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A Systematic Study on the Existence of $^{7-9}$B, $^{16-19}$Ne, $^{8-11}$C, $^{23-30}$P and $^{26-32}$S Nuclei via Cluster decay in the Super Heavy Region

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ABSTRACT

Based on the Coulomb and Proximity Potential Model, we have studied the decay probabilities of various exotic nuclei from even-even nuclei in the super heavy region. The half-lives and barrier penetrability for the decay of exotic nuclei such as $^{7-9}$B, $^{16-19}$Ne, $^{8-11}$C, $^{23-30}$P and $^{26-32}$S from the isotopes $^{274-332}$116,$^{274-334}$118 and $^{288-334}$120 are determined by considering them as spherical as well as deformed nuclei. The effect of ground state quadrupole (β_2), Octupole (β_3) and hexadecapole (β_4) deformation of parent, daughter and cluster nuclei on half-lives and barrier penetrability were studied. Calculations have done for the spherical nuclei and deformed nuclei in order to present the effects of the deformations on half-lives. It is found that height and shape of the barrier reduces by the inclusion of deformation and hence half-life for the emission of different clusters decreases and barrier penetrability increases. Changes in the half-lives with and without the inclusion of deformation effects are compared in the graph of half-life and barrier penetrability against neutron number of parents. It is evident from the computed half lives that many of the exotic nuclei emissions are probable. Moreover shell structure effects on the half-lives of decay are evident from these plots. Peak in the plot of half-life and dip in the plot of barrier penetrability against neutron number of parent show shell closure at or near to N=184, N=200 and N=212.

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1. Introduction

Theoretical and experimental studies of unbound exotic nuclei near drip lines constitute one of the promising areas of research in nuclear physics, and many hundreds of studies have done since its discovery in mid-1980s [1]. The study of such nuclei will help to understand the features of their structure and behavior [2]. The drip line determines the basic limit of stability. Nuclei beyond the proton or neutron drip lines [3, 4, 5] are characterized by one or more loosely bound protons or neutrons which form a halo structure [6]. These are having negative proton and neutron separation energy respectively so that they naturally emit protons or neutrons, or have the tendency to transform protons into neutrons due to the large beta decay energy. In halo nuclei, the nucleons are not always arranged within a well-defined boundary; but move beyond the boundary and form a misty cloud. These are larger than normal nuclei because of the orbiting protons or neutrons around the core structure and they are easy to break apart. Since the valance electrons are bounded loosely, their life time is very small and is not stable. There are two types of halo nuclei, proton halo and neutron halo [7, 8], depending on the loosely bound protons and neutrons respectively around the core. Proton halos are less probable, because the presence of repulsive Coulomb interaction holds the valence nucleons closer to the core and hinders the formation of proton halos [9]. Proton halos are further observed as one proton halo and two proton halo structures. The 1p-halo structures are identified for ^{8}B, ^{11,12}N, ^{17}F, ^{23}Al and ^{26,27,28}P; and 2p halos for ^{9}C, ^{17,18}Ne, ^{20}Mg, ^{27,28,29}S [10-17].

The existence of halo structure in nuclei was discovered by a series of experiments done by Tanihata et al. in 1985, at the Lawrence Berkeley Laboratory through the measurement of interaction cross section of light nuclei [18, 19]. Two years later Hansen and Jonson used the term halo [20] for the first time. The first halo nucleus; ^{6}He, was produced in the laboratory by bombarding a beam of neutrons on a ^{9}Be target in 1936 [21]; but ^{11}Li is the most famous halo nuclei, which is considered as the first observed case of neutron halo.

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Many theoretical and experimental predictions on the existence of halo nuclei and its structure and behavior have been made after its discovery. Structure of the halo nuclei is mainly studied through radioactive nuclear beams due to its short lived character. Physics of radioactive ion beams is one of the promising and developing fields of nuclear physics. Recently in 2016, Grigorenko et al. [22], investigated the theoretical results in the field of few body dynamics; a type of nuclear dynamics arises in clustered system near the stability line leads to the phenomenon of the nuclear halo and found that many of the theoretical predictions are in good agreement with the experimental results obtained at Flerov Laboratory of Nuclear Reactions (FLNR) in Dubna, Russia. Also, reaction cross section measurement is an important tool for obtaining more information about halo structure since the low density halo tail strongly affect the reaction cross section and lead to the exciting properties in such nuclei [23]. In 1988 Kobayashi et al. [24] studied the structure of halo from the momentum distribution of fragment ^{9}Li from the breakup of halo state of ^{11}Li [25, 26]. Increase in the radius of halo arises from the neutron tail was proved in 1988, and it was in agreement with that, halo is formed as a consequence of the low binding energy of the last neutron pair [20]. In 1995 Hansen et al. [27] used a simple few body model to explain the basic features of halo states. In 2008 Tanihata et al. [28] measured, in his experiment, for the first time the differential cross section for the transfer reaction of two halo neutron of ^{11}Li, which gave a new insight in the structure of most pronounced halo nucleus ^{11}Li. Kobayashi et al. [29] in 2012 confirmed the 2n halo character of ^{22}C from the measurement of enhanced cross section. Togano et al. [30] in 2016 also reported the halo character of ^{22}C. Many other studies are also carried out to confirm the halo structure of ^{37}Mg [31], ^{17}F [32], ^{11}Be [33, 34], ^{6}He [6, 35, 36] etc.

