Final Report of the MRP(S)-1354/11-12/ KLKA004/UGC- SWRO dated 27.03.2014

On

NUCLEAR STRUCTURE STUDIES VIA CLUSTER DECAY

Submitted by

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to

University Grants Commission

Declaration

I hereby declare that this report is an authentic record of work carried out by me under UGC Minor Research Project; MRP(S)-1354/11-12/ KLKA004/UGC- SWRO dated 27.03.2014 on "NUCLEAR STRUCTURE STUDIES VIA CLUSTER DECAY".

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CHAPTER I

INTRODUCTION

1.1 INTRODUCTION

Cluster radioactivity known today as the spontaneous emission of light clusters (^{14}C to ^{34}Si) occupies the intermediate position between alpha decay and fission. This phenomenon first predicted by Sandulescu et al [1] in 1980 on the basis of quantum mechanical fragmentation theory (QMFT). Rose and Jones [2] in 1984 observed the first evidence of exotic decay and a few months later observed by Alexandrov et al [3] in the spontaneous emission of ^{14}C cluster from ^{223}Ra. Altogether about 24 modes of exotic decay from 18 parent nuclei, emitting clusters ranging from carbon to silicon, were so far confirmed. Upper limit for decay rate for 16 modes were measured and one case of fine structure in the energy spectrum of 14 clusters from ^{223}Ra was found [4]. This phenomenon can be treated as a case of strong asymmetric fission [5] or an exotic of cluster formation and tunneling through the barrier making much assault on the barrier similar to alpha decay [6].

Understanding the structure of the atomic nucleus is one of the central problems in nuclear physics. A nuclear model is a simple way of looking at a nucleus that gives a physical insight in the range of its properties as possible. In the present work I would like to study the nuclear properties (shells, deformation, structure effects) in different mass regions.

1.2 ORIGIN OF THE RESEARCH PROBLEM

The island of stability is a term from nuclear physics that describes the possibility of elements with particularly stable magic numbers of protons and neutrons. The main physical interest to its investigation comes from the fact that cluster radioactivity makes a bridge between these two extreme nuclear many body phenomena strongly differing by nucleon number, decay mechanism, properties of the emitted fragments. For this reason the information obtained in the cluster radioactivity goes beyond nuclear effects. In these new radioactive modes, almost all the residual nuclei resulting from cluster emission have been found to be the doubly magic ^{208}Pb or very close to it (lead radioactivity) [2]. Recently other island of cluster radioactivity having residual nuclei close to doubly magic ^{100}Sn "tin radioactivity" has been predicted theoretically and confirmed experimentally [7,8]. Cluster radioactivity is a cold process (zero excitation energy) since energy released as Q value is completely consumed by kinetic energy alone of the two fragments. Fission also the spontaneous breaking of a nucleus in to two fragments (binary fission) heavier than the one involved in cluster radioactivity but with or without accompanied by neutron emission. The neutron less fission or cold fission was observed at Grenoble [9] in 1982. The neutron less fission is also observed in 1984 at Oak Ridge National Laboratory [10] using the multiple Ge detector compact ball Facility.

In our previous works we have proposed [16-20] the Coulomb and proximity potential models to study the cluster emission from various proton-rich nuclei with $Z = 54$-64 and N = 54-72 leading to ^{100}Sn daughter. We have studied the cold valleys in the radioactive decay of $^{248\text{-}254}$Cf isotopes [20] and the computed alpha decay half-life values are in close agreement with the experimental data. A semi-empirical model [21] for determining the half-lives of radioactive nuclei exhibiting cluster radioactivity is proposed. The semi-empirical formula is applied to alpha decay of parents with Z = 85-102 and is compared with experimental data. Again we study [22] the alpha decay, cluster decay and spontaneous fission in super heavy $^{294–326}$122 isotopes highlighting the comparison between alpha decay and spontaneous fission. We have also extended our studies [23] to find the possibilities of neutron and proton shell closure in the super heavy region via cluster radioactivity in $^{280–314}$116 isotopes.

1.3 OBJECTIVES OF THE STUDY

The present study titled "Nuclear Structure Studies via Cluster Decay" is undertaken with following objectives.

- ✓ So far observed cluster radioactivity are from trans-lead and trans-tin region. So in the proposed work we would like to explore the possibility of cluster emission from the other region preferably in heavy and super heavy region.
- ✓ In the proposed research work we would like to study cluster radioactivity of various nuclei in the heavy and super heavy region using the Coulomb and Proximity Potential Model (CPPM).
- ✓ We would like to explore the possibility of the production of heavy and super heavy elements via cluster radioactivity.
- ✓ To explore the decay possibility of proton halo nuclei from different even-even isotopes in the super heavy region.

1.4 Organisation of the study

This dissertation consists of seven chapters. The first chapter is an introductory, which brings information about radioactivity and its type, scope of the study and the objectives to be achieved in this work are also presented in this chapter I.

The alpha and cluster decay half lives of various isotopes in heavy and super heavy region are computed using coulomb and nuclear proximity potential model as the interacting barrier. The model ingredient with zero point vibration energy, assault frequency, radius (distance between the two centers of the nuclei), penetrability and life time expression, branching ratio are also discussed in chapter II.

Chapter III incorporates the study of alpha decay half life time and all other characteristics of different even-even $^{242-260}$Fm, $^{248-264}$No and $^{254-264}$Rf isotopes.

The ^{12,14}C cluster decay half life time and all other characteristics of different even-even isotopes with atomic number varies from 120 to 126 is studied in Chapter IV.

Computed the alpha and cluster decay half lives of various even-even isotopes (with Z ranging from 116 to 126) in the super heavy region in which the decay leading to Z = 114 daughter, using Coulomb and Proximity potential [3] as interacting barrier is discussed in chapter V

The decay possibility of proton halo nuclei (^{13}N, ^{17}F, ^{17}Ne, ^{26}P, ^{27}S) from different even-even $^{260-280}$110, $^{264-284}$112, $^{268-288}$114 and $^{278-298}$116 isotopes is studied in Chapter VI

Finally in chapter seven, we summarize the salient features of this work and conclusion drawn from the study.

References

[1] A Sandulescu, D Poenaru and W Greiner, *Sov. J. Part. Nucl.* **II**, 528 (1980)

[2] H J Rose and G A Jones, *Nature* **307,** 245 (1984)

[3] D V Alexandrov, A F Belyatsky, Yu A Glukhov, E Yu Nikolsky, B V Novatsky, A A Ogloblin and D N Stepanov, *JEPT.Lett*. **40,** 909 (1984)

[4] R Bonetti and A Guglielmetti in *Heavy elements and related new phenomena,* edited by W Greiner and R K Gupta (World Scientific Pub., Singapore, 1999), Vol. **II**, p.643

[5] D N Poenaru, M Ivascu and A Sandulescu, *J. Phys. G: Nucl. Part. Phys.* **5,** L169 (1979)

[6] R Blendoaske, T Fliessbach and H Walliser, *Nucl. Phys* **A 464,** 75 (1987)

[7] D N Poeranu, D Schnabel, W Grireiner, D Mazilu and Gherghescu, *At.Data.Nucl.Data.Table* **48**, 231 (1991)

[8] Yu Ts Oganessian and S P Tretyakova, *JINR Report No. E 7-93-57* (1993)

[9] F J Gonnenwein, *Int.Conf. on Nucl.Data for Basic and Applied Sciences* (New Mexico,USA,(1985)

[10] G M Ter-Akopian et al, *Phy.Rev.Lett* **73**, 1477 (1994)

[11] D N Poenaru and M Ivascu, *J.Phys.G* **45**, 1099 (1984)

[12] Y J Shi and W J Swiatecki, *Phys.Rev.Lett* **54**, 300 (1985)

[13] G Shanmugam and B Kamalaharan, *Phys.Rev.C* **38**, 1377 (1988)

[14] S S Malik and R K Gupta, *Phys.Rev.C* **39**, 1992 (1989)

[15] B Buck and A C Merchant, *J.Phys.G* **15**, 615 (1989)

[16] K P Santhosh and Antony Joseph, *Proc. Int. Natl. Symp. Nucl. Phys. (India)* B43, 296 (2000)

[17] K P Santhosh and Antony Joseph, *Pramana. J. Phys.* 58, 611 (2002)

[18] K P Santhosh and Antony Joseph, *Ind. J. Pure Appl. Phys.* 42, 806 (2004)

[19] K P Santhosh and Antony Joseph, *Pramana. J. Phys*. 62, 957 (2004)

[20] R K Biju, Sabina Sahadevan, K P Santhosh and Antony Joseph, *Pramana. J. Phys*. 70, 617 (2008)

[21] K P Santhosh, R K Biju and Antony Joseph, *J. Phys. G: Nucl. Part. Phys.* 35, 085102 (2008)

[22] K P Santhosh, R K Biju, *J. Phys. G: Nucl. Part. Phys.* 36, 015107 (2009)

[23] K P Santhosh, R K Biju, *Pramana. J. Phys*. 72, 689 (2009)

CHAPTER II

COULOMB AND NUCLEAR PROXIMITY POTENTIAL MODEL

2.1. INTRODUCTION

The possibility to have a cluster process is related to its exotermicity:

$$Q = M\,(A, Z) - M\,(A_1, Z_1) - M\,(A_2, Z_2) > 0. \quad (2.1)$$

Where M (A, Z), M (A_1, Z_1) and M (A_2, Z_2) are the atomic masses of the parent, daughter and cluster respectively. The cluster radioactivity based on the potential barrier determined by two sphere approximation, as the sum of Coulomb and nuclear proximity potential [1] for z > 0. Where 'z' is the distance between the near surface of the fragments. For the overlap region (z < 0) we used simple power law interpolation. For the elements found in the second half of the periodic system, which have average binding energy per nucleon smaller than the lighter elements, this condition is fulfilled for a large range of nuclear decays. However, in majority of cases the possibility of decay is hindered by the small barrier penetrability. This quantity reaches large values only in two cases: α-decay and spontaneous fission of heavy nuclei. An exception is given by high penetrabilities (values which can be sometimes even larger than those corresponding to the α-decay) of the daughter nuclei ^{14}C, ^{24}Ne, etc, when the complementary nucleus is close to the double-magic ^{208}Pb. This fact is connected to the much larger value of the ratio Q_C/B_Crelative to the value Qα/Bα, where BC,α are the heights of the corresponding barriers.

