9	29.4	30.37	7.4×10^{17}	--	-17.7
$^{224}Th \rightarrow {}^{14}C + {}^{210}Po$	6.2	9.7 = 2.7 + 7.0	11.5	22.0	26.0	32.94	1.2×10^{13}	--	-12.91
$^{224}Th \rightarrow {}^{15}N + {}^{209}Bi$	6.2	9.7 = 2.7 + 7.0	11.5	21.9	29.8	38.16	2.1×10^{18}	--	-18.15
$^{224}Th \rightarrow {}^{16}O + {}^{208}Pb$	6.2	9.8 = 2.8 + 7.0	11.5	20.3	30.4	46.5	6.8×10^{16}	--	-16.66
$^{224}Th \rightarrow {}^{17}O + {}^{207}Pb$	6.2	9.8 = 2.86 + 6.99	11.6	21.8	33.1	43.26	3.8×10^{23}	--	-23.41
$^{224}Th \rightarrow {}^{18}O + {}^{206}Pb$	6.1	9.9 = 2.9 + 7.0	11.6	21.2	31.4	44.57	2.8×10^{21}	--	-21.28
$^{224}Pa \rightarrow {}^{8}Be + {}^{216}Fr$	6.4	9.3 = 2.2 + 7.1	11.2	31.4	25.9	15.95	1.5×10^{18}	--	-18.92
$^{224}Pa \rightarrow {}^{12}C + {}^{212}At$	6.3	9.6 = 2.53 + 7.04	11.4	22.6	28.0	32.49	2.1×10^{14}	--	-15.06
$^{224}Pa \rightarrow {}^{14}C + {}^{210}At$	6.2	9.7 = 2.7 + 7.0	11.5	22.4	26.8	32.83	3.0×10^{14}	--	-15.22
$^{224}Pa \rightarrow {}^{15}N + {}^{209}Po$	6.2	9.7 = 2.7 + 7.0	11.5	21.1	28.7	40.14	3.0×10^{15}	--	-16.22
$^{224}Pa \rightarrow {}^{16}O + {}^{208}Bi$	6.2	9.8 = 2.8 + 7.0	11.5	20.1	30.3	47.48	2.2×10^{16}	--	-17.08
$^{224}U \rightarrow {}^{15}N + {}^{209}At$	6.2	9.7 = 2.7 + 7.0	11.5	22.3	31.2	38.49	1.2×10^{20}	--	-23.41
$^{225}Ra \rightarrow {}^{14}C + {}^{211}Pb$	6.2	9.7 = 2.7 + 7.0	11.6	24.0	27.9	29.46	1.7×10^{19}	--	-9.31

$^{225}Ra \rightarrow ^{20}O + ^{205}Hg$	6.1	10.0 = 3.0 + 7.0	11.7	22.8	32.8	40.49	3.4×10^{28}	--	-18.61
$^{225}Ac \rightarrow ^{14}C + ^{211}Bi$	6.2	9.7 = 2.7 + 7.0	11.6	23.5	27.6	30.48	6.5×10^{17}	1.4×10^{17}	-12.29
$^{225}Ac \rightarrow ^{15}N + ^{210}Pb$	6.2	9.8 = 2.74 + 7.02	11.5	22.8	30.8	36.27	1.3×10^{21}	--	-15.59
$^{225}Ac \rightarrow ^{18}O + ^{207}Tl$	6.1	9.9 = 2.9 + 7.0	11.7	21.5	31.5	43.46	1.8×10^{22}	--	-16.73
$^{225}Th \rightarrow ^{12}C + ^{213}Po$	6.3	9.6 = 2.53 + 7.05	11.4	25.0	30.7	28.97	1.1×10^{21}	--	-18.09
$^{225}Th \rightarrow ^{14}C + ^{211}Po$	6.2	9.7 = 2.7 + 7.0	11.5	22.9	27.1	31.73	7.8×10^{15}	--	-12.94
$^{225}Th \rightarrow ^{15}N + ^{210}Bi$	6.2	9.8 = 2.74 + 7.02	11.5	22.6	30.9	37.01	5.3×10^{20}	--	-17.77
$^{225}Th \rightarrow ^{16}O + ^{209}Pb$	6.2	9.8 = 2.8 + 7.0	11.5	21.1	32.1	44.67	1.4×10^{20}	--	-17.2
$^{225}Th \rightarrow ^{17}O + ^{208}Pb$	6.2	9.9 = 2.9 + 7.0	11.6	21.0	31.4	44.87	2.0×10^{20}	--	-17.35
$^{225}Th \rightarrow ^{18}O + ^{207}Pb$	6.1	9.9 = 2.9 + 7.0	11.7	20.7	30.3	45.55	2.3×10^{19}	--	-16.41
$^{225}Pa \rightarrow ^{12}C + ^{213}At$	6.3	9.6 = 2.53 + 7.05	11.3	23.7	29.5	30.92	4.4×10^{17}	--	-17.39
$^{225}Pa \rightarrow ^{14}C + ^{211}At$	6.2	9.7 = 2.7 + 7.0	11.5	22.3	26.6	32.97	1.2×10^{14}	--	-13.83
$^{225}Pa \rightarrow ^{15}N + ^{210}Po$	6.2	9.8 = 2.74 + 7.02	11.5	21.1	28.6	40.2	2.0×10^{15}	--	-15.05
$^{225}Pa \rightarrow ^{16}O + ^{209}Bi$	6.2	9.8 = 2.8 + 7.0	11.5	20.2	30.4	47.34	3.2×10^{16}	--	-16.25
$^{225}Pa \rightarrow ^{17}O + ^{208}Bi$	6.2	9.9 = 2.9 + 7.0	11.5	21.7	33.2	44.02	2.2×10^{23}	--	-23.09
$^{225}U \rightarrow ^{15}N + ^{210}At$	6.2	9.8 = 2.74 + 7.02	11.5	21.8	30.4	39.25	2.7×10^{18}	--	-19.89
$^{225}U \rightarrow ^{16}O + ^{209}Po$	6.2	9.8 = 2.8 + 7.0	11.5	20.0	30.2	48.49	5.4×10^{15}	--	-17.19
$^{225}Np \rightarrow ^{12}C + ^{213}Fr$	6.3	9.5 = 2.5 + 7.0	11.4	21.4	26.8	35.14	8.8×10^{10}	--	-14.40
$^{225}Np \rightarrow ^{14}C + ^{211}Fr$	6.2	9.7 = 2.7 + 7.0	11.5	23.0	28.3	32.72	9.2×10^{16}	--	-20.42
$^{225}Np \rightarrow ^{16}O + ^{209}At$	6.2	9.8 = 2.8 + 7.0	11.5	19.9	30.5	49.21	5.4×10^{15}	--	-19.19
$^{226}Ra \rightarrow ^{14}C + ^{212}Pb$	6.3	9.7 = 2.7 + 7.0	11.6	25.1	29.1	28.20	3.2×10^{22}	1.8×10^{21}	-11.52
$^{226}Ra \rightarrow ^{20}O + ^{206}Hg$	6.1	10.0 = 3.0 + 7.0	11.8	22.6	32.4	40.83	4.7×10^{27}	--	-16.69
$^{226}Ac \rightarrow ^{14}C + ^{212}Bi$	6.3	9.7 = 2.7 + 7.0	11.5	24.4	28.6	29.41	3.2×10^{20}	--	-12.35
$^{226}Ac \rightarrow ^{17}N + ^{211}Pb$	6.2	9.8 = 2.74 + 7.03	11.5	23.8	32.3	34.7	4.0×10^{24}	--	-16.45
