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Determining the probable isotopic existence of superheavy nuclei

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Abstract

Superheavy nuclei, due to a higher neutron to proton ratio, its formation is highly complicated and predicting the feasible isotope which can be synthesised is an important task in the research on superheavy nuclei. Here we propose a method for predicting the isotopic feasibility by determining the coexistence of odd-even effect in the context of calculating E_α, $T_{1/2}(\alpha)$ using the binding energy by FRDM model. The prominent decay mode of Superheavy nuclei, α-decay, is been evaluated for Z=101-130 with A= 220-360 by considering both preformed α-cluster and 2n+2p instant decay. The intersection points in the graphs corresponding to the minimum difference between odd and even neutron contribution yield the most probable isotope to be formed and is compared with α-decay half-life calculations by Brown formula. Comparison of the results with known synthesised nuclei yield a close agreement with each other.

Keywords: Superheavy nuclei, graphs corresponding, brown formula

1. Introduction

Understanding the origin of universe routed from the formations of elements in astrophysical events, which is a fascinating question of search. Physics research, particularly the subject of nuclear physics mainly through various studies provide essential information on the nuclear structure, stability, decay rates, masses, nuclear cross section, location of island of stability across the nuclear landscape which goes into governing the creation of elements, their existence, and elemental abundance at the astronomical sites. Currently nuclear physics is at a fascinating period of time due to the discovery of superheavy elements one after another.

In laboratory superheavy nuclei have been formed in heavy-ion reactions of ^{226}Ra, ^{238}U, ^{237}Np, $^{242, 244}$Pu, ^{243}Am, ^{245}Cm, ^{249}Cf target nuclei with ^{48}Ca projectile and ^{208}Pb and ^{209}Bi target nuclei with ^{50}Ti, ^{54}Cr, ^{58}Fe, ^{64}Ni, ^{70}Zn projectile nuclei [1-8]. Most of these nuclei live for seconds or milliseconds. Several other reactions have been proposed to form other superheavy isotopes [9-12].

Recently [13], a search for production of the superheavy elements with atomic numbers 119 and 120 was performed in the ^{50}Ti + ^{249}Bk and ^{50}Ti + ^{249}Cf fusion-evaporation reactions. A detailed study on Z=119 was presented recently by us [14].

Spontaneous fission and α-decay are the main decay modes of superheavy nuclei. The competition between these two decay channels of superheavy nuclei has been studied within fission models and analytical semi-empirical formulas [10, 15-17]. The superheavy nuclei which have small alpha decay half-life compared to spontaneous fission half-life will survive fission which can be detected in the laboratory through alpha decay. A new decay mode, the heavy particle radioactivity, beyond the usual cluster radioactivity was also proposed recently [18-22].

Kiren *et al.*, [23] studied the alpha decay half-life and spontaneous fission half-life of some super heavy elements in the atomic range Z = 100-130. They have calculated the Spontaneous fission half-lives using the phenomenological formula and the alpha decay half-lives using Viola-Seaborg-Sobiczewski formula [24], semi empirical relation of Brown [25] and generalized liquid drop model based formula proposed by Dasgupta-Schubert and Reyes [26]. Due to the availability of modern accelerators and advanced detectors the synthesis of superheavy nuclei has received considerable attention in recent years [27-33]. The alpha decay of superheavy nuclei is possible if the shell effect supplies the extra binding energy and increases the barrier height of fission [34-38]. Royer *et al.*, [39] determined the α decay and the heavy particle emission half-lives of superheavy nuclei used Generalized Liquid Drop Model (GLDM) [40-43] and analytical

Semi empirical formulas [44-46] and Q value extracted from the new NUBASE2020 tables [47] and other literatures [46, 48, 49]. Patra *et al.*, [50] calculated the alpha decay energies and lifetimes for the alpha-decay chain of the superheavy nuclei $^{292}120$ and $^{304}120$ using the various parameter sets in both the non-relativistic Skyrme-Hartree-Fock and the axially deformed Relativistic Mean Field formalisms and they have compared their results with FRDM calculations.