2.2. COULOMB AND PROXIMITY POTENTIAL MODEL

The interacting potential barrier for a parent nucleus exhibiting exotic decay is given by

$$V \quad \frac{Z_1 Z_2 e^2}{r} + V_p(z) + \frac{\hbar^2 l(l+1)}{2\mu r^2} \qquad \text{, for } z > 0 \qquad (2.2)$$

Here Z_1 and Z_2 are the atomic numbers of daughter and emitted cluster, 'r' is the distance between fragment centers, ℓ the angular momentum, μ the reduced mass and Vp is the proximity potential is given by Blocki et al [2]. These are represented in fig.2.1 pictorially and fig.2.2 represents the Pre-Scission and Post Scission configuration of a nucleus.

$$V_p(z) \quad 4\Pi \gamma b\left[\frac{C_1 C_2}{(C_1 + C_2)}\right]\phi\left(\frac{z}{b}\right) \qquad (2.3)$$

With the nuclear surface tension coefficient,

$$\gamma \quad 0.9517\left[1 - {1.7826(N-Z)^2}\big/{A^2}\right] \text{ MeV/fm}^2 \qquad (2.4)$$

Where N, Z and A represent neutron, proton and mass number of parent, respectively. Φ, represents the universal the proximity potential is given as [3].

$$\Phi(\varepsilon) \quad -4.41 e^{-\varepsilon/0.7176}, \text{ for } \varepsilon \geq 1.9475 \qquad (2.5)$$

$$\Phi(\varepsilon) \quad -1.7817 + 0.9270\,\varepsilon + 0.0169\,\varepsilon^2 - 0.05148\,\varepsilon^3,$$

$$\text{for } 0 \leq \varepsilon \leq 1.9475 \qquad (2.6)$$

With,

$$\varepsilon = z/b \qquad (2.7)$$

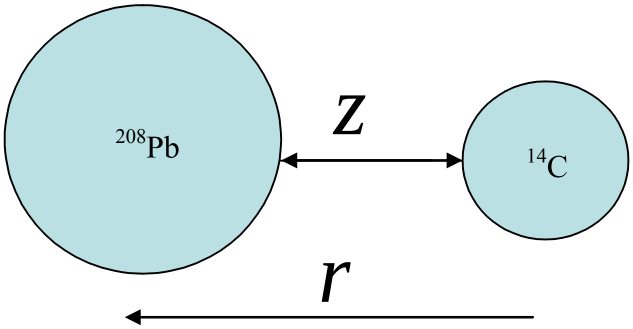


Figure 2.1. Shows ‘Z’ and ‘r’ pictorially.

where the width (diffuseness)of the nuclear surface b ≈1 and Sissmann central radii C_i of fragments related to sharp radii R_i is

$$C_i \quad R_i - \left(\frac{b^2}{R_i} \right) \tag{2.8}$$

For R_i we use semi empirical formula in terms of mass number A_i as [2]

$$R_i \quad 1.28 A_i^{1/3} - 0.76 + 0.8 A_i^{-1/3} \tag{2.9}$$

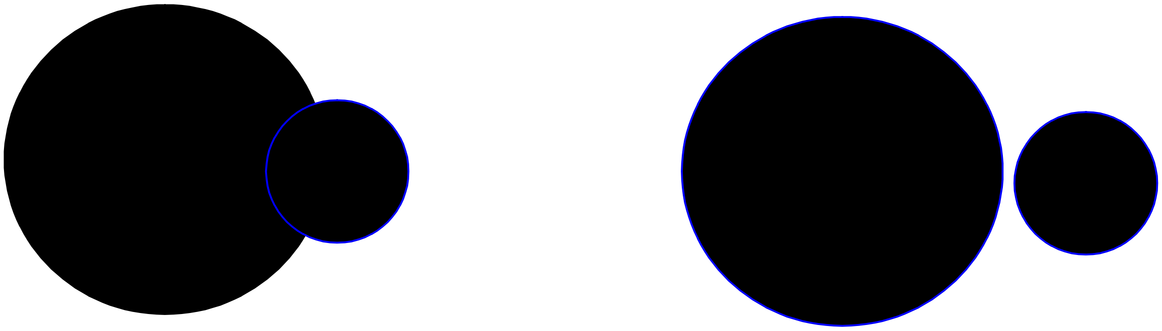
The barrier penetrably P is given as:

$$\mathbf{P} \quad \exp\{-\frac{2}{\hbar}\int_a^b \sqrt{2\mu(V-Q)}dz\} \tag{2.10}$$

Here the mass parameter is replaced by

$$\mu \quad \frac{(mA_1A_2)}{A} \tag{2.11}$$

Where ‘m’ is the nucleon mass and A_1, A_2 are the mass numbers of daughter and emitted cluster respectively.



(A) Pre-Scission (B) Post Scission configuration

Figure 2.2. Represent the Pre-Scission and Post Scission configuration of a nucleus.

The turning points ‘a’ and ‘b’ are given by

$$V(a) \quad V(b) \quad Q, \tag{2.12}$$

Where Q is the energy released. The above integral can be evaluated numerically or analytically, and the half life time is given by

$$T_{1/2} \quad \left(\frac{\ln 2}{\lambda}\right) \quad \left(\frac{\ln 2}{\upsilon P}\right) \tag{2.13}$$

Where,

$$\upsilon \quad \left(\frac{\omega}{2\pi}\right) \quad \left(\frac{2E_v}{h}\right), \tag{2.14}$$

represent the number of assaults on the barrier per second and λ the decay constant. $E_{v,}$ the empirical zero point vibration energy is given as [4]

$$E_v \quad Q\left\{0.056+0.039\exp\left[\frac{(4-A_2)}{2.5}\right]\right\} \quad \text{for, } A_2 \geq 4. \tag{2.15}$$

REFERENCE

[1] K P Santhosh and Antony Joseph Pramana- J.Phys 55, 375 (2000)

[2] J Blocki, J Randrup W J Swiatecki and C F Tsang, Ann. Phys(N.Y) 105, 427(1977)

[3] J Blocki and W J Swiatecki, Ann. Phys (N.Y) 132, 53(1981)

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

CHAPTER III

Alpha Radioactivity of various Fm, No and Rf Isotopes

3.1 INTRODUCTION

Alpha decay is a type of radioactive decay in which an atomic nucleus emits an alpha particle and thereby transforms (or 'decays') into an atom with a mass number 4 less and atomic number 2 less. Alpha decay is fundamentally a quantum tunneling process. In 1928 George Gamow had solved the theory of the alpha decay via tunneling. The alpha particle is trapped in a potential well by the nucleus. Gamow solved a model potential for the nucleus and derived, from first principles, a relationship between the half-life of the decay, and the energy of the emission, which had been previously discovered empirically, and was known as the Geiger–Nuttall law.

During the last two decades the tremendous progress in experimental technologies made it possible to reach very near the islands of stability in the heavy and super heavy region. The possibility of an island of stability was first proposed by Glenn T. Seaborg in 1960 [1]. The hypothesis is based upon the nuclear shell model, which implies that the atomic nucleus is built up in shells in a manner similar to the structure of the much larger electron shells in atoms. In both cases, shells are just groups of quantum energy levels that are relatively close to each other. Energy levels from quantum states in two different shells will be separated by a relatively large energy gap. So the number of neutrons and protons that completely fills the energy levels of a given shell in the nucleus represents the shell closure. In the present work we would like to study the alpha decay half life time and all other characteristics of different even-even $^{242-260}$Fm, $^{248-264}$No and $^{254-264}$Rf isotopes.

3.2 RESULTS, DISCUSSION AND CONCLUSION

We have done our calculations by taking potential barrier as the sum of Coulomb potential, proximity potential and centrifugal potential for the touching configuration and for the separated fragments. For the pre-scission (overlap) region, simple power law interpolation [2] is used. The inclusion of proximity potential reduces the height of the barrier which closely agrees with the experimental values. The possibility to have a cluster emission process is,

$$Q = M(A, Z) - M(A_1, Z_1) - M(A_2, Z_2) > 0,$$

(3.1)

where M (A, Z), M (A_1, Z_1) and M (A_2, Z_2) are the atomic masses of the parent, daughter and cluster respectively. . The Q-values are computed using experimental binding energies of Audi and Wapstra [3].

Table 3.1 gives the logarithm of the computed half-life time and other characteristics of ^{4}He clusters from various Fm, No and Rf isotopes. It is found that most of the predicted half-life times fall well within the present upper limit for measurement ($T_{1/2}<10^{30}$s).