$^{226}Ac \rightarrow ^{18}O + ^{208}Tl$	6.2	9.9 = 2.9 + 7.0	11.7	22.3	33.0	41.85	4.5×10^{25}	--	-17.5
$^{226}Ac \rightarrow ^{20}O + ^{206}Tl$	6.1	10.0 = 3.0 + 7.0	11.8	21.8	31.4	42.77	4.6×10^{24}	--	-16.51
$^{226}Th \rightarrow ^{14}C + ^{212}Po$	6.3	9.7 = 2.7 + 7.0	11.6	23.8	28.2	30.55	6.1×10^{18}	$> 2.0\times10^{15}$	-15.29
$^{226}Th \rightarrow ^{15}N + ^{211}Bi$	6.2	9.8 = 2.74 + 7.03	11.5	23.9	32.9	34.95	1.9×10^{25}	--	-21.79

$^{226}Th \rightarrow ^{16}O + ^{210}Pb$	6.2	9.8 = 2.8 + 7.0	11.5	22.1	34.0	42.67	9.4×10^{23}	--	-20.48
$^{226}Th \rightarrow ^{17}O + ^{209}Pb$	6.2	9.9 = 2.9 + 7.0	11.6	22.7	34.6	41.62	7.7×10^{26}	--	-23.40
$^{226}Th \rightarrow ^{18}O + ^{208}Pb$	6.2	9.9 = 2.9 + 7.0	11.6	20.7	30.1	45.73	9.0×10^{18}	$> 2.0\times10^{15}$	-15.46
$^{226}Th \rightarrow ^{20}O + ^{206}Pb$	6.1	10.0 = 3.0 + 7.0	11.8	21.9	31.9	43.19	1.7×10^{25}	--	-21.74
$^{226}Pa \rightarrow ^{14}C + ^{212}At$	6.3	9.7 = 2.7 + 7.0	11.5	23.2	27.9	31.63	1.8×10^{17}	--	-15.56
$^{226}Pa \rightarrow ^{15}N + ^{211}Po$	6.2	9.8 = 2.74 + 7.03	11.5	22.1	30.3	38.36	1.1×10^{19}	--	-17.35
$^{226}Pa \rightarrow ^{16}O + ^{210}Bi$	6.2	9.8 = 2.8 + 7.0	11.5	21.0	32.1	45.56	5.1×10^{19}	--	-18.02
$^{226}Pa \rightarrow ^{17}O + ^{209}Bi$	6.2	9.9 = 2.9 + 7.0	11.5	21.2	32.1	45.10	1.4×10^{21}	--	-19.46
$^{226}Pa \rightarrow ^{18}O + ^{208}Bi$	6.2	9.9 = 2.9 + 7.0	11.7	20.9	31.1	45.68	2.8×10^{20}	--	-18.76
$^{226}U \rightarrow ^{15}N + ^{211}At$	6.2	9.8 = 2.74 + 7.03	11.5	22.0	30.6	38.89	1.3×10^{19}	--	-19.56
$^{226}U \rightarrow ^{16}O + ^{210}Po$	6.2	9.8 = 2.8 + 7.0	11.5	20.1	30.6	48.03	3.1×10^{16}	--	-16.94
$^{227}Ac \rightarrow ^{15}N + ^{212}Pb$	6.2	9.8 = 2.74 + 7.04	11.5	24.8	33.6	33.3	7.6×10^{27}	--	-17.46
$^{227}Ac \rightarrow ^{20}O + ^{207}Tl$	6.1	10.0 = 3.0 + 7.0	11.8	21.6	31.0	43.09	7.4×10^{23}	--	-13.45
$^{227}Th \rightarrow ^{16}O + ^{211}Pb$	6.2	9.8 = 2.8 + 7.0	11.5	23.0	35.6	41.04	1.8×10^{27}	--	-21.93
$^{227}Th \rightarrow ^{17}O + ^{210}Pb$	6.2	9.9 = 2.9 + 7.0	11.6	22.8	34.8	41.35	2.6×10^{27}	--	-22.09
$^{227}Th \rightarrow ^{18}O + ^{209}Pb$	6.2	9.9 = 2.9 + 7.0	11.7	21.4	31.5	44.21	1.0×10^{22}	--	-16.68
$^{227}Th \rightarrow ^{20}O + ^{207}Pb$	6.1	10.0 = 3.0 + 7.0	11.8	21.2	30.6	44.47	1.8×10^{22}	--	-16.93
$^{227}Th \rightarrow ^{22}Ne + ^{205}Hg$	6.1	10.1 = 3.1 + 7.0	11.8	20.5	35.5	56.13	1.0×10^{28}	--	-22.68
$^{227}Pa \rightarrow ^{16}O + ^{211}Bi$	6.2	9.8 = 2.8 + 7.0	11.5	22.0	34.2	43.43	5.4×10^{23}	--	-20.37
$^{227}Pa \rightarrow ^{17}O + ^{210}Bi$	6.2	9.9 = 2.9 + 7.0	11.6	22.5	34.7	42.44	3.0×10^{26}	--	-23.12
$^{227}Pa \rightarrow ^{18}O + ^{209}Bi$	6.2	9.9 = 2.9 + 7.0	11.7	20.8	30.8	45.88	9.7×10^{19}	--	-16.63
$^{227}Pa \rightarrow ^{22}Ne + ^{205}Tl$	6.1	10.1 = 3.1 + 7.0	11.7	19.9	34.1	58.68	7.9×10^{24}	--	-21.54
$^{227}U \rightarrow ^{15}N + ^{212}At$	6.2	9.8 = 2.74 + 7.04	11.5	22.8	31.9	37.54	8.5×10^{21}	--	-18.98
$^{227}U \rightarrow ^{16}O + ^{21}Po$	6.2	9.8 = 2.8 + 7.0	11.5	20.9	23.4	46.19	5.8×10^{19}	--	-16.81
$^{227}U \rightarrow ^{17}O + ^{210}Po$	6.2	9.9 = 2.9 + 7.0	11.6	21.1	32.3	45.78	1.2×10^{21}	--	-18.12
$^{227}U \rightarrow ^{18}O + ^{209}Po$	6.2	9.9 = 2.9 + 7.0	11.7	21.0	31.5	46.17	6.2×10^{20}	--	-17.84
$^{227}Np \rightarrow ^{14}C + ^{213}Fr$	6.3	9.7 = 2.7 + 7.0	11.5	22.7	27.8	33.10	9.7×10^{15}	--	-16.4

$^{227}Np \rightarrow {}^{16}O + {}^{211}At$	6.2	9.8 = 2.8 + 7.0	11.5	20.0	30.6	48.96	1.1×10^{16}	--	-16.45
$^{227}Np \rightarrow {}^{17}O + {}^{210}At$	6.2	9.9 = 2.9 + 7.0	11.6	21.6	33.7	45.36	1.8×10^{23}	--	-23.66
$^{227}Np \rightarrow {}^{18}O + {}^{209}At$	6.2	9.9 = 2.9 + 7.0	11.7	21.2	32.4	46.23	1.1×10^{22}	--	-22.45
$^{228}Ra \rightarrow {}^{22}O + {}^{206}Hg$	6.1	10.1 = 3.1 + 7.0	11.9	22.7	32.0	40.62	1.3×10^{29}	--	-10.92
$^{228}Ac \rightarrow {}^{20}O + {}^{208}Tl$	6.1	10.0 = 3.0+7.0	11.8	22.3	32.2	41.86	4.7×10^{26}	--	-13.93