In this paper, investigation on α-decay properties of heavy and superheavy nuclei are carried out since α-decay is the most prominent tool to investigate the superheavy nuclei [51]. Emphasis is given to the α-decay energy of heavy and superheavy nuclei, Z=101-130 and thus calculating the α decay half-life by Brown formula. The binding energy by FRDM is been used in this paper for the entire calculation and the calculated values are compared with AME2020 [52].

2. Methodology

It is known that the α-particle is preformed inside the nucleus before an α-decay and electrons are just formed during a β-decay. In this context we have taken the decay of 2p+2n particle combination just at the time of α-decay and compared this with the decay of preformed α-particle.

The α particle energy E_α is calculated using the Formula

$$E_\alpha = \Delta W\,(A, Z) - \Delta W\,(A-4, Z-2) - \Delta W\,(^4{}_2\mathrm{He}) \qquad (1)$$

The 2n and 2p separation energy is calculated by

$$S_{2n} = \{2m_n + M\,(A-2, Z) - M\,(A, Z)\}\,c^2 \qquad (2)$$

$$S_{2p} = \{2m_p + M\,(A-2, Z-2) - M\,(A, Z)\}\,c^2 \qquad (3)$$

The binding energy is calculated based on FRDM model, by Moller *et al.*, [53]

$$\Delta W\,(Z, N, \mathrm{Shape}) = M_H Z + M_n N + \left(-a_1 + J\bar{\delta}^2 - \frac{1}{2}K\bar{\varepsilon}^2\right)A +$$

$$\left(a_2 B_1 + \frac{9}{4}\frac{J^2}{Q}\bar{\delta}^2\frac{B_s{}^2}{B_1}\right)A^{2/3} + a_3 A^{1/3} B_K + a_0 A^0 + c_1\frac{Z^2}{A^{1/3}}B_3$$

$$- c_2 Z^2 A^{1/3} B_r - c4(Z^{4/3}/A^{1/3}) - c_5 Z^2 \frac{B_W B_s}{B_1} - f_0\frac{Z^2}{A} - c_a$$

$$(N - Z) + \Delta - a_{el} Z^{2.39} + w$$

$$\left(|I| + \begin{cases} 1/A, \\ 0, \end{cases} \text{Z and N odd and equal otherwise}\right) \text{-------}(4)$$

Where

The mass number A= Z + N the relative neutron excess I = (N $-$Z)/A the pairing gap $\Delta = \bar{\Delta}_p + \bar{\Delta}_n - \delta_{np}$, Odd Z and Odd N $\Delta = \bar{\Delta}_p$, odd Z and even N

$\Delta = \bar{\Delta}_n$, even Z and odd N

$\Delta = 0$, even Z and even N

The average neutron pairing gap $\bar{\Delta}_n = \dfrac{r_{mac} B_s}{N^{1/3}}$

The average proton pairing gap $\bar{\Delta}_p = \dfrac{r_{mac} B_s}{Z^{1/3}}$

The average neutron-proton interaction energy $\delta_{np} = \dfrac{h}{B_s A^{2/3}}$.

The quantities c_1, c_2, c_4, and c_5 are defined by

$$c_1 = \frac{3}{5}\frac{e^2}{r_0} \quad c_2 = \frac{1}{336}\left(\frac{1}{J} + \frac{18}{K}\right)c_1^2$$

$$c_4 = \frac{5}{4}\left(\frac{3}{2\pi}\right)^{2/3} c_1$$

$$c_5 = \frac{1}{64Q}\; c_1^2$$

The α-decay half-life of SHN can be calculated by Universal Decay Law (UDL), Viola-Seaborg-Sobiczewski formula (VSS), Generalised Liquid Drop Model (GLDM), Tagepera-Nurmia Formula (TN), Brown formula, etc. In this paper we have used the Brown formula [25],

$$\mathrm{Log}_{10}T_{1/2}(\mathrm{sec}) = (9.54\, Z_d^{0.6}/Q_\alpha^{1/2} - 51.37) \qquad \text{------}(5)$$