Figures 3.1-3.3 represent the plot of computed $\log_{10}(T_{1/2})$ versus neutron number of parent nuclei for the ^{4}He emission from different Fm, No and Rf isotopes respectively. It is found from the plots that there is a peak in half life time at N = 152. The maxima in half life time and minima in barrier penetrability at N = 152 stress the neutron shell closure of the parent in the superheavy region. That is N=152 represents the stability of the parent nuclei against alpha decay. In addition to this peak, there is a peak in half life time at N = 162 and is shown in the figure 4.3, which represents the stability of the corresponding parents. That is N = 152 and 162 are the next predicted neutron shell closure in the super heavy region. We would like to point out that many authors have predicted that N=152, 162 [4, 5] are sub magic neutron shell closure in the super heavy region.

Figures 3.4-3.6 represent the Geiger-Nuttall plots of the predicted $\log_{10}$ ($T_{1/2}$) versus –ln(p) for ^{4}He emission from different Fm, No and Rf isotopes. These plots are found to be linear. We would like to point out that the Geiger-Nuttall law is for pure coulomb potential, but our study shows that inclusion of the nuclear potential will not affect its linear nature [6]. Figures 3.7-3.9 represent the Geiger-Nuttall plot of the predicted $\log_{10}$ ($T_{1/2}$) versus $Q^{-1/2}$ for alpha decay from different Fm, No and Rf isotopes. These plots are also found to be in linear. From the observed linear nature of the Geiger-Nuttall plot [9], we have arrived at an equation for the logarithm of the predicted half-life times as,

$$\log_{10}(T_{1/2}) \quad \frac{X}{\sqrt{Q}} + Y$$

(4.2)

From the plots we can calculate the X and Y. Knowing the values of X, Y we can easily compute the half lives for the corresponding decays.

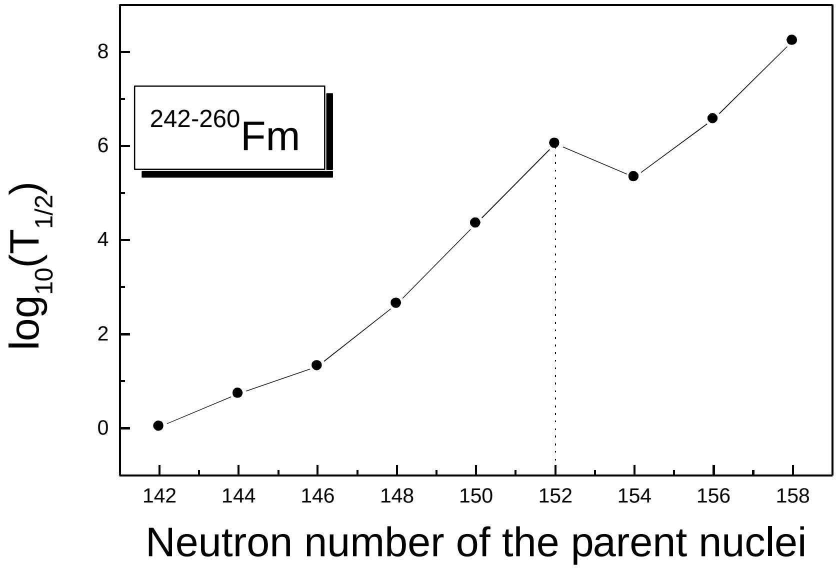


Figure 3.1: Computed half life time versus Neutron number of parent nuclei for the alpha decay of various Fm isotopes.

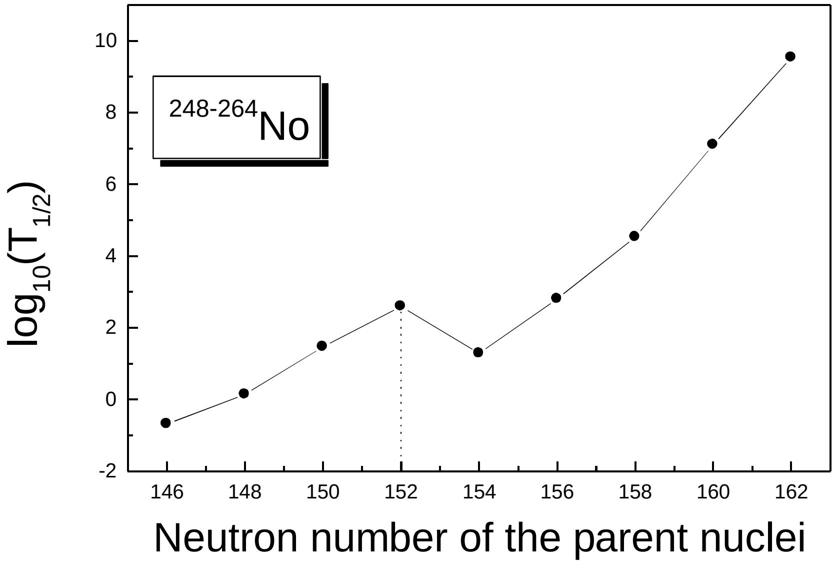


Figure 3.2: Computed half life time versus neutron number of the parent nuclei for the alpha decay of different No isotopes.

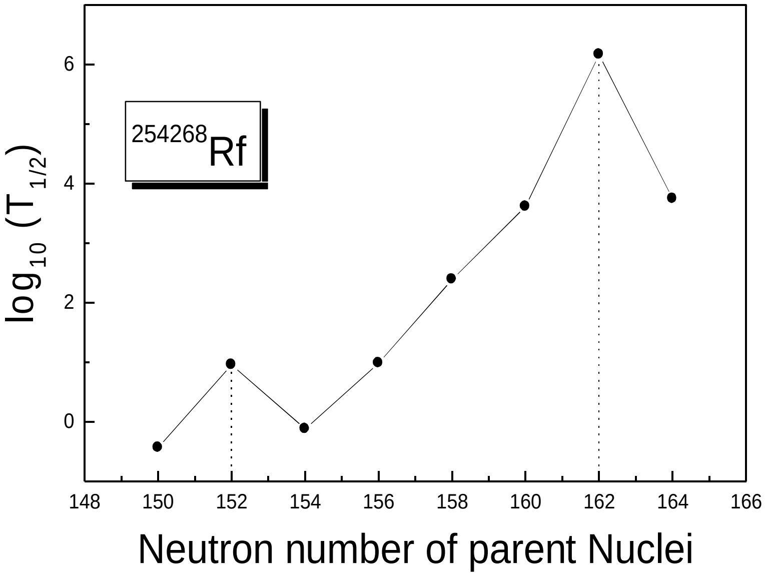


Figure 3.3: Computed half life time versus Neutron number of parent nuclei for the alpha decay of different Rf isotopes.

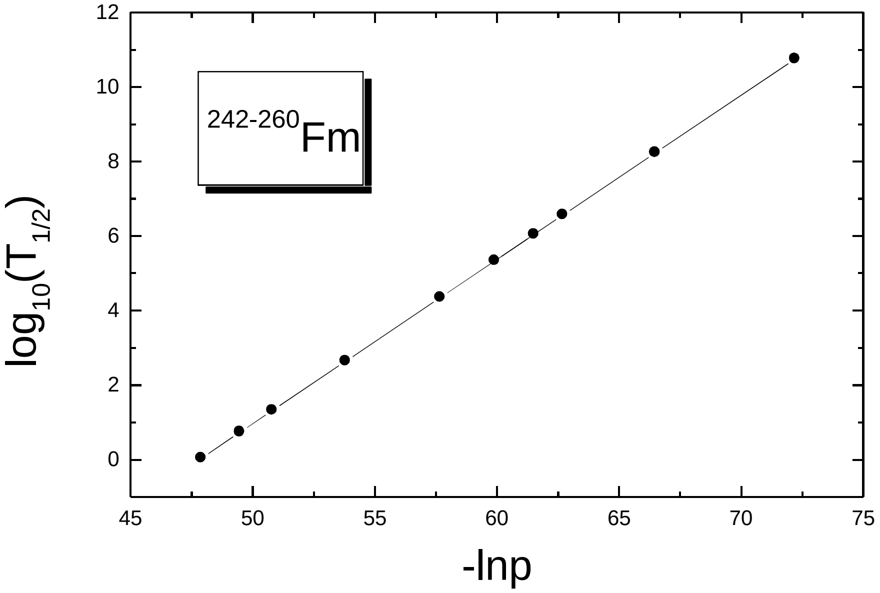


Figure 3.4: Geiger Nuttall plot for the logarithm of penetrability versus half life time for the alpha decay of different Fm isotopes.

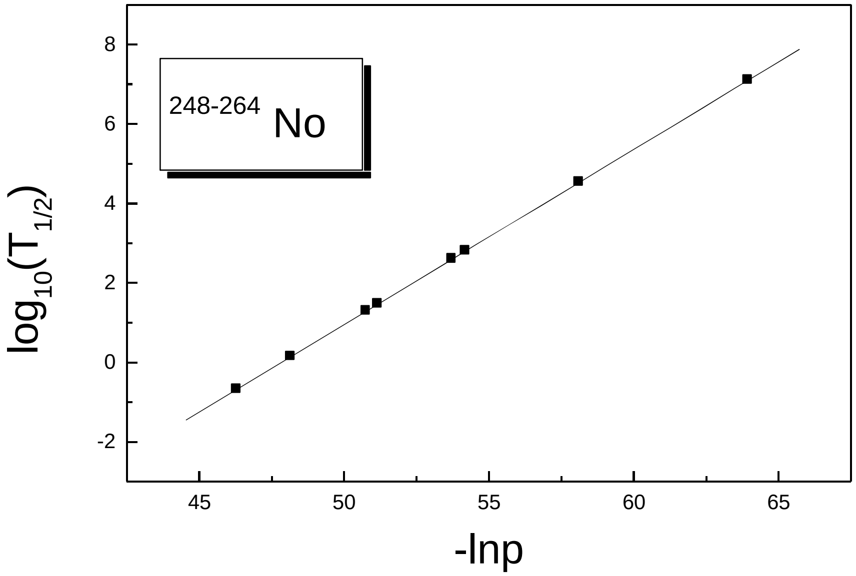


Figure 3.5: Geiger Nuttall plot for the logarithm of penetrability versus half life time for the alpha decay of different No isotopes.