$^{228}Ac \rightarrow {}^{23}F + {}^{205}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	21.7	33.8	47.86	7.6×10^{29}	--	-17.14
$^{228}Th \rightarrow {}^{14}C + {}^{214}Po$	6.3	9.7 = 2.7 + 7.0	11.6	25.7	30.4	28.23	5.2×10^{24}	--	-16.64
$^{228}Th \rightarrow {}^{16}O + {}^{212}Pb$	6.2	9.8 = 2.8 + 7.0	11.5	24.2	37.5	39.06	3.1×10^{31}	--	-23.42
$^{228}Th \rightarrow {}^{18}O + {}^{210}Pb$	6.2	9.9 = 2.9 + 7.0	11.7	22.3	33.4	42.29	1.1×10^{26}	--	-17.97
$^{228}Th \rightarrow {}^{20}O + {}^{208}Pb$	6.1	10.0 = 3.0+7.0	11.8	21.1	30.3	44.73	4.1×10^{21}	5.0×10^{20}	-13.54
$^{228}Th \rightarrow {}^{22}O + {}^{206}Pb$	6.1	10.1 = 3.1 + 7.0	11.9	22.9	33.2	41.28	5.1×10^{30}	--	-22.64
$^{228}Th \rightarrow {}^{22}Ne + {}^{206}Hg$	6.1	10.1 = 3.1 + 7.0	11.8	20.7	35.8	55.75	4.8×10^{28}	--	-20.61
$^{228}Th \rightarrow {}^{24}Ne + {}^{204}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	20.1	33.4	57.42	1.8×10^{26}	--	-18.18
$^{228}Pa \rightarrow {}^{17}O + {}^{211}Bi$	6.2	9.9 = 2.9 + 7.0	11.6	23.0	35.4	41.62	1.5×10^{28}	--	-23.00
$^{228}Pa \rightarrow {}^{20}O + {}^{208}Bi$	6.1	10.0 = 3.0+7.0	11.8	21.7	31.9	44.00	6.0×10^{24}	--	-19.60
$^{228}Pa \rightarrow {}^{22}Ne + {}^{206}Tl$	6.1	10.1 = 3.1 + 7.0	11.7	19.7	33.5	59.2	7.5×10^{23}	--	-18.69
$^{228}U \rightarrow {}^{18}O + {}^{210}Po$	6.2	9.9 = 2.9 + 7.0	11.7	21.0	31.6	45.97	1.4×10^{21}	--	-18.29
$^{228}U \rightarrow {}^{22}Ne + {}^{206}Pb$	6.1	10.1 = 3.1 + 7.0	11.7	19.3	32.8	61.05	1.5×10^{22}	--	-19.32
$^{228}Pu \rightarrow {}^{15}N + {}^{213}Fr$	6.3	9.8 = 2.7 + 7.1	11.5	22.2	31.6	39.53	1.2×10^{20}	--	-20.56
$^{229}Ac \rightarrow {}^{23}F + {}^{206}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	21.5	33.3	48.3	6.6×10^{28}	--	-12.79
$^{229}Ac \rightarrow {}^{22}O + {}^{207}Tl$	6.1	10.1 = 3.1 + 7.0	11.9	22.0	31.0	42.43	1.2×10^{26}	--	-10.05
$^{229}Th \rightarrow {}^{18}O + {}^{211}Pb$	6.2	9.9 = 2.9 + 7.0	11.7	23.1	34.7	40.86	1.4×10^{29}	--	-17.49
$^{229}Th \rightarrow {}^{20}O + {}^{209}Pb$	6.1	10.0 = 3.0 + 7.0	11.8	21.8	31.5	43.41	3.5×10^{24}	--	-12.88
$^{229}Th \rightarrow {}^{22}O + {}^{207}Pb$	6.1	10.1 = 3.1 + 7.0	11.9	22.1	31.6	42.77	7.5×10^{26}	--	-15.21
$^{229}Th \rightarrow {}^{24}Ne + {}^{205}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	19.9	32.9	57.83	2.4×10^{25}	--	-13.72
$^{229}Pa \rightarrow {}^{20}O + {}^{209}Bi$	6.1	10.0 = 3.0 + 7.0	11.8	21.5	31.5	44.37	7.7×10^{23}	--	-16.20
$^{229}Pa \rightarrow {}^{23}F + {}^{206}Pb$	6.1	10.2 = 3.2 + 7.0	11.9	21.1	33.3	50.36	4.4×10^{27}	--	-19.95
$^{229}Pa \rightarrow {}^{22}Ne + {}^{207}Tl$	6.1	10.1 = 3.1 + 7.0	11.7	19.8	33.7	58.96	1.7×10^{24}	--	-16.54

$^{229}Pa \rightarrow {}^{24}Ne + {}^{205}Tl$	6.1	10.2 = 3.2 + 7.0	11.9	19.5	32.2	59.67	3.5×10^{23}	--	-15.85
$^{229}U \rightarrow {}^{20}O + {}^{209}Po$	6.1	10.0 = 3.0 + 7.0	11.8	22.1	33.0	43.78	5.4×10^{26}	--	-22.46
$^{229}U \rightarrow {}^{22}Ne + {}^{207}Pb$	6.1	10.1 = 3.1 + 7.0	11.7	19.1	32.1	61.7	8.8×10^{20}	--	-16.67
$^{229}Np \rightarrow {}^{18}O + {}^{211}At$	6.2	9.9 = 2.9 + 7.0	11.7	21.2	32.3	46.2	9.8×10^{21}	--	-19.56
$^{229}Pu \rightarrow {}^{15}N + {}^{214}Fr$	6.3	9.8 = 2.7 + 7.1	11.6	22.9	32.8	38.26	4.7×10^{22}	--	-21.91
$^{230}Th \rightarrow {}^{20}O + {}^{210}Pb$	6.2	10.0 = 3.0 + 7.0	11.8	22.6	33.0	41.81	1.6×10^{28}	--	-15.45
$^{230}Th \rightarrow {}^{22}O + {}^{208}Pb$	6.1	10.1 = 3.1 + 7.0	11.9	21.8	31.0	43.34	2.4×10^{25}	--	-12.63
$^{230}Th \rightarrow {}^{23}F + {}^{207}Tl$	6.1	10.2 = 3.2 + 7.0	11.9	21.6	34.0	48.57	7.2×10^{29}	--	-17.11
$^{230}Th \rightarrow {}^{24}Ne + {}^{206}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	19.9	32.9	57.76	2.8×10^{25}	4.1×10^{24}	-12.70
$^{230}Pa \rightarrow {}^{23}F + {}^{207}Pb$	6.1	10.2 = 3.2 + 7.0	11.9	20.7	32.3	51.3	3.3×10^{25}	--	-15.80
$^{230}Pa \rightarrow {}^{24}Ne + {}^{206}Tl$	6.1	10.2 = 3.2 + 7.0	11.9	19.3	31.4	60.38	1.2×10^{22}	--	-12.36