Where

Q_α, the α-decay Q-value is expressed in units of MeV. The Q_α-values for SHN α-emitters are determined from the kinetic energy E_α of the α-particle by means of the relation [54],

$$Q_\alpha = (A/(A-4))\,E_\alpha + [6.53(Z-2)^{7/5} - 8.0\,(Z-2)^{2/5}]10^{-5}\ \mathrm{MeV}. \ (6)$$

3. Result and Discussion

In this work the nuclei considered are from Z=101 to 130 covering both heavy elements and superheavy elements. The mass number is taken from 220 to 360 and hence considered the even-even, even-odd, odd-even and odd-odd nuclei. The α-particle energy obtained using equation (1) for each nucleus is analysed separately. For α-particle decay, 2p and 2n must be either preformed as a He nucleus or emitted as 2p+2n particles.

According to Yukawa theory of mesons, the pion exchange gives an identity to the nucleon as positive or neutral. The non-identity of the nucleus (positive or neutral) can be possible only at the point of energy equivalence, i.e., the coexistence of odd-even effect.

The mass number falls at this point may be the most survival isotope of the particular nucleus. So we have taken the point of intersection in (Fig-1) (graph for Z=111 only is given) as the most probable isotopic existence.

The mass number corresponding to the point of intersection (Fig-1) is plotted against Z number and which fits well with a straight line (Fig-2).

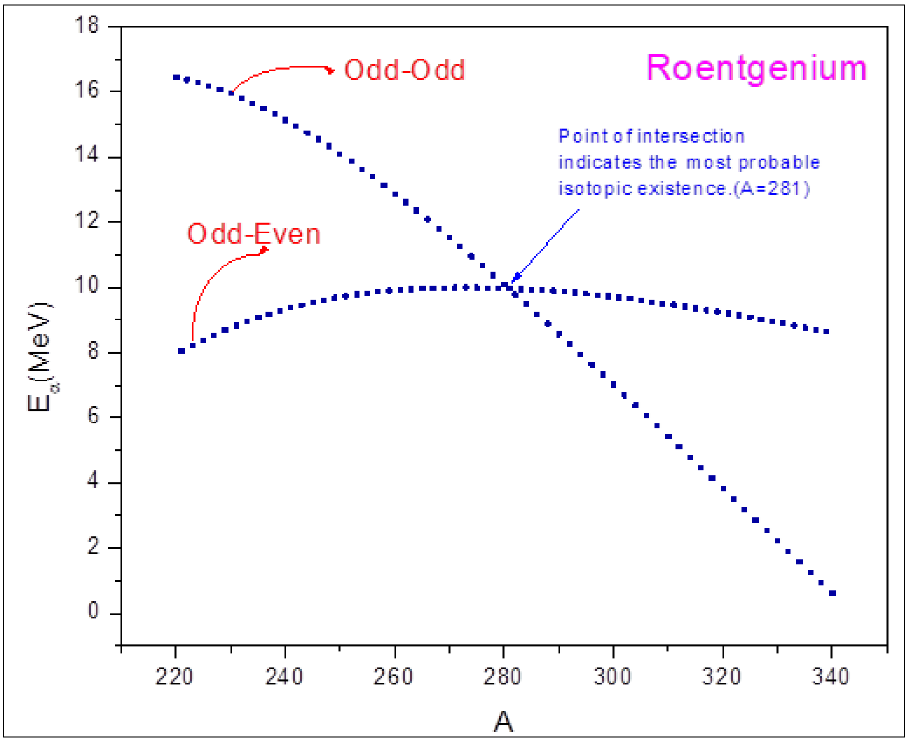
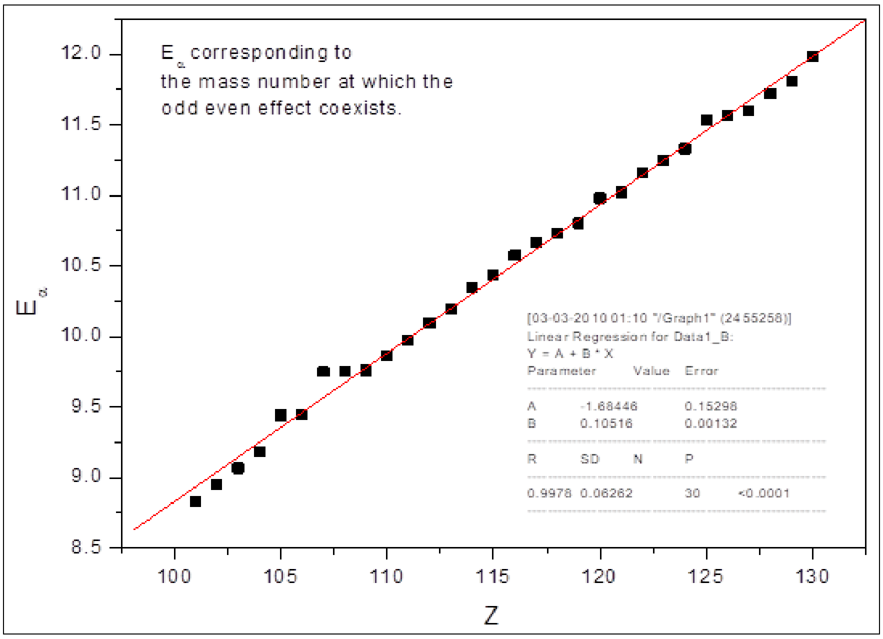