Study of proton halo is one of the major challenges in theoretical and experimental nuclear physics. In 1995 M.V Zhukov et al. [37] have first identified the 2p halo nuclei from the borromean structure and matter radius of ^{17}Ne. Further the 1p halo structure of ^{26}P and 2p halo structure of ^{27}S are explained by Zhongzhou Ren et al. [38] in 1996 from the RMS matter radii measurements by nonlinear relativistic mean field theory. In 1999, R. Lewis and A. Hayes [39] identified that the first excited state of ^{17}F was a proton halo state. In 2002, proton halo structure in ^{23}Al and ^{27}P were demonstrated by H Y Zhang et al. [40] by measuring the abnormally large reaction cross section. The existence of proton halo was experimentally confirmed by T. Sumikama et al. [41] in 2008 from the measurement of quardrupole moment, nucleon radii and the density distribution of ^{8}B. In 2014 Emil Rydberg et al. [42] have applied halo effective field theory, for the first time, to 1p halo nuclei to analyze the universal features of them. In 2016, G. Sawhney et al. [43] have investigated the effect of deformations and orientations on the observed and proposed cases of proton rich light nuclei. They also analyzed the 1p and 2p halo cases in terms of potential energy surfaces calculated as the sum of binding energies, coulomb repulsion, nuclear proximity attraction and the centrifugal potential. In 2017 M.K Gaidarov et al. [44] studied the proton halo nature of the ^{8}B nucleus through elastic scattering and breakup reactions which revealed the internal spatial structure of the ^{8}B nucleus supporting its proton halo nature. The theoretical study on the two proton radio activity with 2p halo in light mass nuclei by Saxena et al. [45] in 2017 provided the structural evidence for the existence of halo nuclei. Very recently, in 2019, A.A Ibraheem et al. [46] studied the elastic scattering of 1p halo nucleus ^{17}F on different mass targets at different energies using semi macroscopic potentials. Another study on halo nuclei was done by K.P Santhosh et al [47] in 2019. They analyzed the structure of a halo nucleus on the basis of potential energy considerations and separation energy calculations. Many other fusion studies and cross-section studies are also carried out for proton halo systems [48-51].

The stability of isotopes in the super heavy region can be predicted through the computation of half-life and barrier penetrability of various cluster decay processes. Elements having atomic number greater than 104 are referred to as super heavy elements and their existence was due to the quantum shell effects. Their definite shell gaps can stabilize the nuclei. The stability of various super heavy nuclei was hypothesized for about 40 years, and many recent experiments proved its validity. Many of the isotopes of elements 116 and 118 [52] were identified at JINR FLNR, Dubna, in collaboration with the LLNL researchers [53-60]. The isotopes $^{293-297}$118 were experimentally synthesized at the Flerov laboratory of nuclear reactions (FLNR) in Dubna, Russia by bombarding a beam of ^{48}Ca on a target consisting of a mixture of $^{249-252}$Cf isotopes [53, 61]. Isotopes of element 116 are the decay products of the isotopes of 118 which are produced through ^{249}Cf+ ^{48}Ca reaction [59]. In recent decades there have been some attempts to synthesize super heavy nuclei with $Z>118$. Many experiments were performed with different projectile target combinations to produce the element $Z=120$. Among the different studied reactions, ^{54}Cr+^{248}Cm is most preferred for the synthesis of the super heavy element with $Z=120$ [62]. Studies on the existence of super heavy elements will help us to familiarize the concept of magic numbers and island of stability, which predict why some elements are more stable and why others are not.