$^{230}Pa \rightarrow {}^{22}Ne + {}^{208}Tl$	6.1	10.1 = 3.1 + 7.0	11.7	20.5	35.6	56.95	8.4×10^{27}	--	-18.20
$^{230}U \rightarrow {}^{14}C + {}^{216}Rn$	6.3	9.8 = 7.1 + 2.7	11.6	26.2	31.7	28.34	5.0×10^{26}	--	-20.16
$^{230}U \rightarrow {}^{20}O + {}^{210}Po$	6.2	10.0 = 3.0 + 7.0	11.8	22.1	33.0	43.77	4.9×10^{26}	--	-20.15
$^{230}U \rightarrow {}^{22}Ne + {}^{208}Pb$	6.1	10.1 = 3.1+ 7.0	11.7	19.2	32.3	61.40	2.5×10^{21}	$>1.6\times10^{18}$	-14.86
$^{230}U \rightarrow {}^{24}Ne + {}^{206}Pb$	6.1	10.2 = 3.2 + 7.0	11.9	19.2	31.6	61.36	9.3×10^{21}	$>1.6\times10^{18}$	-15.43
$^{231}Th \rightarrow {}^{24}Ne + {}^{207}Hg$	6.1	10.2 = 3.2 + 7.0	11.9	20.6	34.5	55.99	8.6×10^{28}	--	-10.79
$^{231}Th \rightarrow {}^{25}Ne + {}^{206}Hg$	6.1	10.3 = 3.3 + 7.0	12.0	20.3	33.4	56.83	4.1×10^{27}	--	-9.47
$^{231}U \rightarrow {}^{22}O + {}^{209}Pb$	6.1	10.1 = 3.1+7.0	11.9	22.4	32.1	42.15	2.2×10^{28}	--	-19.45
$^{231}U \rightarrow {}^{22}Ne + {}^{209}Pb$	6.1	10.1 = 3.1+7.0	11.8	19.9	34.2	59.46	6.8×10^{24}	--	-15.94
$^{231}Pa \rightarrow {}^{22}O + {}^{209}Bi$	6.1	10.1 = 3.1+7.0	11.9	22.5	32.8	42.41	2.0×10^{29}	--	-17.73
$^{231}Pa \rightarrow {}^{23}F + {}^{208}Pb$	6.1	10.2 = 3.2+7.0	11.9	20.5	31.7	51.86	1.8×10^{24}	1.0×10^{26}	-12.68
$^{231}Pa \rightarrow {}^{24}Ne + {}^{207}Tl$	6.1	10.2 = 3.2+7.0	11.9	19.3	31.3	60.42	8.6×10^{21}	7.9×10^{22}	-10.36
$^{231}Pa \rightarrow {}^{25}Ne + {}^{206}Tl$	6.1	10.3 = 3.3 + 7.0	12.0	20.2	33.6	57.75	3.4×10^{27}	--	-15.96
$^{231}Np \rightarrow {}^{20}O + {}^{211}At$	6.2	10.1 = 3.03+7.04	11.8	22.5	34.14	43.47	6.7×10^{28}	--	-23.66
$^{231}Np \rightarrow {}^{22}Ne + {}^{209}Bi$	6.1	10.1 = 3.1+7.0	11.8	19.3	32.9	61.91	1.1×10^{22}	--	-16.87
$^{232}Th \rightarrow {}^{26}Ne + {}^{206}Hg$	6.1	10.3 = 3.3 + 7.0	12.0	20.6	33.9	55.97	5.2×10^{29}	$>1.6\times10^{29}$	-11.54
$^{232}Pa \rightarrow {}^{23}F + {}^{209}Pb$	6.1	10.2 = 3.2 + 7.0	11.9	21.1	33.2	50.24	4.8×10^{27}	--	-12.34

$^{232}U \rightarrow ^{24}Ne + ^{208}Pb$	6.1	10.2 = 3.2 + 7.0	11.9	18.9	30.5	62.31	9.7×10^{19}	2.5×10^{20}	-10.30
$^{232}U \rightarrow ^{26}Ne + ^{206}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	20.4	34.2	57.97	1.6×10^{29}	--	-19.51
$^{232}U \rightarrow ^{28}Mg + ^{204}Hg$	6.0	10.4 = 3.4+7.0	12.0	18.6	33.6	74.33	5.5×10^{25}	$> 4.5\times10^{22}$	-16.05
$^{232}Pu \rightarrow ^{22}Ne + ^{210}Po$	6.1	10.1 = 3.1 + 7.0	11.8	19.4	33.6	62.35	6.6×10^{22}	--	-18.78
$^{233}U \rightarrow ^{24}Ne + ^{209}Pb$	6.1	10.3 = 3.25+7.05	11.9	19.5	32.2	60.51	2.3×10^{23}	6.8×10^{24}	-10.49
$^{233}U \rightarrow ^{25}Ne + ^{208}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	19.4	31.6	60.75	1.4×10^{23}	2.0×10^{23}	-10.28
$^{233}U \rightarrow ^{26}Ne + ^{207}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	20.0	33.2	58.95	1.2×10^{27}	--	-14.21
$^{233}U \rightarrow ^{28}Mg + ^{205}Hg$	6.0	10.4 = 3.4+7.0	12.0	18.6	33.6	74.25	6×10^{25}	$> 3.9\times10^{27}$	-12.91
$^{233}Np \rightarrow ^{22}Ne + ^{211}Bi$	6.1	10.2 =3.13+7.05	11.8	20.7	36.8	57.83	2.3×10^{29}	--	-21.53
$^{233}Np \rightarrow ^{24}Ne + ^{209}Bi$	6.1	10.2 = 3.2 + 7.0	11.9	19.2	31.7	62.16	9.0×10^{21}	--	-14.12
$^{233}Np \rightarrow ^{25}Ne + ^{208}Bi$	6.1	10.3 = 3.3 + 7.0	12.0	20.3	34.7	58.88	4.9×10^{28}	--	-20.86
$^{233}Pu \rightarrow ^{22}Ne + ^{211}Po$	6.1	10.2 = 3.13+7.05	11.8	20.0	35.3	60.51	1.1×10^{26}	--	-20.66
$^{233}Pu \rightarrow ^{24}Ne + ^{209}Po$	6.1	10.2 = 3.2 + 7.0	11.9	19.4	32.7	62.37	2.0×10^{23}	--	-17.92
$^{234}U \rightarrow ^{24}Ne + ^{210}Pb$	6.1	10.3 = 3.25+7.05	11.9	20.1	33.8	58.84	3.5×10^{26}	7.9×10^{25}	-13.33
$^{234}U \rightarrow ^{26}Ne + ^{208}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	19.9	32.5	59.47	8.1×10^{25}	7.9×10^{25}	-12.70
$^{234}U \rightarrow ^{28}Mg + ^{206}Hg$	6.1	10.4 = 3.4 + 7.0	12.0	18.6	33.6	74.13	7.9×10^{25}	5.6×10^{25}	-12.69