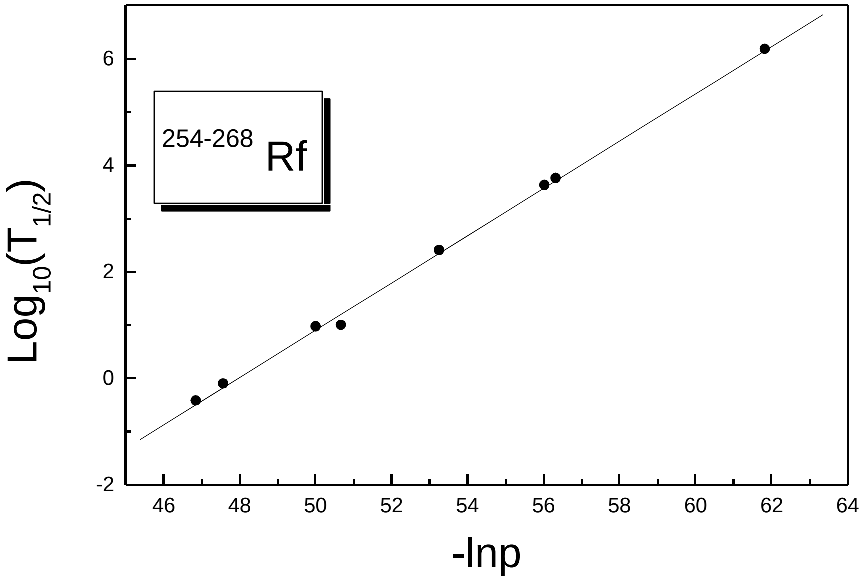


Figure 3.6: Geiger Nuttall plot for the logarithm of penetrability versus half life time for the alpha decay of different Rf isotopes.

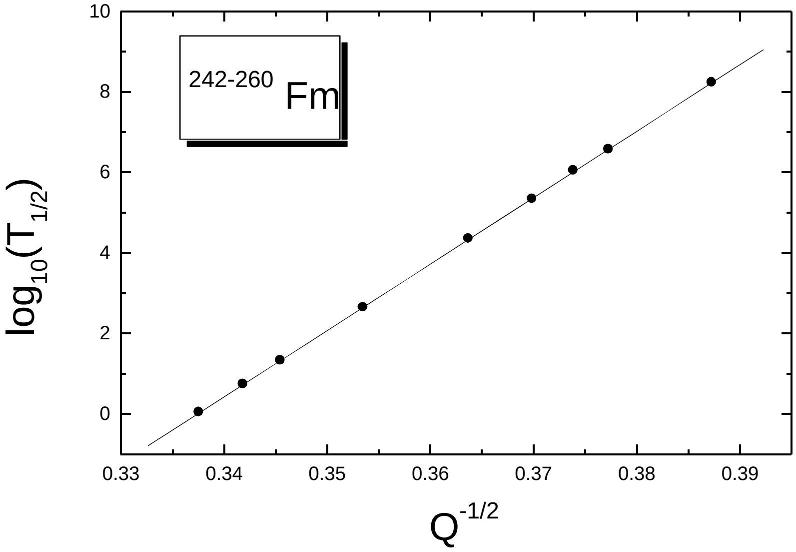


Figure 3.7: Geiger Nuttall plot for $Q^{-1/2}$ versus half life time for the alpha decay of different Fm isotopes.

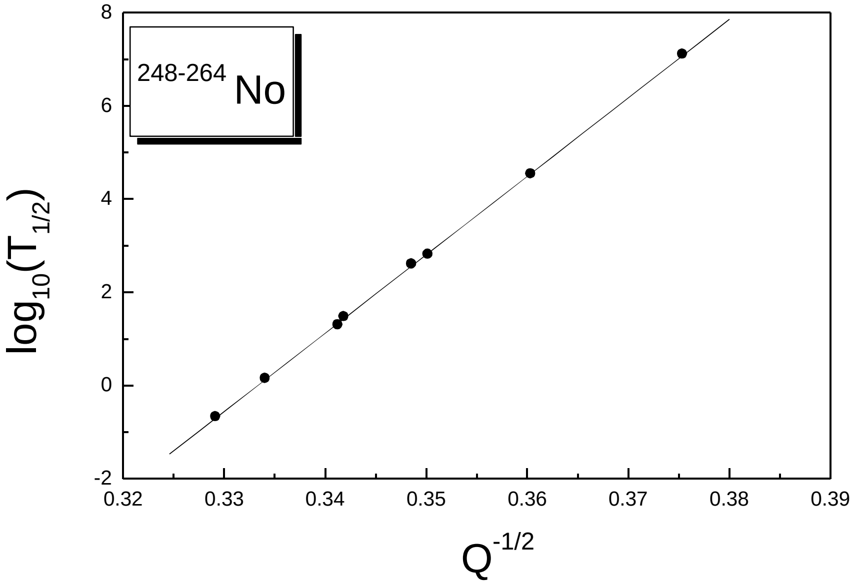


Figure 3.8: Geiger Nuttall plot for $Q^{-1/2}$ versus half life time for the alpha decay of different No isotopes.

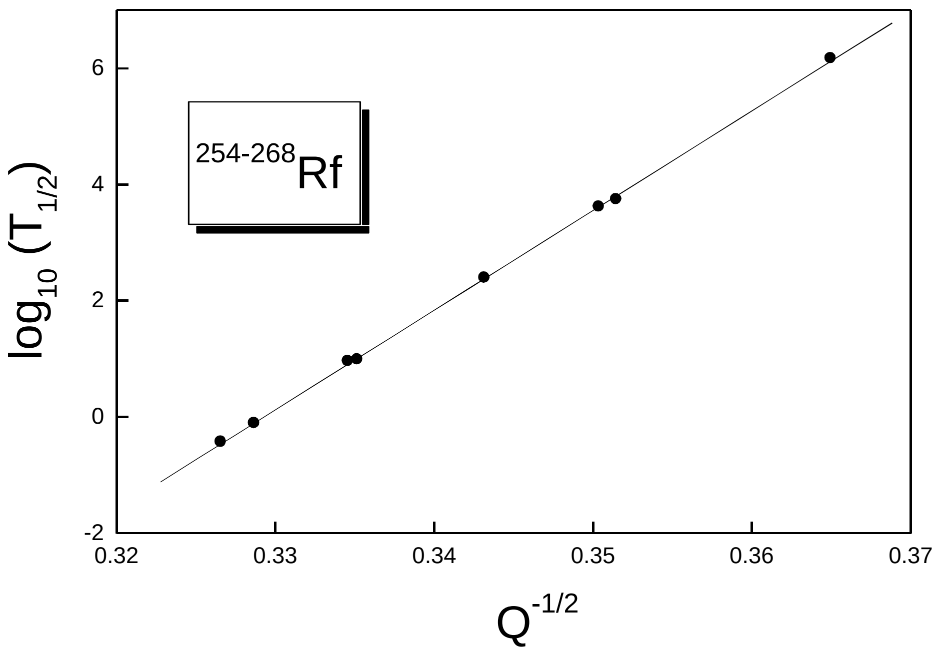


Figure 3.9: Geiger Nuttall plot for $Q^{-1/2}$ versus half life time for the alpha decay of different Rf isotopes.

Table 3.1: Logarithm of the computed half life times and other characteristics of He emission from various Fm, No and Rf isotopes.

Parent nuclei	Daughter nuclei	Q-value (MeV)	Penetrability	Decay constant	$Log_{10}(T_{1/2})$
^{242}Fm	^{238}Cf	8.776	1.57 e-21	0.637	0.037
^{244}Fm	^{240}Cf	8.556	3.24 e-22	0.127	0.736
^{246}Fm	^{242}Cf	8.376	8.56 e-23	0.033	1.322
^{248}Fm	^{244}Cf	8.002	4.27 e-24	0.002	2.644
^{250}Fm	^{246}Cf	7.558	8.86 e-26	3.078 e-05	4.352
^{252}Fm	^{248}Cf	7.153	1.90 e-27	6.245 e-07	6.045
^{254}Fm	^{250}Cf	7.308	9.54 e-27	3.204 e-06	5.335
^{256}Fm	^{252}Cf	7.023	5.82 e-28	1.879 e-07	6.566
^{258}Fm	^{254}Cf	6.665	1.32 e-29	4.063 e-09	8.232
^{260}Fm	^{256}Cf	6.176	4.34 e-32	1.233 e-11	10.749
^{248}No	^{244}Fm	9.226	7.77 e-21	3.295	-0.677
^{250}No	^{246}Fm	8.956	1.20 e-21	0.497	0.144
^{252}No	^{248}Fm	8.551	5.98 e-23	0.023	1.469
^{254}No	^{250}Fm	8.226	4.63 e-24	0.002	2.597
^{256}No	^{252}Fm	8.583	8.97 e-23	0.035	1.292
^{258}No	^{254}Fm	8.152	2.88 e-24	0.001	2.807
^{260}No	^{256}Fm	7.700	5.76 e-26	2.039 e-05	4.531
^{262}No	^{258}Fm	7.096	1.68 e-28	5.491 e-08	7.101
^{264}No	^{260}Fm	6.586	6.66 e-31	2.015 e-10	9.536
^{254}Rf	^{250}No	9.376	4.38 e-21	1.887	-0.435
^{256}Rf	^{252}No	8.931	-1.87 e-22	0.076	0.955
^{258}Rf	^{254}No	9.252	2.13 e-21	0.908	-0.117
^{260}Rf	^{256}No	8.902	1.75 e-22	0.072	0.984
^{262}Rf	^{258}No	8.486	7.25 e-24	0.003	2.389
^{264}Rf	^{260}No	8.146	4.53 e-25	0.002	3.611
^{266}Rf	^{262}No	7.506	1.37 e-27	4.759 e-07	6.164
^{268}Rf	^{264}No	8.096	3.38 e-25	1.257 e-04	3.741