The present work aims to study the possibility for the existence of various exotic nuclei $^{7-9}$B, $^{16-19}$Ne, $^{8-11}$C,

$^{23-30}$P, $^{26-32}$S from even-even super heavy isotopes $^{274-332}$116, $^{274-334}$118, $^{288-334}$120 with and without the inclusion of deformation effect using Coulomb and Proximity Potential Model [63-67]. In addition with this we would like to point out that most of the exotic nuclei belong to proton halo structure. CPPM is an effective model for the study of cluster radioactivity and half lives for the various mass regions on the nuclear chart. It can be used as the interacting barrier to study the decay probabilities of proton halo nuclei from different even-even parent isotopes. Studies on nuclear deformation are very important in the field of nuclear physics. The deviation from the spherical shape of a nucleus is generally termed as nuclear deformation. The nuclear deformation has a major role in determining the properties of nuclei. Till now many authors [43, 68-72] have theoretically studied the effect of parent and daughter deformations on the half-lives. In this work the model (CPPM) is modified by incorporating the deformation effects (β_2, β_3 and β_4) for parent, daughter and cluster and the effect of deformations (β_2, β_3 and β_4) on half-lives and barrier penetrability are studied.

2. The Model

The total interacting potential barrier for the parent nuclei showing exotic decay is the combination of three potentials, coulomb potential, nuclear potential, and centrifugal potential.

$$V=\frac{Z_1Z_2e^2}{r}+V_p(z)+\frac{\hbar^2 l(l+1)}{2\mu r^2}; \qquad \text{For } z>0 \quad (1)$$

Here the first term represents the coulomb potential, the second term indicates nuclear potential, and the last term is centrifugal potential. Z_1 and Z_2 are the atomic numbers of the daughter and the emitted cluster, z is the distance between nearby surfaces of daughter and cluster, r is the distance between the fragment centers, l is the angular momentum quantum number, and $V_p(z)$ is the proximity potential which is given by Blocki et al. [73]

$$V_p(z)=4\pi\gamma b\left[\frac{C_1C_2}{(C_1+C_2)}\right]\Phi\left(\frac{z}{b}\right) \quad (2)$$

The above two equations are for spherical nuclei. γ is the surface tension coefficient, given by

$$\gamma=0.9517\left[1-1.7826(N-Z)^2/A^2\right]\ Mev/fm^2 \quad (3)$$

Φ represents the universal proximity potential given as [74]

$$\Phi(\varepsilon)=-4.41e^{-\varepsilon/0.7176} \text{ for } \varepsilon\geq 1.9475 \quad (4)$$

$$\Phi(\varepsilon)=-1.7817+0.9270\varepsilon+0.0169\varepsilon^2 -0.05148\varepsilon^3 \text{ for } 0\leq\varepsilon\leq 1.9475 \quad (5)$$

With $\varepsilon = z/b$, where the width (diffuseness) of the nuclear surface $b\approx 1$

The Sussmann central radii C_i of fragments,

$$C_i=R_i-\left(\frac{b^2}{R_i}\right) \quad (6)$$

R_i is the sharp radii and can be calculated by the empirical formula in terms of mass number A_i as [73]

$$R_i=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3} \quad (7)$$

Using the one dimensional WKB approximation, barrier penetrability P is given by

$$P=\exp\left\{-\frac{2}{\hbar}\int_a^b\sqrt{2\mu(V-Q)}dz\right\} \quad (8)$$

Where $\mu = m A_1A_2/A$ is the reduced mass with A_1 and A_2 are the mass numbers of the emitted daughter and cluster nuclei respectively. a, b are turning points, which are determined from the equation V (a) =V (b) = Q, where Q is the energy released.

If $M(A, Z)$, $M(A_1, Z_1)$ and $M(A_2, Z_2)$ are the atomic masses of the parent, daughter and the emitted cluster respectively in units of MeV, then

$$Q=M(A,Z)-M(A_1,Z_1)-M(A_2,Z_2) \quad (9)$$

The above integral can be evaluated numerically or analytically, and the half-life of this decay process is given by

$$T_{1/2}=\frac{\ln 2}{\lambda}=\frac{\ln 2}{\nu P} \quad (10)$$

Where, $\nu=\frac{\omega}{2\pi}=\frac{2E_V}{h}$, the number of assaults on the barrier per second and λ is the decay constant. E_V the empirical zero point vibration energy given by [75];

$$E_V=Q\left\{0.056+0.039\exp\left[\frac{(4-A_2)}{2.5}\right]\right\}, \text{for } A_2\geq 4 \quad (11)$$