$^{234}Np \rightarrow ^{25}Ne + ^{209}Bi$	6.1	10.3 = 3.3 + 7.0	12.0	19.8	33.2	60.28	6.0×10^{25}	--	-14.53
$^{234}Np \rightarrow ^{28}Mg + ^{206}Tl$	6.1	10.4 = 3.4 + 7.0	12.0	18.1	31.9	77.24	2.6×10^{22}	--	-11.16
$^{234}Pu \rightarrow ^{24}Ne + ^{210}Po$	6.1	10.3= 3.23 +7.04	11.9	19.4	32.7	62.25	2.8×10^{23}	--	-17.57
$^{234}Pu \rightarrow ^{28}Mg + ^{206}Pb$	6.1	10.4 = 3.4 + 7.0	12.0	17.9	31.4	79.16	1.2×10^{21}	--	-15.20
$^{235}U \rightarrow ^{24}Ne + ^{211}Pb$	6.1	10.3 = 3.2 + 7.1	11.9	20.6	35.2	57.36	2.5×10^{29}	2.8×10^{27}	-13.46
$^{235}U \rightarrow ^{25}Ne + ^{210}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	20.4	34.5	57.73	1.2×10^{29}	2.8×10^{27}	-13.14
$^{235}U \rightarrow ^{26}Ne + ^{209}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	20.3	33.8	58.12	4.4×10^{28}	--	-12.70
$^{235}U \rightarrow ^{28}Mg + ^{207}Hg$	6.1	10.4 = 3.4 + 7.0	12.0	19.1	35.4	72.21	1.8×10^{29}	$> 2.8\times10^{28}$	-13.31
$^{235}U \rightarrow ^{29}Mg + ^{206}Hg$	6.0	10.5 = 3.5 + 7.0	12.0	19.0	34.7	72.55	9.1×10^{28}	--	-13.02
$^{235}Np \rightarrow ^{28}Mg + ^{207}Tl$	6.1	10.4 = 3.4 + 7.0	12.0	18.1	31.9	77.1	3.7×10^{22}	--	-10.59

$^{235}Np \rightarrow {}^{29}Mg + {}^{206}Tl$	6.0	10.5 = 3.5 + 7.0	12.0	18.9	34.7	73.97	2.5×10^{28}	--	-16.42
$^{235}Pu \rightarrow {}^{25}Ne + {}^{210}Po$	6.1	10.3 = 3.3 + 7.0	11.9	20.1	34.3	60.21	4.2×10^{27}	--	-20.28
$^{235}Pu \rightarrow {}^{28}Mg + {}^{207}Pb$	6.1	10.4 = 3.4 + 7.0	12.0	17.8	30.7	79.67	1.3×10^{20}	--	-12.77
$^{235}Pu \rightarrow {}^{29}Mg + {}^{206}Pb$	6.0	10.5 = 3.5 + 7.0	12.0	18.5	33.4	76.64	4.1×10^{25}	--	-18.27
$^{236}U \rightarrow {}^{24}Ne + {}^{212}Pb$	6.1	10.3 = 3.2 + 7.1	12.0	21.1	36.5	55.96	1.5×10^{32}	$>7.9\times10^{25}$	-16.95
$^{236}U \rightarrow {}^{26}Ne + {}^{210}Pb$	6.1	10.3 = 3.3 + 7.0	12.0	20.8	35.1	56.75	3.0×10^{31}	$>7.9\times10^{25}$	-16.25
$^{236}U \rightarrow {}^{30}Mg + {}^{206}Hg$	6.0	10.5 = 3.5 + 7.0	12.1	19.1	34.4	72.48	1.9×10^{29}	3.8×10^{27}	-14.05
$^{236}Np \rightarrow {}^{28}Mg + {}^{208}Tl$	6.1	10.4 = 3.4 + 7.0	12.0	18.6	33.8	75.15	8.2×10^{25}	--	-12.29
$^{236}Np \rightarrow {}^{29}Mg + {}^{207}Tl$	6.1	10.5 = 3.5 + 7.0	12.0	18.6	33.5	75.07	1.9×10^{26}	--	-11.05
$^{236}Np \rightarrow {}^{30}Mg + {}^{206}Tl$	6.0	10.5 = 3.5 + 7.0	12.1	18.8	33.8	74.52	3.4×10^{27}	--	-12.30
$^{236}Pu \rightarrow {}^{28}Mg + {}^{208}Pb$	6.1	10.4 = 3.4 + 7.0	12.0	17.8	30.6	79.67	1.0×10^{20}	4.7×10^{21}	-11.99
$^{236}Pu \rightarrow {}^{29}Mg + {}^{207}Pb$	6.1	10.5 = 3.5 + 7.0	12.0	18.6	34.0	76.02	4.2×10^{26}	--	-18.61
$^{236}Pu \rightarrow {}^{30}Mg + {}^{206}Pb$	6.0	10.5 = 3.5 + 7.0	12.0	18.7	33.9	75.76	2.1×10^{27}	--	-19.31
$^{237}Np \rightarrow {}^{30}Mg + {}^{207}Tl$	6.1	10.5 = 3.5 + 7.0	12.1	18.7	33.2	74.99	3.6×10^{26}	$>3.7\times10^{27}$	-12.97
$^{237}Np \rightarrow {}^{32}Si + {}^{205}Au$	6.0	10.6 = 3.6 + 7.0	12.1	18.1	35.2	87.94	1.1×10^{29}	--	-15.45
$^{237}Pu \rightarrow {}^{29}Mg + {}^{208}Pb$	6.1	10.5 = 3.5+ 7.0	12.0	18.3	32.4	77.51	6.9×10^{23}	--	-13.47
$^{237}Pu \rightarrow {}^{30}Mg + {}^{207}Pb$	6.1	10.5 = 3.5 + 7.0	12.1	18.5	32.9	76.62	4.3×10^{25}	--	-15.26
$^{237}Pu \rightarrow {}^{32}Si + {}^{205}Hg$	6.0	10.6 = 3.6 + 7.0	12.0	17.6	33.2	91.47	2.7×10^{25}	--	-15.06
$^{237}Am \rightarrow {}^{28}Mg + {}^{209}Bi$	6.1	10.4 = 3.4 + 7.0	12.0	18.0	31.8	79.84	4.3×10^{21}	--	-15.09
$^{237}Am \rightarrow {}^{29}Mg + {}^{208}Bi$	6.1	10.5 = 3.5 + 7.0	12.0	18.8	35.2	76.09	2.7×10^{28}	--	-21.89
$^{237}Am \rightarrow {}^{32}Si + {}^{205}Tl$	6.0	10.6 = 3.6 + 7.0	12.0	17.3	31.9	94.47	5.9×10^{22}	--	-16.23
$^{238}Pu \rightarrow {}^{28}Mg + {}^{210}Pb$	6.1	10.5 = 3.5 + 7.0	12.0	18.7	34.2	75.93	2.2×10^{26}	4.7×10^{25}	-16.80
$^{238}Pu \rightarrow {}^{29}Mg + {}^{209}Pb$	6.1	10.5 = 3.5 + 7.0	12.0	19.0	35.3	74.45	1.9×10^{29}	--	-19.74
$^{238}Pu \rightarrow {}^{30}Mg + {}^{208}Pb$	6.1	10.5 = 3.5 + 7.0	12.1	18.4	32.5	77.00	6.7×10^{24}	4.7×10^{25}	-15.29