REFERENCE

[1] G T Seaborg, *Contemporary Physics* **28**, 33 (1987)

[2] Y J Shi and W J Swiatecki, *Nucl. Phys.* A438, 450 (1985)

[3] G Audi, A H Wapstra and C Thivault, *Nucl. Phys. A* 729, 337 (2003)

[4] K P Santhosh, R K Biju, Sabina Sahadevan, *Nucl. Phys. A* 832, 220 (2010)

[5] K P Santhosh, R K Biju, *J. Phys. G: Nucl. Part. Phys*. 36, 015107 (2009)

[6] K P Santhosh, R K Biju, Sabina Sahadevan and Antony Joseph, *Phys. Scr*. **77,** 065201 (2008)

CHAPTER IV

N=184 MAGICITY THROUGH CLUSTER DECAY SYSTEMATIC IN SUPERHEAVY REGION

4.1 INTRODUCTION

The island of stability is a term from nuclear physics that describes the possibility of elements with particularly stable magic numbers of protons and neutrons. Over the last thirty years, experimentalists have, so to speak, launched an expedition to explore the predicted “island of super heavy elements”. Nuclei which have both neutron number and proton number equal to one of the magic numbers are called "double magic" and are especially stable against decay. ^{4}He, ^{16}O, ^{40}Ca, ^{48}Ca and ^{208}Pb are the examples of double magic isotopes. During the last ten years, the Flerov Laboratory of Nuclear Reactions in Dubna, Russia, has made considerable progress in laying out new terrain in the super heavy elements-progress that is providing nuclear physicists with the information they need to understand what factors govern stability for these elements[1,2].

The theoretical description of the masses and fission barriers of the new nuclei in the mid-1960s led to the prediction of "islands of stability" for the very heavy (super heavy) nuclides in the vicinity of the closed proton and neutron shells. Cluster radioactivity known today as the spontaneous emission of light clusters occupies the intermediate position between alpha decay and fission. This phenomenon was first predicted by Sandulescu et al [3] in 1980 on the basis of quantum mechanical fragmentation theory (QMFT). In 1984 Rose and Jones [4] confirmed this phenomenon. In these new radioactive modes, almost all the residual nuclei resulting from cluster emission have been found to be the doubly magic ^{208}Pb or very close to it (lead radioactivity) [4]. Recently other island of cluster radioactivity having residual nuclei close to doubly magic ^{100}Sn, “tin radioactivity”, has been predicted theoretically and confirmed experimentally [5,6]. So far observed cluster radioactivities are from trans-lead and trans-tin region, our interest to this study stems from the recent predictions of new magic numbers beyond Z = 82, N=126 for both protons and neutrons. In the present work we would like to study the ^{12,14}C cluster decay half life time and all other characteristics of different even-even isotopes with atomic number varies from 120 to 126.

4.2 RESULTS, DISCUSSION AND CONCLUSION

We have done our calculations taking potential barrier as the sum of Coulomb potential, proximity potential and centrifugal potential for the touching configuration and for the separated fragments. For the pre-scission (overlap) region, simple power law interpolation [7] is used. The inclusion of proximity potential reduces the height of the barrier which closely agrees with the experimental values. The possibility to have a cluster emission process is,

$$Q = M(A, Z) - M(A_1, Z_1) - M(A_2, Z_2) > 0, \qquad (4.1)$$

where M (A, Z), M (A_1, Z_1) and M (A_2, Z_2) are the atomic masses of the parent, daughter and cluster respectively. The Q values are computed using the table of KTUY [8].

Figures 4.1-4.2 represent the computed cluster decay half lives for ^{12,14}C clusters against neutron number of the daughter nuclei for different even-even parents with atomic number varies from Z = 120-126. It is found from the plots that the half life time values decreases with increasing neutron number of the daughter nucleus and reaches a minimum value at N = 184 and then a sharp increase on half lives. The minimum value of half life time at N = 184 suggest the stability of the daughter nuclei against $^{12,14}C$ cluster decay.

Mass parabola (Plot connecting $-\Delta M$, the difference in masses of parent and daughter nuclei versus neutron number of daughter nuclei) for $^{12,14}C$ clusters emitted from various parents in the super heavy region is also studied. Figures 4.3-4.4 represent the isotopic mass parabola for $^{12,14}C$ cluster emission from various parents with atomic number ranging from 120-126. It is found from the plot that the minima (slope discontinuity) of mass parabola occur at neutron number N=184. We would like to mention that minima of mass parabola represent the lowest half life $T_{1/2}$ for the corresponding cluster. Half life measurement for cluster emission may not be possible because few atoms of short lived super heavy nuclei are produced but in future more mass measurements will be available and by noting the minima in mass difference, it will be possible to find neutron magicity in super heavy region [9]. These plots also indicate the neutron shell closures at N=184.

Figure 4.5 represents the plot connecting computed barrier penetrability (ln P) for $^{12,14}C$ cluster emission from different even-even parents with Z ranging from 120 to 126 against neutron number of the daughter nuclei. It is found from the plot that the largest value of barrier penetrability is obtained at N= 184 which also refer to the stability of the daughter nuclei at N=184. That is shell structure effect is evident in this plot in terms of largest barrier penetrability value. From these studies we have identified that N = 184 is the most probable magic number in the super heavy region. We would like to point out that many authors [10-11] predicted that in super heavy region the possible magic number of neutrons for spherical nuclei is 184 and some possible matching proton numbers are 114, 120 and 126 which would mean that the most stable spherical isotopes would be $^{298}114$, $^{304}120$ and $^{310}126$ which are doubly magic and likely to have a very long half life.

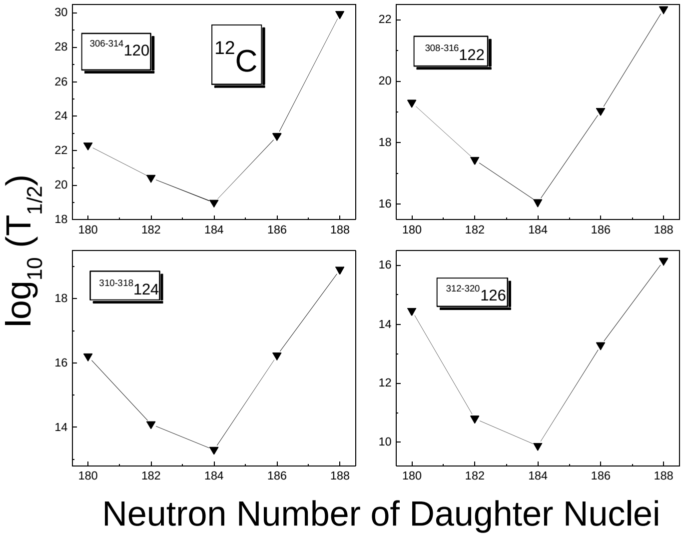


Figure 4.1. The computed half lives for ^{12}C clusters from various even-even parents with atomic number ranging from 120-126 against neutron number of the daughter nuclei.

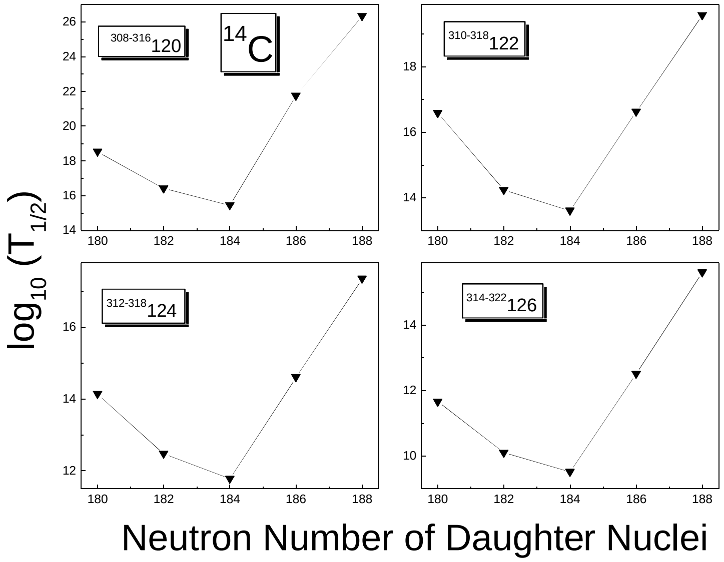


Figure 4.2. The computed half lives for ^{14}C clusters from various even-even parents with atomic number ranging from 120-126 against neutron number of the daughter nuclei.