The coulomb interaction between two deformed and oriented nuclei taken from [76] with higher multipole deformation included [77, 78] is given as

$$V=\frac{Z_1Z_2e^2}{r}+3Z_1Z_2e^2\sum_{\lambda i=1,2}\frac{1}{2\lambda+1}\frac{R_{0,i}^{\lambda}}{r^{\lambda+1}}Y_{\lambda}^{(0)}(\alpha_i)\times\left[\beta_{\lambda i}+\frac{4}{7}\beta_{\lambda i}^2Y_{\lambda}^{(0)}(\alpha_i)\delta_{\lambda,2}\right] \quad (12)$$

With

$$R_i(\alpha_i)=R_{0i}\left[1+\sum_{\lambda}\beta_{\lambda i}Y_{\lambda}^{o}(\alpha_i)\right] \quad (13)$$

Where $R_{0i}=1.28A_i^{1/3}-0.76+0.8A_i^{-1/3}$. Here α_i is the angle between the radius vector and the symmetry axis of the i^{th} nuclei (Figure 1 of ref [78]). The quadrupole interaction term proportional to $\beta_{21}\beta_{22}$ is neglected because of its short range character.

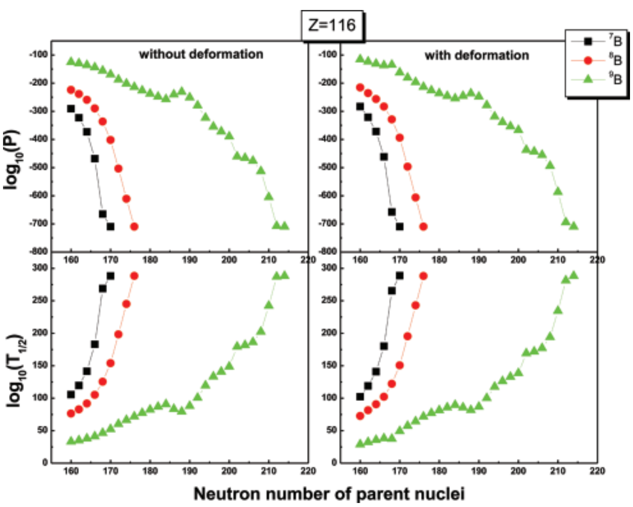

Figure 1: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{7-9}$B from $^{276-330}$116 without and with deformation.

Results and Discussion

In the present work, we have applied the Coulomb and Proximity Potential Model for the decay of various exotic nuclei from the super heavy parent isotopes. Our study begins with the identification of probable clusters from the selected parent isotopes by the calculation of Q values. Q value for the reactions are computed using mass tables of Audi et al [79] and the remaining masses are taken from the table of KTUY05 [80]. From the calculated Q value, half-life and barrier penetrability for a specific parent for all possible (Q>0) cluster-daughter combinations are calculated using CPPM. Stability of the parent nuclei can be studied by the computation of half-life, and barrier penetrability. Calculations are also done by considering the ground state quadrupole deformation (β_2), Octupole deformation (β_3) and hexadecapole deformation (β_4) of parent daughter and cluster nuclei, and the deformation values are taken from the deformation table [81].

Figures 1-11 represent the plot of half-life and barrier penetrability versus neutron number of parent nuclei for the emission of different clusters without and with deformation. From these figures we have studied the emission of various clusters $^{7-9}$B, $^{16-19}$ Ne, $^{8-11}$ C, $^{23-30}$ P, $^{26-32}$ S from even-even super heavy isotopes $^{276-332}$116 , $^{276-334}$118 and $^{288-334}$120. The selected neutron number of the parent ranges from 158 to 216. From all these plots we can notice that, as the neutron number of the parent increases the half -life of the parent for the emission of clusters also increases except at some points. These points indicate the shell closure effects of parent and daughter nuclei. Peaks in the half-life correspond to the shell closure of parent and dip in the half-life corresponds to the shell closure of daughter nuclei. In these figures, the plot of half-life versus neutron number of parent nucleus is always a mirror reflection of the plot of barrier penetrability versus neutron number of parent nucleus. That is, a peak in the half-life corresponds to the dip in the barrier penetrability and vice versa.

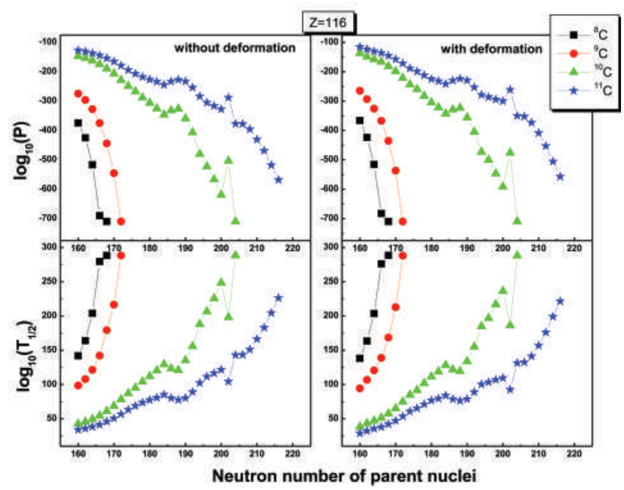

Figure 2: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{8-11}$C from $^{276-332}$116 without and with deformation.