$^{238}Pu \rightarrow {}^{32}Si + {}^{206}Hg$	6.0	10.6 = 3.6 + 7.0	12.1	17.7	33.4	91.21	5.4×10^{25}	1.9×10^{25}	-16.19
$^{238}Pu \rightarrow {}^{33}Si + {}^{205}Hg$	6.0	10.6 = 3.6 + 7.0	12.1	18.1	35.3	88.95	5.6×10^{29}	--	-20.21
$^{238}Am \rightarrow {}^{28}Mg + {}^{210}Bi$	6.1	10.4 = 3.4 + 7.0	12.0	18.3	33.3	78.24	2.0×10^{24}	--	-16.72
$^{238}Am \rightarrow {}^{29}Mg + {}^{209}Bi$	6.1	10.5 = 3.5 + 7.0	12.0	18.5	33.8	77.35	1.2×10^{26}	--	-18.5

$^{238}Am \rightarrow ^{30}Mg + ^{208}Bi$	6.1	10.5 = 3.5 + 7.0	12.1	18.8	34.7	76.18	2.8×10^{28}	--	-20.87
$^{238}Am \rightarrow ^{32}Si + ^{206}Tl$	6.0	10.6 = 3.6 + 7.0	12.1	17.2	31.4	94.77	1.4×10^{22}	--	-14.57
$^{238}Am \rightarrow ^{33}Si + ^{205}Tl$	6.0	10.6 = 3.6 + 7.0	12.1	17.6	33.1	92.75	4.2×10^{25}	--	-18.04
$^{238}Cm \rightarrow ^{28}Mg + ^{210}Po$	6.1	10.4 = 3.4 + 7.0	12.0	18.1	32.5	80.37	4.2×10^{22}	--	-16.97
$^{238}Cm \rightarrow ^{32}Si + ^{206}Pb$	6.0	10.6 = 3.6 + 7.0	12.1	17.0	30.6	97.26	2.4×10^{20}	--	-14.73
$^{239}Pu \rightarrow ^{30}Mg + ^{209}Pb$	6.1	10.5 = 3.5 + 7.0	12.1	18.8	34.1	75.28	8.4×10^{27}	--	-16.27
$^{239}Pu \rightarrow ^{33}Si + ^{206}Hg$	6.0	10.6 = 3.6 + 7.0	12.1	17.9	34.1	90.03	6.1×10^{27}	--	-16.13
$^{239}Pu \rightarrow ^{34}Si + ^{205}Hg$	6.0	10.7 = 3.7 + 7.0	12.1	17.7	33.0	90.84	3.6×10^{26}	--	-14.91
$^{239}Am \rightarrow ^{30}Mg + ^{209}Bi$	6.1	10.5 = 3.5 + 7.0	12.1	18.7	34.2	76.54	4.7×10^{27}	--	-19.20
$^{239}Am \rightarrow ^{32}Si + ^{207}Tl$	6.0	10.6 = 3.6 + 7.0	12.1	17.3	31.6	94.51	2.8×10^{22}	--	-13.98
$^{239}Am \rightarrow ^{33}Si + ^{207}Tl$	6.0	10.6 = 3.6 + 7.0	12.1	17.7	33.6	92.14	3.4×10^{26}	--	-18.06
$^{239}Am \rightarrow ^{34}Si + ^{205}Tl$	6.0	10.7 = 3.7 + 7.0	12.1	17.5	32.2	93.18	7.8×10^{24}	--	-16.42
$^{239}Cm \rightarrow ^{32}Si + ^{207}Pb$	6.0	10.6 = 3.6 + 7.0	12.1	16.9	30.0	97.75	2.7×10^{19}	--	-13.64
$^{240}Pu \rightarrow ^{34}Si + ^{206}Hg$	6.0	10.7 = 3.7 + 7.0	12.2	17.7	32.6	91.05	1.2×10^{26}	$>1.6\times10^{24}$	-12.69
$^{240}Am \rightarrow ^{33}Si + ^{207}Tl$	6.0	10.6 = 3.6 + 7.0	12.1	17.5	32.6	93.04	7.7×10^{24}	--	-14.85
$^{240}Am \rightarrow ^{34}Si + ^{206}Tl$	6.0	10.7 = 3.7 + 7.0	12.1	17.4	31.6	93.72	6.8×10^{23}	--	-13.79
$^{240}Cm \rightarrow ^{30}Mg + ^{210}Po$	6.1	10.5 = 3.5 + 7.0	12.1	19.0	35.5	76.56	4.1×10^{29}	--	-23.36
$^{240}Cm \rightarrow ^{32}Si + ^{208}Pb$	6.1	10.6 = 3.6 + 7.0	12.1	16.9	30.0	97.57	4.0×10^{19}	--	-13.35
$^{240}Cm \rightarrow ^{34}Si + ^{206}Pb$	6.0	10.7 = 3.7 + 7.0	12.2	17.3	31.4	95.48	1.6×10^{23}	--	-16.95
$^{241}Am \rightarrow ^{33}Si + ^{208}Tl$	6.1	10.6 = 3.6 + 7.0	12.1	18.1	35.3	90.18	4.0×10^{29}	--	-19.52
$^{241}Am \rightarrow ^{34}Si + ^{207}Tl$	6.0	10.7 = 3.7 + 7.0	12.2	17.4	31.2	93.94	2.1×10^{23}	$>2.1\times10^{25}$	-13.24
$^{241}Cm \rightarrow ^{32}Si + ^{209}Pb$	6.1	10.6 = 3.6 + 7.0	12.1	17.3	32.1	95.41	1.1×10^{23}	--	-15.00
$^{242}Cm \rightarrow ^{32}Si + ^{210}Pb$	6.1	10.6 = 3.6 + 7.0	12.1	17.7	33.7	93.62	6.8×10^{25}	--	-18.72
$^{242}Cm \rightarrow ^{34}Si + ^{208}Pb$	6.0	10.7 = 3.7 + 7.0	12.2	17.1	30.1	96.53	1.3×10^{21}	--	-14.00
$^{242}Cf \rightarrow ^{32}Si + ^{210}Po$	6.1	10.6 = 3.6 + 7.0	12.1	17.0	31.2	99.38	1.1×10^{21}	--	-18.71
$^{242}Cf \rightarrow ^{33}Si + ^{209}Po$	6.1	10.6 = 3.6 + 7.0	12.1	17.6	34.0	96.20	2.0×10^{26}	--	-23.97
$^{242}Cf \rightarrow ^{34}Si + ^{208}Po$	6.0	10.7 = 3.7 + 7.0	12.2	17.5	33.1	96.77	3.2×10^{25}	--	-23.17
$^{242}Cf \rightarrow ^{36}S + ^{206}Pb$	6.0	10.7 = 3.7 + 7.0	12.1	16.6	31.2	113.7	3.9×10^{22}	--	-20.26

$^{243}Cm \rightarrow ^{34}Si + ^{209}Pb$	6.1	10.7 = 3.7 + 7.0	12.2	17.4	31.8	94.77	1.1×10^{24}	--	-15.17
$^{244}Cm \rightarrow ^{34}Si + ^{210}Pb$	6.1	10.7 = 3.7 + 7.0	12.2	17.7	33.3	93.15	4.9×10^{26}	--	-18.01
$^{244}Cf \rightarrow ^{34}Si + ^{210}Po$	6.1	10.7 = 3.7 + 7.0	12.2	17.4	32.2	97.39	1.5×10^{24}	--	-21.19