Fig 1: Alpha particle energy of Z=111



```
[03-03-2010 01:10 "/Graph1" (2455258)]
Linear Regression for Data1_B:
Y = A + B * X
Parameter          Value      Error
------------------------------------------------------
A          -1.68446          0.15298
B          0.10516           0.00132
------------------------------------------------------
R          SD        N        P
------------------------------------------------------
0.9978   0.06262             30         <0.0001
------------------------------------------------------
```

Fig 2: E_α of the odd-even nullifying point for Z=101-130

Similarly, the 2n separation energy and 2p separation energy are calculated for Z=101-130. From these values the mass number corresponding to the difference in S_{2n} and S_{2p} are least (Fig-3; graph for Z=111 only is given) is taken. From the figure plotted for S_{2p}~S_{2n} against Z (Fig-4) shows a higher difference at Z ≈115 and it gradually reduces to both the ends i.e., when Z approaches 100 as well as 130. This is a crucial point of discussion that the feasibility of elements synthesized was difficult when approaching from Z=104 to Z=118. Synthesizing higher elements Z>118, will also be a tough task but when approaching to Z ≥ 130 the formation process may little ease since at Z=138 the next magicity is expected[55-57]. At Z=115 the S_{2n} value is high compared to S_{2p} value which shows the nuclei Z=115 and near to it (Z=114) be more stable than neighbouring nuclei and α-decay may be the most probable decay mode.

The neutron number with the least difference between S_{2p} and S_{2n} for a particular Z value is been plotted in the figure [Fig.5] and found that the S_{2n} value corresponding to these Z values fits well with a straight line.

The corresponding E_α for Z=101-130 and the combination of 2proton separation energy and 2neutron separation energy are presented in fig-2 and fig-3 respectively. The value obtained for S_{2n} and S_{2p} are compared with AME2020 [34] and is presented in Table-1.

From the Fig.6, it is very clear that fitting the probable mass number stable against the decay of 2n & 2p as He nucleus, i.e., preformed α-particle or the instantly formed 2p+2n particle decay are parallel to each other with a shift towards higher mass numbers for the decay of instantly formed 2p+2n particles. This shift may be due to the influence of binding energy of α-particle.