Also, it is evident from these plots that half-life for the emission of different clusters decreases and barrier penetrability increases with the inclusion of deformation values because the effect of deformation reduces the height and shape of the barrier. Figures 1-3, gives the variation of half-life and barrier penetrability as the function of neutron number of parent nuclei for the decay of $^{7-9}$B, $^{8-11}$C and $^{16-19}$Ne from $^{276-332}$116 without and with deformation effect. It is clear from these figures that when the deformation effects are included, half life time values are found to decrease. For example $\log_{10}(T_{1/2})$ for the emission of ^{7}B from the parent with N= 160 in figure 1 is 105.684sec when it is considered as spherical nuclei, whereas $\log_{10}(T_{1/2})$ for the same is decreased to 102.335sec in the deformed case. In figure 2, $\log_{10}(T_{1/2})$ for the emission of ^{8}C from the super heavy parent with N=160 is reduced from 141.924sec to 138.198sec, when deformation effects are included.

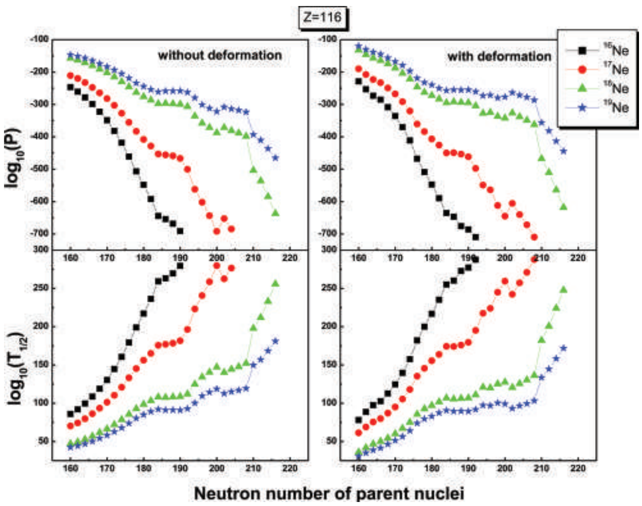

Figure 3: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{16-19}Ne$ from $^{276-332}116$ without and with deformation.

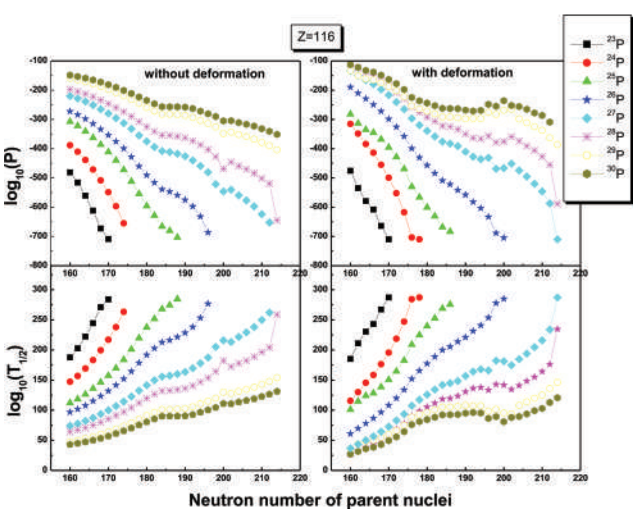

Figure 4: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{23-30}P$ from $^{276-332}116$.

Figures 6 and 7 gives the variation of half-life and barrier penetrability as the function of neutron number of parent nuclei for the decay of ^{7-9}B, ^{8-11}C from $^{276-334}118$ without and with deformation. Here also, when the deformation effects are included, half life time values are found to decrease. In figure 6, $\log_{10}(T_{1/2})$ for the emission of ^{7}B from the parent with N=158 is 75.639sec when it is considered as spherical nuclei, whereas $\log_{10}(T_{1/2})$ for the same is decreased to 72.285sec when the deformation effects are included. From figure 7, $\log_{10}(T_{1/2})$ for the emission of ^{8}C from the super heavy parent with N=158 is reduced from 98.751sec to 94.933sec when deformation effects are included.