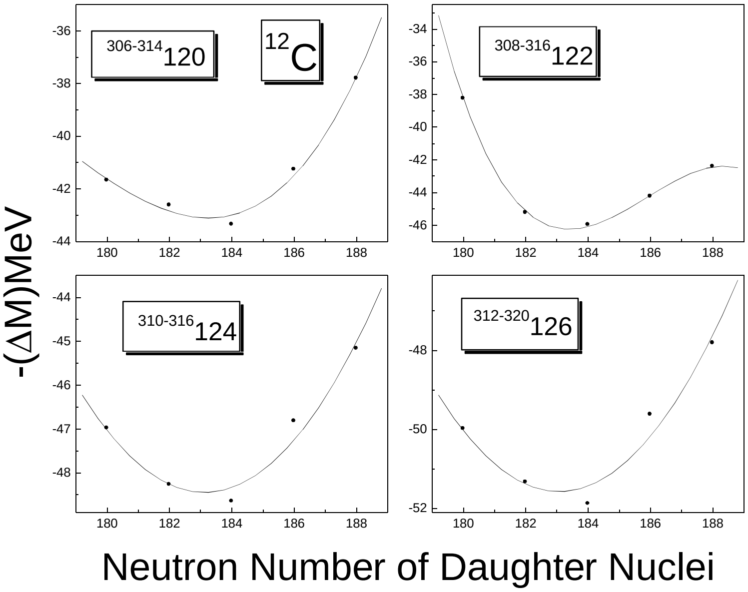


Figure 4.3. The isotopic mass parabola for ^{12}C cluster emission from various even-even parents with Z=120-126 against neutron number of daughter nuclei.

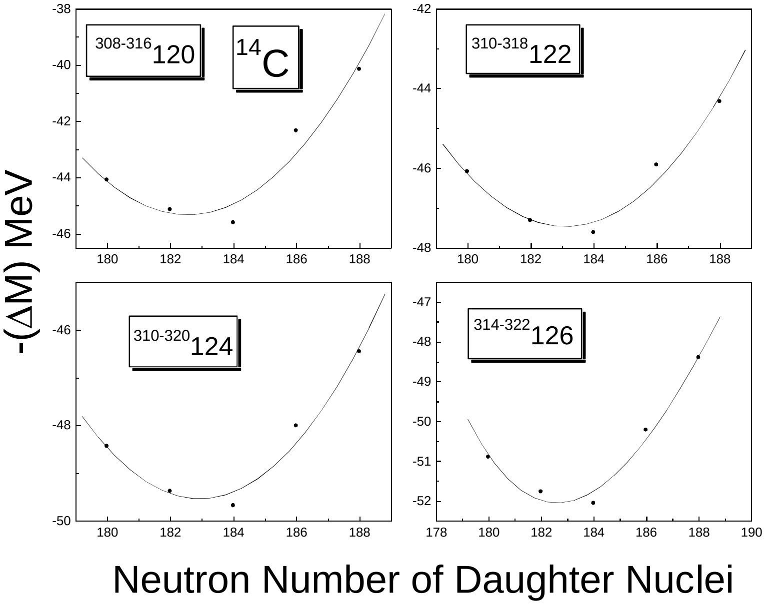


Figure 4.4. The isotopic mass parabola for ^{14}C cluster emission from various even-even parents with Z=120-126 against neutron number of daughter nuclei.

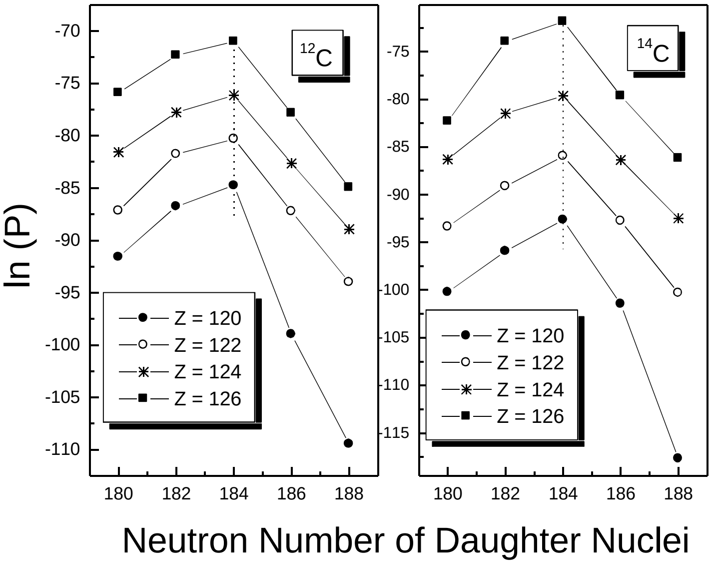


Figure 4.5. The plot connecting computed barrier penetrability for ^{12,14}C cluster emission from various parents against neutron number of the daughter nuclei.

References

[1] S Hofmann et al, *Rev. Mod. Phys.* **72**, 733 (2000)

[2] K Morita et al*, J Phys. Soc. Jpn* **73**, 2593 (2004)

[3] A Sandulescu et al, *Sov. J. Part. Nucl.* **II**, 528 (1980)

[4] H J Rose and G A Jones, *Nature* **307,** 245 (1984)

[5] D N Poeranu et al, A*t.Data.Nucl. Data. Table* **48**, 231 (1991)

[6] Yu Ts Oganessian and S P Tretyakova, *JINR Report No E 7-93-57* (1993)

[7] Y J Shi and W J Swiatecki, *Nucl. Phys.* A438, 450 (1985)

[8] H Koura, T Tachibana, M Uno and M Yamada, *Prog. Theor. Phys.* 113, 305 (2005)

[9] K P Santhosh and R K Biju, *Pramana J. Phys*. **72**, 689 (2009)

[10] S K Patra et al, Mod. Phys. Lett. A **12**, 1727 (1997)

[11] K Rutz et al, *Phys. Rev.* C **56** 238 (1997)

CHAPTER V

^{298}114, next predicted doubly magic nuclei in the SHE

5.1 INTRODUCTION

In the early stage of the nuclear development, one of the main objectives in this field is to reproduce the so-called magic numbers. The spontaneous emission of radioactive nuclei with the emission of fragments heavier than α- particle is termed as cluster radioactivity. This phenomenon was first predicted by Sandulescu [1] in 1980s On the basis of Quantum mechanical fragmentation theory(QMFT). The exploration of cluster radioactivity in Super Heavy Island did not receive much attention, because of the instability of nuclei in this region. From theoretical point of view, the extension of the periodic table towards the super heavy 'island of stability' is very important for testing and developing nuclear structure models.

The main physical interest to the present study comes from the fact that cluster radioactivity makes a bridge between these two extreme nuclear many body phenomena strongly differing by nucleon number, decay mechanism, properties of the emitted fragments. For this reason the information obtained in the cluster radioactivity goes beyond nuclear effects. In these new radioactive modes, almost all the residual nuclei resulting from cluster emission have been found to be the doubly magic ^{208}Pb or very close to it (lead radioactivity). Recently other island of cluster radioactivity having residual nuclei close to doubly magic ^{100}Sn "tin radioactivity" has been predicted theoretically and confirmed experimentally [2]. So far observed cluster radioactivity are from trans-lead and trans-tin region. In the present work we would like to explore the possibility of cluster emission from the other region preferably in the super heavy region. We have computed the alpha and cluster decay half lives of various even-even isotopes (with Z ranging from 116 to 126) in the super heavy region in which the decay leading to Z = 114 daughter, using Coulomb and Proximity potential [3] as interacting barrier.

5.2 Results discussion and conclusion

We have studied the cluster radioactivity of various isotopes in super heavy region based on the potential barrier determined by two sphere approximation [4], as the sum of coulomb and nuclear proximity potentials for the touching and separated configuration ($z>0$). Here z is the distance between near surface of the fragments. The possibility to have a cluster decay process is,

$$Q = M(A,Z) - M(A_1,Z_1) - M(A_2,Z_2) > 0 \qquad (5.1)$$

Where, $M(A,Z)$, $M(A_1,Z_1)$ and $M(A_2,Z_2)$ are the atomic masses of the parent, daughter and cluster nuclei respectively. Thus the cluster radioactivity is energetically possible only if Q value is positive. The proper choice of the Q-value or half lives will give the information about magicity. The present work Q-values are computed using experimental binding energies of Audi and Wapstra [5] and some values are taken from the tables of KTUY [6].

The radioactive decay (^{4}He, ^{6,8}Be, ^{12,14,16}C, ^{18,20}O, ^{20,22,24}Ne and ^{28}Mg) of various even-even isotopes with Z=116-126 leading to Z = 114 daughter nuclei was studied taking the coulomb and proximity potentials as the interacting barrier. One of the fundamental factors in the study of superheavy elements is the prediction and/or production of doubly magic nucleus, In the superheavy mass region. Figures 5.1 and 5.2 represent the plot of computed half lives and barrier penetrability for clusters like ^{4}He, ^{6,8}Be, ^{12,14,16}C, ^{18,20}O, ^{20,22,24}Ne, ^{28}Mg against the neutron number of the daughter nuclei. It is found that these two figures are mirror reflections of one another. That is a peak in barrier penetrability appears as a dip in half lives or vice versa. In half life plots, the half life times decreases and reaches to a minimum value at ^{298}114and then increases. The reverse effect is also shown in the barrier penetrability plots. If a decay having small half life time value or greater barrier penetrability indicate such decay represents the doubly magic behaviour of the daughter nuclei [7]. Hence we would like to mention that the daughter nuclei ^{298}114 (Z=114, N = 184) is the next predicted spherical doubly magic nucleus in super heavy region after the experimentally observed doubly magic isotopes ^{208}Pb (Z=82, N=208). In addition with this we would like to mention that many authors [8,9] predicted the spherical doubly magic behavior of ^{298}114 (Z=114, and N=184) isotopes in the superheavy region.