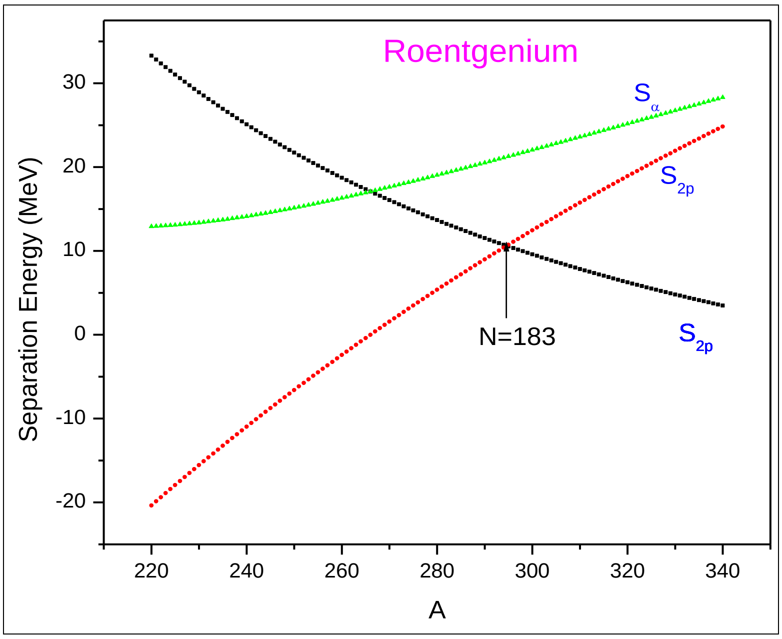


Fig 3: 2n, 2p and α-particle separation energy of Z=111

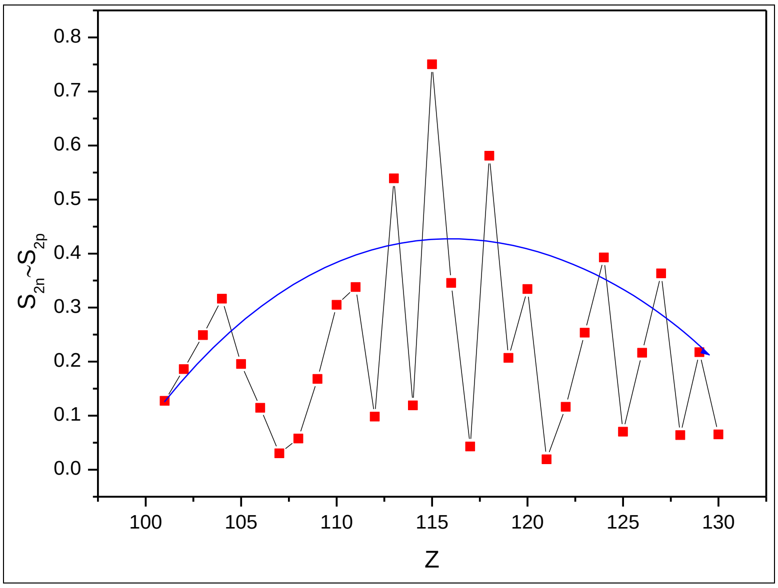
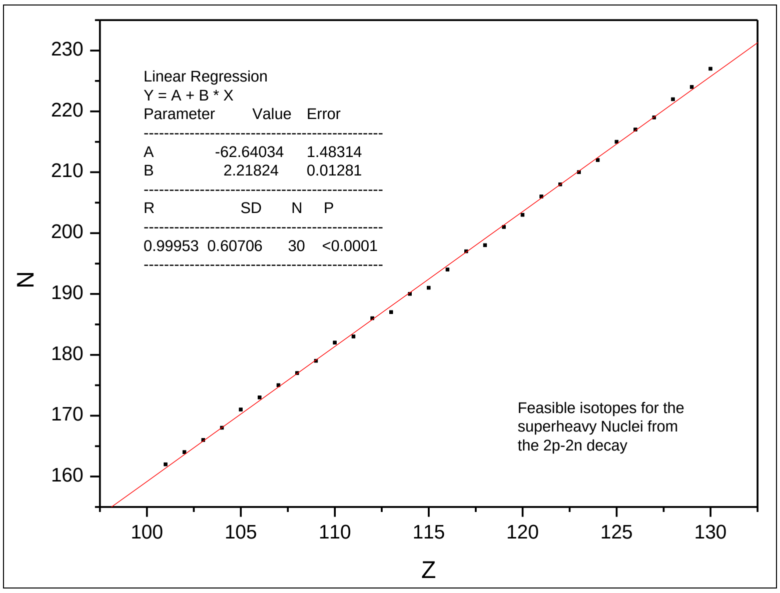