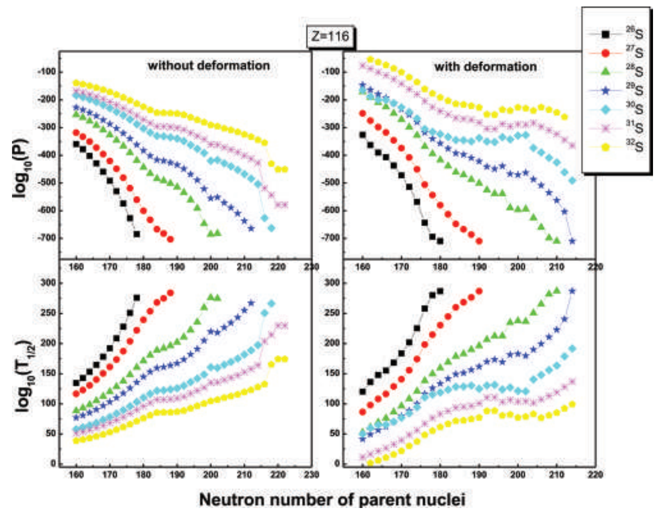

Figure 5: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{26-32}S$ from $^{276-332}116$ without and with deformation.

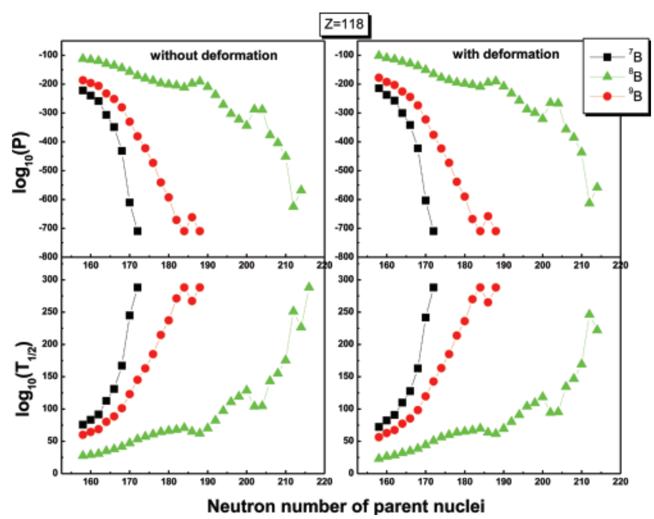

Figure 6: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of ^{7-9}B from $^{276-334}118$ without and with deformation.

A common behavior which is observed in the plot of half-life verses the neutron number is the appearance of prominent peak at N=184, N=200 and N=212 or near to them and correspondingly there are dips in the plot of barrier penetrability. Figures 1-5 shows the variation of half-life and barrier penetrability for the emission of different clusters from the super heavy parent isotopes $^{276-332}116$ with and without including deformation. Here half-life for the emission of ^{9}B, $^{10\text{-}11}$C, $^{16\text{-}19}$Ne, $^{28\text{-}30}$P, $^{29\text{-}32}$S shows peaks at ^{300}116(N=184) and ^{316}116(N=200), indicating the shell closure of these parent isotopes. Figures 6-8 represent the variation of half-life and barrier penetrability of parent nuclei, with Z=118, for the emission of different cluster nuclei. It is clear from these plots that ^{302}118(N=184), ^{318}118(N=200) and ^{330}118(N=212) shows maxima in the half life or minima in the barrier penetrability for the emission of $^{8\text{-}9}$B, $^{10\text{-}11}$C, $^{17\text{-}19}$Ne. So ^{302}118, ^{318}118, ^{330}118 are other stable parent isotopes for the emission of these cluster nuclei. The half-life and barrier penetrability for the emission of various clusters from the super heavy isotopes with Z=120 are shown in the figures 9 to 11. Here, $^{8\text{-}9}$B, $^{10\text{-}11}$C, $^{16\text{-}19}$Ne shows peaks at ^{304}120(N=184), ^{320}120(N=200) and ^{332}120(N=212). From the behavior of all these plots, it is clear that neutron magicity occurs at 184, 200 and 212 and thereby the stability of the parent isotopes with these neutron numbers. We would like to point out that the possibility of magicity at N=184 has already been predicted by many authors [57, 59, 82-84]. Magicity near N=200 also has been pointed out previously from large fluctuation in S_{2n} from the microscopic skyrme HFB calculations [85] and studies on the numerical generalization of the Bethe–Weizacker mass formula [86] and probable heavy particle decay from various super heavy nuclei by K.P. Santhosh et al. [84]. Our observations and calculations strongly support the possibility of neutron magic numbers N=184, 200. We can also identify that proton shell closure occurs at Z=120 in the super heavy region which have already pointed out in [87] and hence $^{304}_{184}$120 and $^{320}_{200}$120 are doubly magic nuclei. From our observation N=212 can be a neutron magic number, so $^{332}_{212}$120 is also be a doubly magic nucleus.