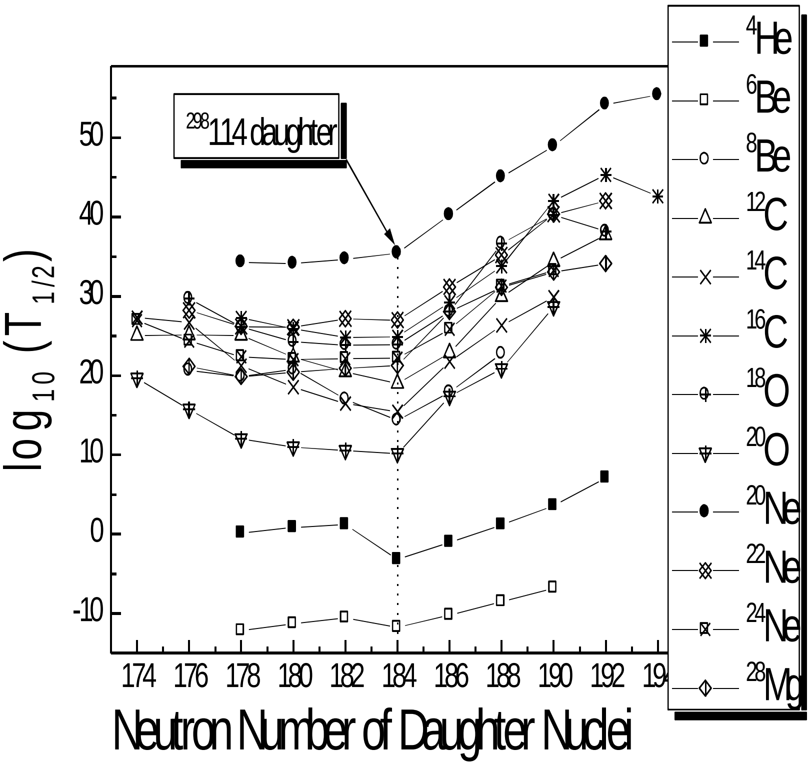


Fig. 5.1 Computed half life time versus neutron number of daughter nuclei for various cluster emissions leading to Z=114 daughter nuclei.

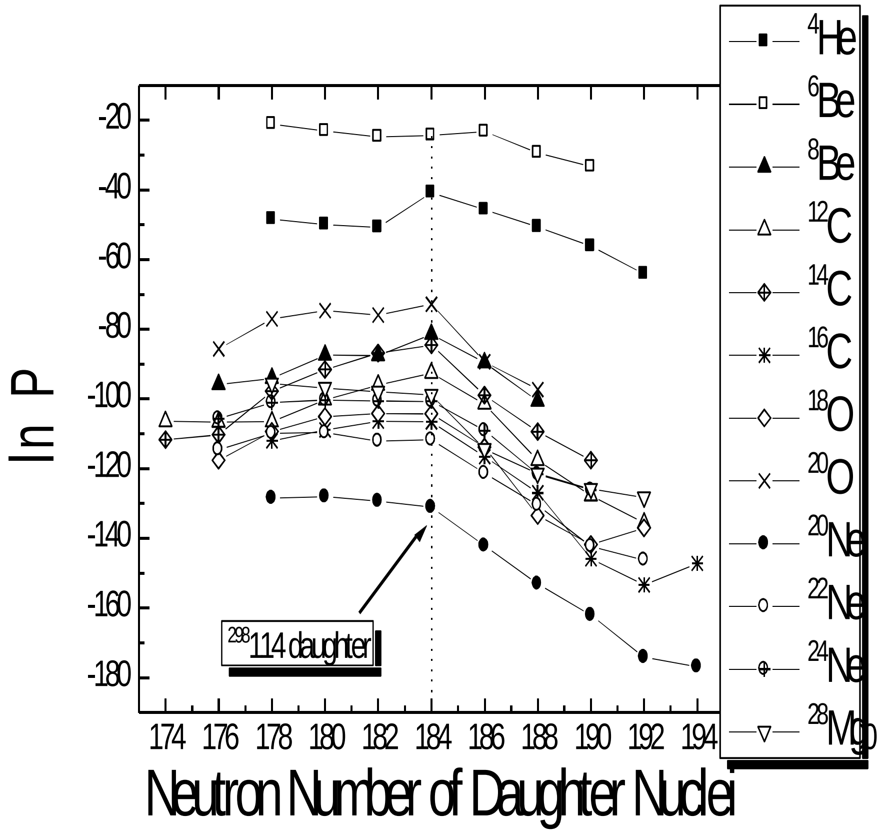


Fig.5.2 Computed barrier penetrability versus neutron number of daughter nuclei for various cluster emissions leading to Z=114 daughter nuclei

References

[1] A Sandulescu, Sov.J.Part.Nucl.**11**,528(1980)

[2] Yu Ts Oganessian, JINR Report No. E 7-93-57 (1993)

[3] R K Biju et al,Pramana J.Phys.**70**,617(2008)

[4] Y J Shi et al, Nucl. Phys. A **438**, 450 (1985)

[5] G Audi et al, Nucl. Phys. A**595**, 409 (1995)

[6] H Koura, Prog.Theor.Phys.**113**, 305 (2005)

[7] K P Santhosh,Pramana J.Phys.**72**,689(2009)

[8] A.Sobiczewski et al, Phys.Lett.**22**,500(1966)

[9] H. Meldner, Ark. Fys. **36** (1967) 593

CHAPTER VI

EXISTENCE OF PROTON HALO NUCLEI VIA CLUSTER RADIOACTIVITY

6.1 **INTRODUCTION**

Exotic isotopes along the neutron and proton drip lines are important for understanding the formation of elements and they constitute tests of understanding nuclear structure. The proton- and neutron-rich regimes in the chart of nuclei are therefore the focus of existing and forthcoming experimental facilities around the world. An atomic nucleus is called a halo nucleus (nuclear halo) when it has a core nucleus surrounded by a halo of orbiting protons or neutrons, which makes the radius of the nucleus appreciably larger than that predicted by the liquid drop model. The field of halo nuclei has generated much excitement and many hundreds of papers were produced since its discovery in the mid-1980s. The first halo nucleus to be produced in the laboratory was ^{6}He, as long ago as 1936, using a beam of neutrons on a ^{9}Be target[1]. Some of the examples for proton halo nuclei are ^{13}N, ^{17}F, ^{17}Ne, ^{26}P, ^{27}S etc. The present works aims to explore the possibility of production of proton halo nuclei against cluster radioactivity [2]. In this work, we have studied the decay possibility of proton halo nuclei (^{13}N, ^{17}F, ^{17}Ne, ^{26}P, ^{27}S) from different even-even $^{260-280}$110, $^{264-284}$112, $^{268-288}$114 and $^{278-298}$116 isotopes using Coulomb and Proximity potential [2] as interacting barrier.

6.3 RESULTS DISCUSSION AND CONCLUSION

In this model the interacting potential for the post scission region is taken as the sum of coulomb and proximity potential and for the overlap region we use simple power law interpolation. Q-values are computed using experimental binding energies of Audi and Wapstra [3] and some values are taken from the tables of KTUY [4].

Figures 6.1 to 6.5 represent the computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{13}N, ^{17}F, ^{17}Ne, ^{26}P and ^{27}S from different even-even $^{260-280}$110, $^{264-284}$112, $^{268-288}$114 and $^{278-298}$116 isotopes respectively. It is found from the plots that some of the decays has half life time values less than or equal to 10^{30} sec and is probable for emission. It is also found that these figures are mirror reflections of others. That is a peak in barrier penetrability appears as a dip in half lives or vice versa. In addition with this there is a peak in half life time and a dip in barrier penetrability at N=172. The minimum value of barrier penetrability is obtained at N= 172 which also refer to the stability of the parent nuclei at N=172. That is shell structure effect is evident in these plots in terms of largest barrier penetrability value.

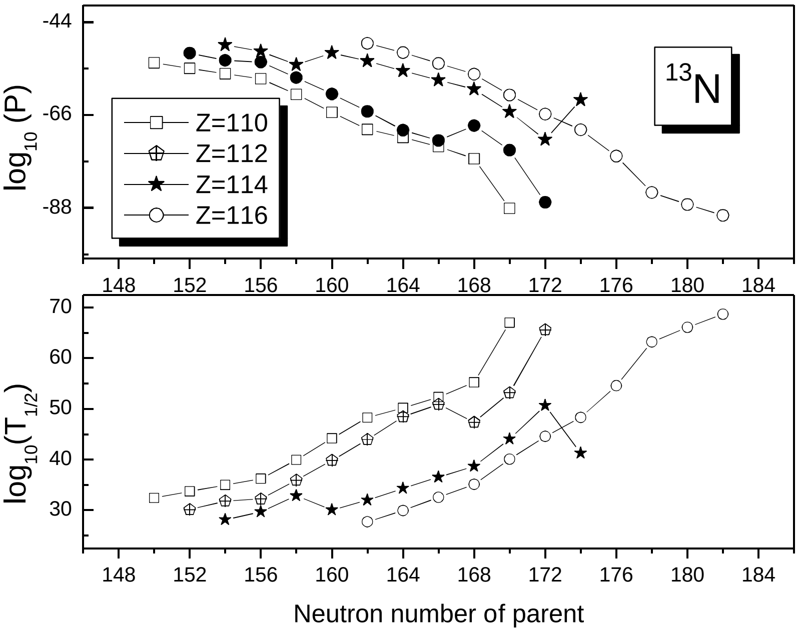


Fig. 6.1 Computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{13}N emissions from different even-even parents with Z ranging from 110 to 116.