Fig 4: The difference in 2nº and 2p separation energy at the coexisting point of mass number



```
Linear Regression
Y = A + B * X
Parameter        Value     Error
------------------------------------------------------------
A              -62.64034   1.48314
B                2.21824   0.01281
------------------------------------------------------------
R                SD        N    P
------------------------------------------------------------
0.99953  0.60706    30   <0.0001
------------------------------------------------------------
```

Fig 5: The N Vs Z chart according to two particle separation energy.

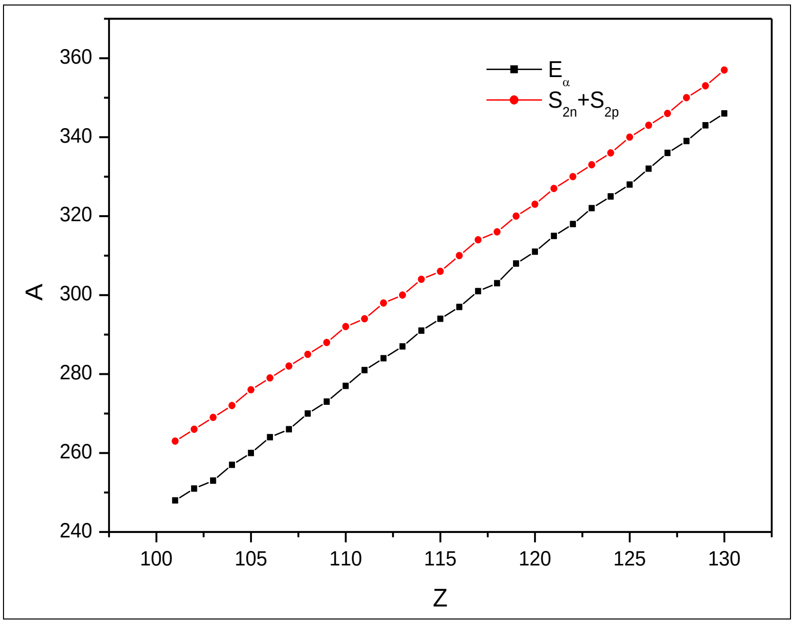


Fig 6: The mass number of coexistence of odd-even effect by α-particle decay (black line) and $2n^0$ + 2p decay (red line).

The nuclear stability not only depends on its structure but also its life time. Hence calculating the half-life of an isotope based on its decay mode provides information about its structure and stability. In SHN, since the prominent decay mode is α-particle decay we have calculated the half-life using Brown formula [25] [eqn.(5)] and are analysed in the context of odd-even effect for the nuclei Z=101 to 130.

It is understood from the figure (Fig.7) that the odd Z-odd N nuclei are having a low $T_{1/2}$ value and odd Z-even N nuclei have a high $T_{1/2}$ value upto A=281 for Z=111and it is vice versa for A>282. The difference in $T_{1/2}$ value for neighbouring isotope is comparatively negligible at the probable mass number isotopic existence.

In the odd Z-odd N system when the mass number increases, the $T_{1/2}$ value gets increases and the $T_{1/2}$ of odd Z-even N system gets decreases until the point of coexistence of odd - even effect, which will be the most probable isotopic existence.

Further increase of mass number leads to an inverse effect i.e., a higher value of $T_{1/2}$ for odd-odd isotopes is obtained which is beyond the feasibility.