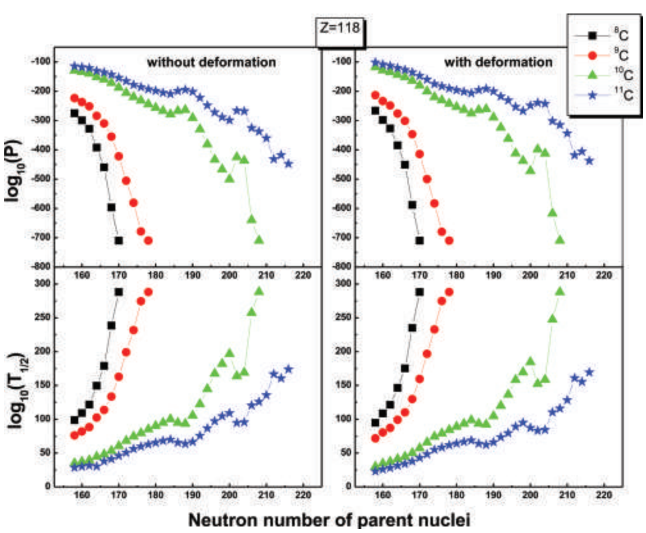

Figure 7: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{8\text{-}11}$C from $^{276\text{-}334}$118 without and with deformation.

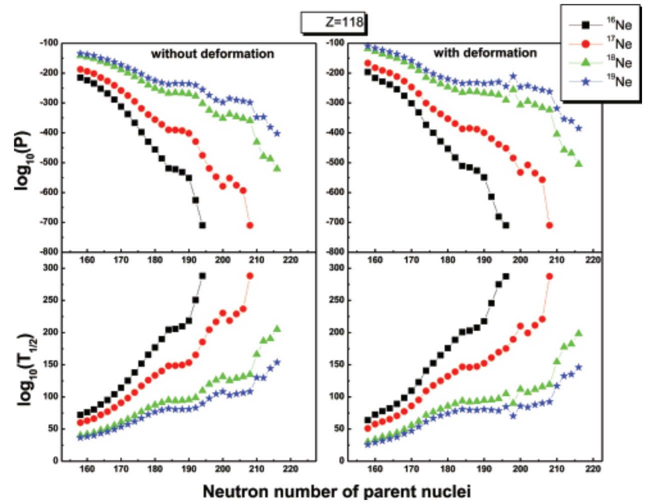

Figure 8: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{16\text{-}19}$Ne from $^{276\text{-}334}$118 without and with deformation.

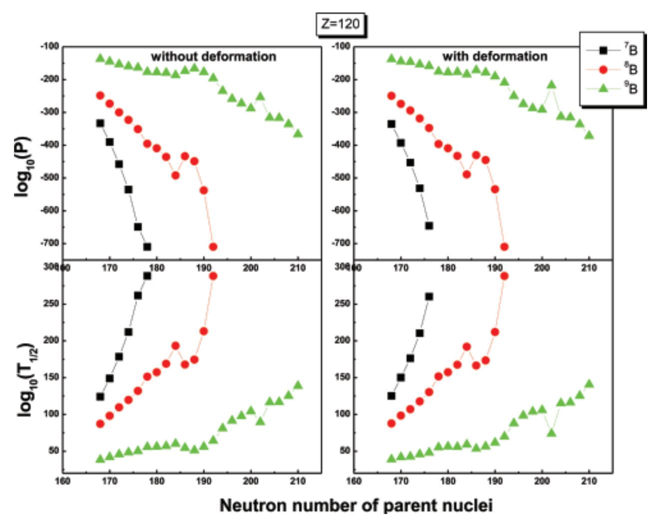

Figure 9: Plot of $\log_{10}T_{1/2}$ and $\log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{7\text{-}9}$B from $^{288\text{-}330}$120 without and with deformation.