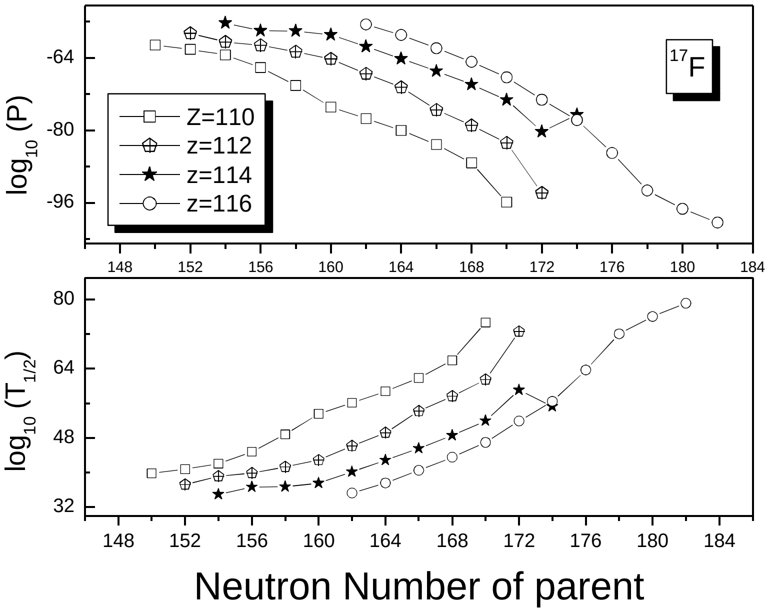


Fig. 6.2 Computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{17}F emissions from different even-even parents with Z ranging from 110 to 116.

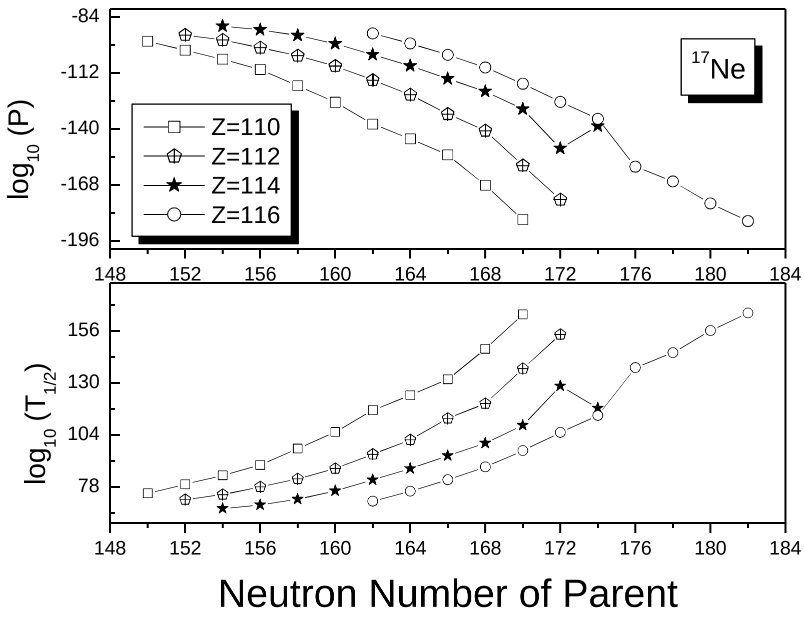


Fig. 6.3 Computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{17}Ne emissions from different even-even parents with Z ranging from 110 to 116.

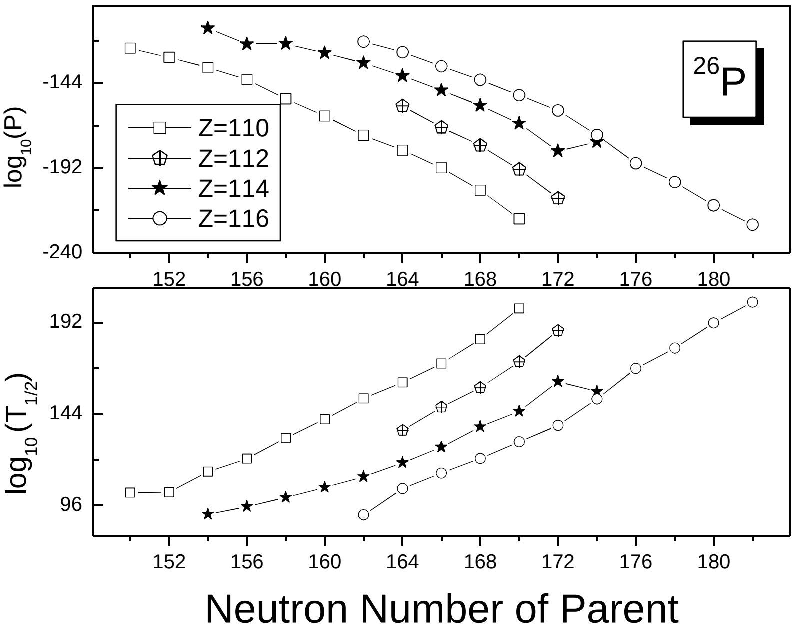


Fig. 6.4 Computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{26}P emissions from different even-even parents with Z ranging from 110 to 116.

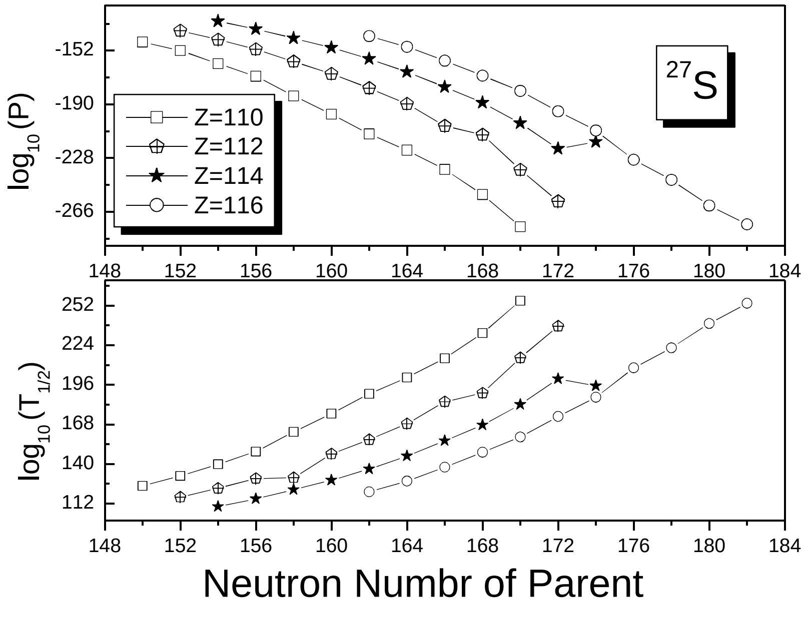


Fig. 6.5 Computed half life time and barrier penetrability versus neutron number of parent nuclei for ^{27}S emissions from different even-even parents with Z ranging from 110 to 116.

References

[1] T Bjerge et al, Nature **138**, 400 (1936)

[2] R K Biju et al,Pramana J.Phys.**70**,617(2008)

[3] G Audi et al, Nucl. Phys. A**595**, 409 (1995)

[4] H Koura, Prog.Theor.Phys.**113**, 305 (2005)

CHAPTER VIII

CONCLUSION

This dissertation consists of seven chapters. The first chapter is an introductory, which brings information about radioactivity and its type, scope of the study and the objectives to be achieved in this work are also presented in this chapter I.

The alpha and cluster decay half lives of various isotopes in heavy and super heavy region are computed using coulomb and nuclear proximity potential model as the interacting barrier. The model ingredient with zero point vibration energy, assault frequency, radius (distance between the two centers of the nuclei), penetrability and life time expression, branching ratio are also discussed in chapter II.

Chapter III incorporates the study of alpha decay half life time and all other characteristics of different even-even $^{242-260}$Fm, $^{248-264}$No and $^{254-264}$Rf isotopes.

The ^{12,14}C cluster decay half life time and all other characteristics of different even-even isotopes with atomic number varies from 120 to 126 is studied in Chapter IV.

Computed the alpha and cluster decay half lives of various even-even isotopes (with Z ranging from 116 to 126) in the super heavy region in which the decay leading to $Z = 114$ daughter, using Coulomb and Proximity potential [3] as interacting barrier is discussed in chapter V

The decay possibility of proton halo nuclei (^{13}N, ^{17}F, ^{17}Ne, ^{26}P, ^{27}S) from different even-even $^{260-280}$110, $^{264-284}$112, $^{268-288}$114 and $^{278-298}$116 isotopes is studied in Chapter VI

Finally in chapter seven, we summarize the salient features of this work and conclusion drawn from the study.

LIST OF PUBLICATIONS

1. Alpha radioactivity of various Fm, No and Rf isotopes
   R. K. Biju and M. K. Preethi Rajan
   UGC Sponsored national seminar on ETIC (Nemmara, India) 24 (2014)
   ISBN 978-81-89085-92-6

2. ^{298}114, next predicted doubly magic nuclei in the SHE
   R. K. Biju, M. K. Preethi Rajan and K. P. Santhosh
   Int. Nat. Symp., on Nucl. Phys. (BARC, India) **V58** 126 (2014)
   ISBN 81-8372-070-6

3. Existence of proton halo nuclei via cluster radioactivity
   R. K. Biju, M. K. Preethi Rajan and K. P. Santhosh
   DAE BRNS Symp. on Nucl. Phys. (Andhra Pradesh., India) V**60** 152 (2015)
   ISBN 81-8372-077-3