For example the odd –even isotope of Z=111 shows a small variation with respect to the mass number i.e., the higher feasibility of having odd Z-even N isotope, which coincides well with the synthesized isotope of mass number A=281.

For even Z-even N isotope the $T_{1/2}$ value gradually increases with n^o number and from the point of coexistence of odd-even effect it starts growing exponentially, but the change in $\log T_{1/2}$(b) is comparatively small for even-odd isotopes (Fig.8).

While increasing the charge number the point of coexistence of odd-even effect is shifted to higher mass numbers. The mass number at the point of coexistence of odd-even effect in accordance to α-particle energy and α-decay half-life is plotted with the mass number of elements in the periodic table (Fig-9).

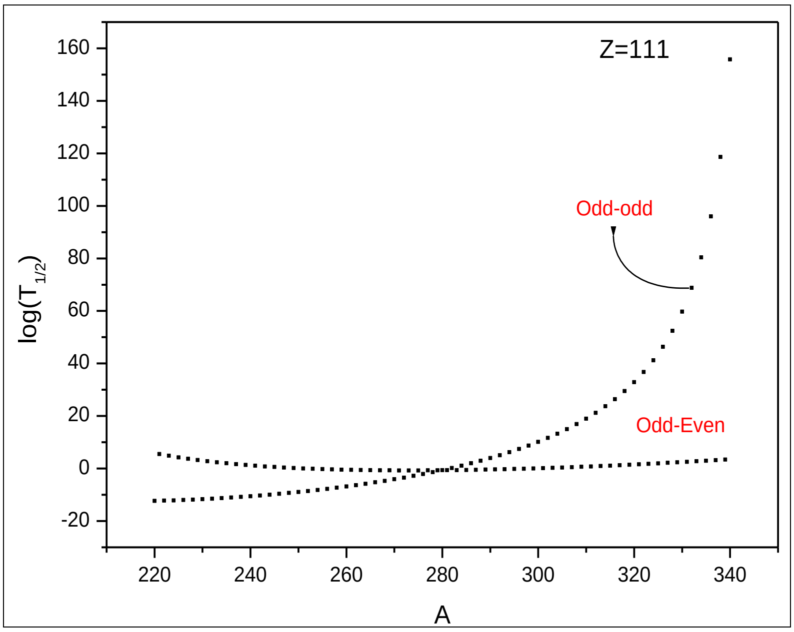


Fig 7: The α-particle half-life of odd Z nucleus Z=111 for A=220 to 340

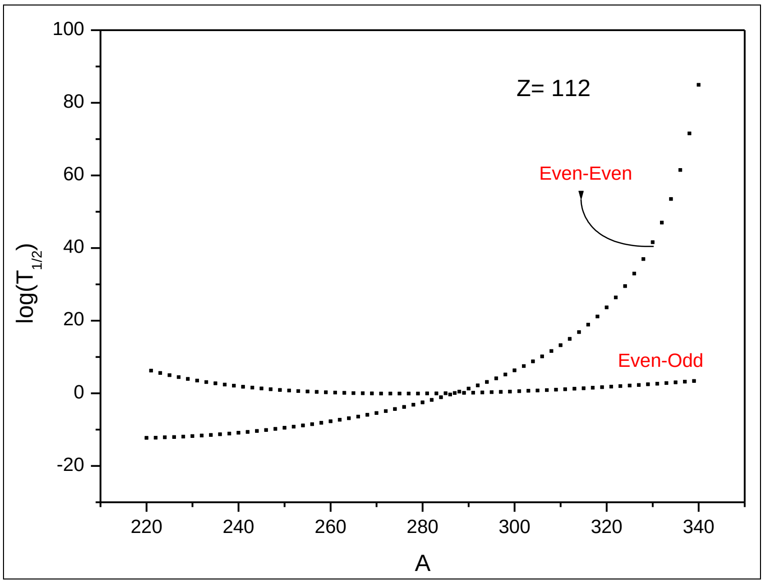


Fig 7: The α-particle half-life of even Z nucleus Z=112 for A=220 to 340

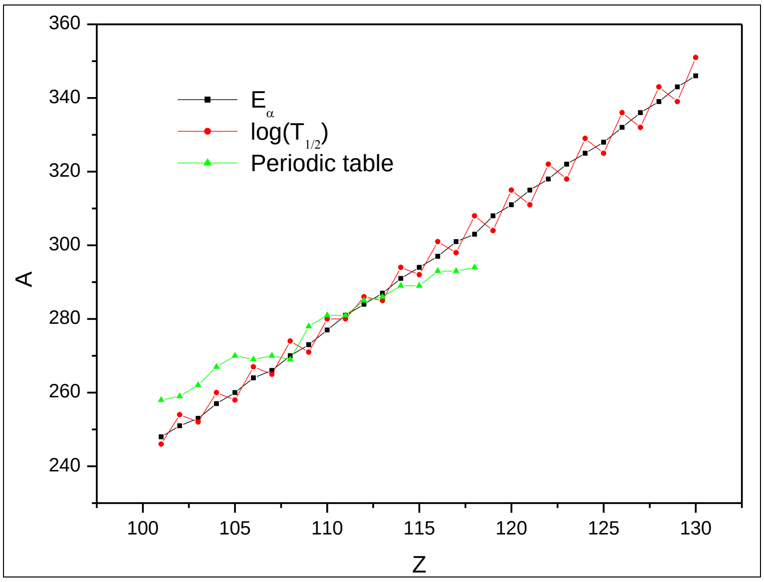


Fig 9: Isotopic existence of SHN as per log$T_{1/2}(\alpha)$, E_α and the periodic table.

4. Summary

It is understood from the analysis that the α-decay in SHN is the predominant one and the possibility of particle decay (equivalent to alpha particle: 2n & 2p) is too less.

The E_α value corresponding to the mass number at which the odd even effect coexists shows a linear dependence of E_α with Z value. But the difference in S_{2n} with S_{2p} (ie S_{2n}~S_{2p}), reveals the fact that the S_{2n} and S_{2p} are very close to each other.