The present experimental limit of half life time measurement is up to 10^{30}s [88, 89]. That means a decay with half lives less than or equal to 10^{30}s is possible. From the figures 1-5, it was observed that the computed half lives for the emission of ^{11}C, ^{19}Ne, ^{29,30}P, ^{32}S isotopes from the parent ^{276}116; ^{30}P, ^{31,32}S from ^{278}116; ^{31,32}S from $^{280\text{-}284}$116 and ^{32}S from $^{286\text{-}290}$116 have less than or equal to 10^{30} s. This indicates that these nuclear decays are possible to occur. Also in the figures 6-8, the computed half lives for the decay of ^{9}B, ^{10,11}C, ^{18,19}Ne from the parent isotope ^{276}118; ^{9}B, ^{10,11}C, ^{19}Ne from ^{278}118 ; ^{9}B, ^{11}C,^{19}Ne from ^{280}118 and ^{9}B, ^{11}C from $^{282\text{-}288}$118 are less than or equal to 10^{30}s, the present experimental limit. Hence we presume that our predictions will be a guide to the future experiments.

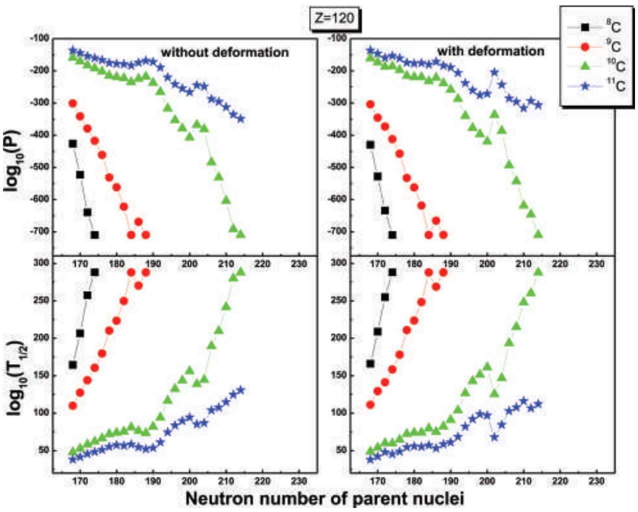

Figure 10: Plot of $log_{10}T_{1/2}$ and $log_{10}P$ verses neutron number of the parent nuclei for the decay of $^{8-11}$C from $^{288-330}$120 without and with deformation.

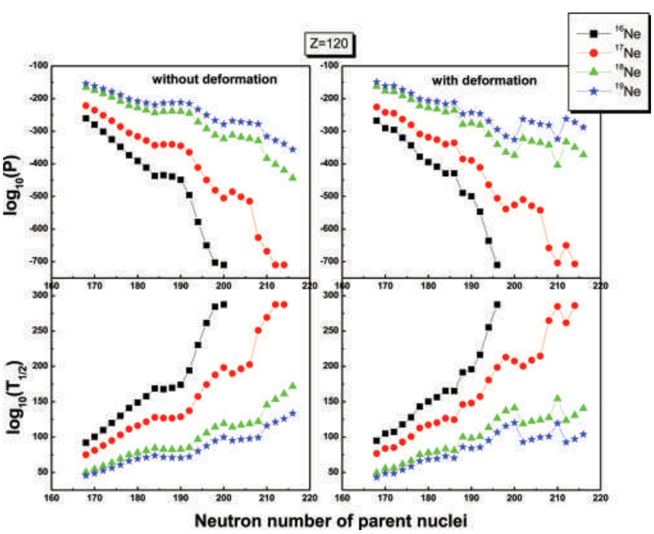

Figure 11: Plot of $log_{10}T_{1/2}$ and $Log_{10}P$ verses neutron number of the parents for the decay of $^{16-19}$Ne from $^{288-334}$120 without and with deformation.

Conclusions

The main Conclusion arrives from the present study is as follows.

- Half-life and barrier penetrability for the emission of various clusters $^{7-9}$B, $^{8-11}$C, $^{16-19}$Ne, $^{23-30}$P, $^{26-32}$S from the parent nuclei in the super heavy region $^{274-332}$116, $^{274-334}$118 and $^{288-334}$120 are calculated using CPPM without and with deformation effects.
- From the computed half-lives, it is found that half life of the same parent for the emission of different clusters decreases as the mass number of the cluster increases.
- The inclusion of ground state quardrupole (β_2), Octupole (β_3) and hexadecapole (β_4) deformation of parent daughter and cluster nuclei reduces the height and shape of the barrier hence half-life for the emission of different clusters decreases and barrier penetrability increases.
- Half-lives of many of the exotic nuclei emissions are less than or equal to 10^{30}s, which indicates that these decays are measurable with the presently available experimental techniques.
- Based on the observations we have also identified that shell closure occurs at or near to neutron numbers 184, 200, and 212 that leads to stability of these nuclei.

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