$^{244}Cf \rightarrow ^{36}S + ^{208}Pb$	6.0	10.8 = 3.75+7.03	12.2	16.6	30.8	113.9	9.0×10^{21}	--	-18.96
$^{246}Cf \rightarrow ^{38}S + ^{208}Pb$	6.0	10.8 = 3.8 + 7.0	12.3	16.8	31.0	112.71	4.1×10^{23}	--	-18.69
$^{249}Cf \rightarrow ^{42}S + ^{207}Pb$	6.0	11.0 = 4.0 + 7.0	12.4	17.3	32.7	109.44	1.1×10^{29}	--	-20.88
$^{249}Cf \rightarrow ^{46}Ar + ^{203}Hg$	6.0	11.1 = 4.1 + 7.0	12.4	16.6	30.6	124.72	1.4×10^{27}	--	-18.99
$^{249}Cf \rightarrow ^{48}Ca + ^{201}Pt$	6.0	11.2 = 4.2 + 7.0	12.5	16.3	30.6	137.69	6.2×10^{27}	--	-19.63
$^{249}No \rightarrow ^{48}Ca + ^{201}Pb$	6.0	11.1 = 4.16 + 6.96	12.4	15.6	25.9	151.31	3.8×10^{19}	--	-21.37
$^{249}Cf \rightarrow ^{50}Ca + ^{199}Pt$	5.9	11.1 = 4.2 + 6.9	12.5	16.4	31.0	136.7	3.5×10^{29}	--	-21.38

Table 2

Emitter and cluster	R_{in} (fm)	$R_{cont} = R_1 + R_2$ (fm)	R_{bar} (fm)	R_{out} (fm)	E_{bar} (MeV)	Q_{exp} (MeV)	Theoretical $T_{1/2}(s)$	$Log_{10}(T_\alpha/T_{cl})$
$^{114}Ba \rightarrow {}^{12}C + {}^{102}Sn$	4.7	8.0 = 2.54 + 5.43	9.9	22.7	21.2	19.05	1.2×10^{10}	-7.39
$^{114}Ba \rightarrow {}^{16}O + {}^{98}Cd$	4.6	8.2 = 2.8 + 5.4	10.1	20.9	24.5	26.5	3.2×10^{14}	-11.81
$^{115}Ba \rightarrow {}^{12}C + {}^{103}Sn$	4.7	8.0 = 2.54 + 5.45	10.0	23.7	21.96	18.24	1.7×10^{12}	-6.99
$^{115}Ba \rightarrow {}^{16}O + {}^{99}Cd$	4.6	8.2 = 2.8 + 5.4	10.1	21.4	25.0	25.88	7.3×10^{15}	-10.62
$^{116}Ba \rightarrow {}^{12}C + {}^{104}Sn$	4.8	8.0 = 2.5 + 5.5	10.0	25.1	22.9	17.22	1.5×10^{15}	-9.49
$^{116}Ba \rightarrow {}^{16}O + {}^{100}Cd$	4.7	8.2 = 2.8 + 5.4	10.1	22.4	26.0	24.72	5.3×10^{18}	-13.03
$^{117}Ba \rightarrow {}^{12}C + {}^{105}Sn$	4.8	8.0 = 2.5 + 5.5	10.0	26.5	23.8	16.27	1.4×10^{18}	-7.92
$^{117}Ba \rightarrow {}^{16}O + {}^{101}Cd$	4.7	8.2 = 2.8 + 5.4	10.2	23.5	27.1	23.54	6.8×10^{21}	-11.60
$^{118}Ba \rightarrow {}^{12}C + {}^{106}Sn$	4.8	8.0 = 2.5 + 5.5	10.0	28.0	24.5	15.43	9.3×10^{20}	-2.85
$^{118}Ba \rightarrow {}^{16}O + {}^{102}Cd$	4.7	8.2 = 2.8 + 5.4	10.2	25.0	28.4	22.12	7.5×10^{25}	-7.75
$^{119}Ba \rightarrow {}^{12}C + {}^{107}Sn$	4.8	8.1 = 2.54 + 5.53	10.1	30.1	25.5	14.34	1.1×10^{25}	-2.34
$^{119}Ce \rightarrow {}^{16}O + {}^{103}Sn$	4.7	8.3 = 2.8 + 5.5	10.1	20.8	25.0	27.69	7.6×10^{14}	1.7
$^{120}La \rightarrow {}^{12}C + {}^{108}Sb$	4.8	8.1 = 2.54 + 5.54	10.1	29.7	25.8	14.82	6.6×10^{24}	-10.36
$^{120}Ce \rightarrow {}^{16}O + {}^{104}Sn$	4.7	8.3 = 2.8 + 5.5	10.2	21.7	26.0	26.58	2.7×10^{17}	0.4
$^{121}La \rightarrow {}^{12}C + {}^{109}Sb$	4.9	8.1 = 2.5 + 5.6	10.1	31.8	26.7	13.86	4.8×10^{28}	-2.08
$^{121}Ce \rightarrow {}^{16}O + {}^{105}Sn$	4.8	8.3 = 2.8 + 5.5	10.2	22.6	27.0	25.49	1.2×10^{20}	-0.13
$^{122}Ce \rightarrow {}^{16}O + {}^{106}Sn$	4.8	8.3 = 2.8 + 5.5	10.2	23.6	27.9	24.43	7.1×10^{22}	-2.37
$^{123}Ce \rightarrow {}^{16}O + {}^{107}Sn$	4.8	8.3 = 2.8 + 5.5	10.2	24.8	29.0	23.23	1.5×10^{26}	-0.28
$^{124}Ce \rightarrow {}^{16}O + {}^{108}Sn$	4.8	8.3 = 2.8 + 5.5	10.3	26.2	30.16	22.02	6.6×10^{29}	-4.32
$^{124}Pr \rightarrow {}^{16}O + {}^{108}Sb$	4.8	8.3 = 2.8 + 5.5	10.3	24.4	29.2	24.12	3.4×10^{25}	-5.96
$^{125}Pr \rightarrow {}^{16}O + {}^{109}Sb$	4.8	8.4 = 2.8 + 5.6	10.3	25.4	30.1	23.09	3.0×10^{28}	-7.82

Table 3

Emitter and cluster	R_{in} (fm)	$R_{cont} = R_1 + R_2$ (fm)	R_{bar} (fm)	R_{out} (fm)	E_{bar} (MeV)	Q_{exp} (MeV)	Theoretical $T_{1/2}$(s)	$Log_{10}(T_\alpha/T_{cl})$
$^{250}No \rightarrow ^{48}Ca + ^{202}Pb$	6.0	11.1 = 4.16 + 6.97	12.4	15.5	25.4	151.66	5.7×10^{18}	-19.88
$^{251}Cf \rightarrow ^{46}Ar + ^{205}Hg$	6.0	11.1 = 4.1 + 7.0	12.4	16.4	28.9	126.16	2.0×10^{24}	-13.98
$^{251}No \rightarrow ^{48}Ca + ^{203}Pb$	6.0	11.1 = 4.16 + 6.98	12.4	15.5	25.0	151.89	1.3×10^{18}	-18.59
$^{252}Cf \rightarrow ^{46}Ar + ^{206}Hg$	6.0	11.1 = 4.1 + 7.0	12.5	16.4	28.2	126.72	1.5×10^{23}	-15.30
$^{252}Cf \rightarrow ^{50}Ca + ^{202}Pt$	6.0	11.1 = 4.0 + 7.1	12.5	16.2	29.1	138.2	2.7×10^{26}	-18.55
$^{252}Md \rightarrow ^{46}Ca + ^{206}Tl$	6.0	11.1 = 4.1 + 7.0	12.4	16.0	29.1	146.1	7.9×10^{23}	-22.11