Since there is a shift in the coexistence of odd-even effect it may be interpreted as this is due to the role play of the binding energy of preformed α-particle.

The α-decay half-life of the compound nucleus formed is an important parameter to be defined while dealing with nuclear reaction of superheavy nuclei. The α-decay half-life of the superheavy nuclei calculated by Brown formula [25] reveals the most probable existence of nuclei will be at the point of coexistence of odd-even effect.

Table 1: 2n^{o} & 2p separation energies calculated using FRDM and with AME 2020 [52]

Z	A	S_{2n}	S_{2n} [52]	S_{2p}	S_{2p}[52]
101	248	15.1323	15.31	5.2607	5.45
102	251	15.5184	15.08	5.2126	5.25
103	253	15.1692	15.45	4.7494	5.02
104	257	14.8007	14.61	5.1044	5.523
105	260	14.6969	13.98	5.045	5.69
106	264	14.3485	13.73	5.3767	6.19
107	266	14.4977	14	4.9161	5.74
108	270	14.1625	14	5.2323	6.27
109	273	14.0731	12.46	5.1556	5.66
110	277	13.7562	12.72	5.4524	5.98
111	281	13.4503	12.53	5.7358	6.83

112	284	13.3745	12.55	5.6428	6.95
113	287	13.301	12.46	5.5479	6.85
114	291	13.0156	12.11	5.8074	
115	294	12.9487		5.7039	
116	297	12.884		5.5986	
117	301	12.6172		5.8362	
118	303	12.7593		5.3816	
119	308	12.304		5.9456	
120	311	12.2505		5.8257	
121	315	12.0083		6.0342	
122	318	11.96		5.9082	
123	322	11.5454		6.4226	
124	325	11.6841		5.9705	
125	328	11.6416		5.8379	
126	332	11.4238		6.0156	
127	336	11.2122		6.1855	
128	339	11.1758		6.043	
129	343	10.9729		6.2012	
130	346	10.9414			

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