$^{252}No \rightarrow ^{48}Ca + ^{204}Pb$	6.0	11.1 = 4.16 + 6.99	12.4	15.5	24.6	152.21	2.1×10^{17}	-17.21
$^{252}No \rightarrow ^{50}Ca + ^{202}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.9	27.8	148.39	3.9×10^{23}	-23.48
$^{253}No \rightarrow ^{48}Ca + ^{205}Pb$	6.0	11.2 = 4.2 + 7.0	12.4	15.5	24.2	152.44	4.7×10^{16}	-16.25
$^{253}No \rightarrow ^{50}Ca + ^{203}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.9	27.2	148.81	4.7×10^{22}	-22.25
$^{253}Fm \rightarrow ^{48}Ca + ^{205}Hg$	6.0	11.2 = 4.2 + 7.0	12.4	15.8	26.3	145.85	3.3×10^{20}	-15.68
$^{254}Md \rightarrow ^{48}Ca + ^{206}Tl$	6.0	11.2 = 4.2 + 7.0	12.4	15.5	24.2	150.06	6.1×10^{16}	-14.62
$^{254}No \rightarrow ^{46}Ca + ^{208}Pb$	6.0	11.1 = 4.1 + 7.0	12.4	15.8	27.5	149.62	2.0×10^{21}	-20.18
$^{254}No \rightarrow ^{48}Ca + ^{206}Pb$	6.0	11.2 = 4.2 + 7.0	12.4	15.11	23.7	152.73	8.3×10^{15}	-14.8
$^{254}No \rightarrow ^{50}Ca + ^{204}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.8	26.4	149.41	2.6×10^{21}	-20.29
$^{255}No \rightarrow ^{48}Ca + ^{207}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.4	22.8	153.53	1.7×10^{14}	-13.19
$^{255}No \rightarrow ^{50}Ca + ^{205}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.7	25.5	150.2	6.9×10^{19}	-18.8
$^{256}No \rightarrow ^{48}Ca + ^{208}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.3	22.3	153.8	3.1×10^{13}	-13.56
$^{256}No \rightarrow ^{50}Ca + ^{206}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.6	24.3	151.19	7.1×10^{17}	-17.92
$^{257}No \rightarrow ^{48}Ca + ^{209}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.5	23.9	152.06	2.2×10^{16}	-16.00
$^{257}No \rightarrow ^{50}Ca + ^{207}Pb$	6.0	11.2 = 4.2 + 7.0	12.5	15.5	23.1	152.26	4.7×10^{15}	-15.33

$^{258}Md \rightarrow {}^{50}Ca + {}^{208}Tl$	6.0	11.2 = 4.2 + 7.0	12.5	15.7	25.0	148.02	1.6×10^{19}	-14.55
$^{258}No \rightarrow {}^{48}Ca + {}^{210}Pb$	6.0	11.2 = 4.16 + 7.06	12.5	15.7	25.4	150.43	8.3×10^{18}	-17.4
$^{258}No \rightarrow {}^{50}Ca + {}^{208}Pb$	6.0	11.3 = 4.22 + 7.04	12.5	15.4	22.4	152.8	2.6×10^{14}	-12.89
$^{258}Rf \rightarrow {}^{48}Ca + {}^{210}Po$	6.0	11.3 = 4.2 + 7.1	12.5	15.4	23.6	156.65	4.6×10^{15}	-17.32
$^{258}Rf \rightarrow {}^{49}Ca + {}^{209}Po$	6.0	11.2 = 4.2 + 7.0	12.5	15.7	25.8	154.14	6.6×10^{19}	-21.48
$^{258}Rf \rightarrow {}^{50}Ca + {}^{208}Po$	6.0	11.3 = 4.22 + 7.04	12.5	15.7	26.1	153.52	6.4×10^{20}	-22.47
$^{258}Rf \rightarrow {}^{50}Ti + {}^{208}Pb$	6.0	11.3 = 4.22 + 7.04	12.4	15.3	24.0	169.65	4.1×10^{17}	-19.27
$^{258}Rf \rightarrow {}^{51}Ti + {}^{207}Pb$	6.0	11.3 = 4.25 + 7.03	12.4	15.4	24.6	168.66	1.2×10^{19}	-20.74
$^{258}Rf \rightarrow {}^{52}Ti + {}^{206}Pb$	6.0	11.3 = 4.3 + 7.0	12.5	15.3	23.2	169.73	1.5×10^{17}	-18.84
$^{258}Rf \rightarrow {}^{53}Ti + {}^{205}Pb$	6.0	11.3 = 4.3 + 7.0	12.5	15.5	25.5	167.07	3.3×10^{21}	-23.18
$^{258}Rf \rightarrow {}^{54}Ti + {}^{204}Pb$	6.0	11.3 = 4.3 + 7.0	12.6	15.5	24.9	167.35	9.5×10^{20}	-22.64
$^{259}No \rightarrow {}^{48}Ca + {}^{211}Pb$	6.1	11.2 = 4.16 + 7.07	12.5	15.9	26.9	148.81	2.5×10^{21}	-18.11
$^{259}No \rightarrow {}^{50}Ca + {}^{209}Pb$	6.0	11.3 = 4.22 + 7.05	12.5	15.6	23.8	151.31	7.9×10^{16}	-13.61
$^{260}No \rightarrow {}^{48}Ca + {}^{212}Pb$	6.1	11.2 = 4.16 + 7.09	12.5	16.0	28.1	147.38	3.6×10^{23}	-20.35
$^{261}No \rightarrow {}^{48}Ca + {}^{213}Pb$	6.1	11.3 = 4.2 + 7.1	12.5	16.2	29.4	145.97	4.4×10^{25}	-21.55
$^{261}No \rightarrow {}^{50}Ca + {}^{211}Pb$	6.1	11.3 = 4.2 + 7.1	12.6	15.9	26.2	148.57	1.8×10^{21}	-17.16
$^{262}No \rightarrow {}^{50}Ca + {}^{212}Pb$	6.1	11.3 = 4.2 + 7.1	12.6	16.0	27.3	147.28	1.8×10^{23}	-18.34
$^{266}Hs \rightarrow {}^{8}Be + {}^{258}Rf$	6.9	9.7 = 2.2 + 7.5	11.6	30.4	28.7	19.71	2.8×10^{18}	-21.35
$^{272}112 \rightarrow {}^{8}Be + {}^{264}Hs$	7.0	9.8 = 2.2 + 7.6	11.6	26.4	26.6	23.54	1.2×10^{11}	-16.72