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Research Article

Keywords: preformation factors, doubly magic nuclei, proton-neutron interaction, Alpha-decay half-lives

Posted Date: December 3rd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-1121549/v1

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New behaviors of $\alpha$-particle preformation factors near doubly magic $^{100}\text{Sn}$

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The $\alpha$-particle preformation factors of nuclei above doubly magic nuclei $^{100}\text{Sn}$ and $^{208}\text{Pb}$ are investigated. The results show that the $\alpha$-particle preformation factors of nuclei near self-conjugate doubly magic $^{100}\text{Sn}$ are larger significantly than those of analogous nuclei just above $^{208}\text{Pb}$, and they will be enhanced as the nuclei move towards the $N = Z$ line. The correlation energy of the proton-neutron $E_{p-n}$ and two protons-two neutrons $E_{2p-2n}$ of nuclei near $^{100}\text{Sn}$ also exhibit similar situations indicating that the interactions between protons and neutrons occupying similar single-particle orbitals could enhance the $\alpha$-particle preformation factors and result in the superallowed $\alpha$ decay. It also provides evidence of the significant role of proton-neutron interaction on $\alpha$-particle preformation. Besides, the linear relationship between $\alpha$-particle preformation factors and the product of valence protons and valence neutrons for nuclei around $^{208}\text{Pb}$ is broken in the $^{100}\text{Sn}$ region because the $\alpha$-particle preformation factor is enhanced when the nucleus near $^{100}\text{Sn}$ moves towards the $N = Z$ line. Furthermore, the calculated $\alpha$ decay half-lives can well reproduce the experimental data including the recent observed self-conjugate nuclei $^{104}\text{Te}$ and $^{108}\text{Xe}$ [Phys. Rev. Lett. 121, 182501 (2018)].

$\alpha$ decay is a fundamental nuclear decay mode. The researches on $\alpha$ decay have long been focused on the vicinities of doubly magic nuclei $^{208}\text{Pb}$ ($Z = 82, N = 126$) and $^{208}\text{Fl}$ ($Z = 114, N = 184$) because $\alpha$ decay can be a probe to study the unstable nucleus structure, and can be the only way to identify the new synthesized super-heavy nuclei [1–27]. Over the past two decades, the $\alpha$ emitters around the self-conjugate doubly magic nucleus $^{100}\text{Sn}$ ($Z = N = 50$) at the opposite end of the mass table have also received a lot of attention and become a hot topic in nuclear physics [18, 28–35]. In particular, there is the fastest $\alpha$ emitter $^{104}\text{Te}$ near doubly magic nucleus $^{100}\text{Sn}$ [34]. Since the $\alpha$ emitters near self-conjugate doubly magic nucleus $^{100}\text{Sn}$ are close to the $N = Z$ line, the nuclear force is extremely sensitive to isospin. Therefore, it is a great chance to study and obtain the unique neutron-deficient nuclear structure information and examine various $\alpha$ decay theoretical models. Moreover, the cluster radioactivity was also predicted as one of the decay modes of the nucleus in the $^{100}\text{Sn}$ region [36–39]. Further interest in the decay rates of nuclei around doubly magic nucleus $^{100}\text{Sn}$ comes from the research of astrophysical processes, for which this region has been considered as the end of the rapid proton capture process due to the Sn-Sb-Te cycle [33, 40, 41].

In addition, in the neutron-deficient Te, Xe, and Ba isotopes near $^{100}\text{Sn}$, one would expect that the interactions between protons and neutrons occupying similar single-particle orbitals could enhance the $\alpha$-particle preformation factors and the reduced $\alpha$-widths significantly when compared to the analogous nuclei just above doubly magic nuclei $^{208}\text{Pb}$, and result in the so-called “superallowed” $\alpha$ decay [42]. And this effect would be expected to be the greatest for the $N = Z$ self-conjugate nuclei [42]. Recently, the first time $\alpha$ radioactivity to a heavy self-conjugate nucleus was observed on the $^{108}\text{Xe} \rightarrow ^{104}\text{Te} \rightarrow ^{100}\text{Sn}$ $\alpha$ decay chain [34], including the measurements of the $\alpha$-particle kinetic energy and $\alpha$ decay half-lives of the $\alpha$ emitters $^{108}\text{Xe}$ ($E_\alpha = 4.4(2)$ MeV, $T_{1/2} = 58^{+10}_{-23}$ μs) and $^{104}\text{Te}$ ($E_\alpha = 4.9(2)$ MeV, $T_{1/2} < 18$ ns]. The authors of this reference suggested that the $\alpha$-reduced width for $^{108}\text{Xe}$ or $^{104}\text{Te}$ is more than a factor of 5 larger than that for $^{212}\text{Po}$ [34].

It is well known that $^{104}\text{Te}$, near the proton drip line, and $^{212}\text{Po}$, near the $\beta$–stability line, are the only two existing $\alpha$ emitters decaying to the doubly magic nuclei. In this work, we focus on the $\alpha$-particle preformation factors of nuclei near self-conjugate doubly magic nucleus $^{100}\text{Sn}$ and compare them to those of analogous nuclei just above the doubly magic nucleus $^{208}\text{Pb}$ based on the available experimental data of $\alpha$ decay [34, 43–53] within the generalized liquid drop model (GLDM) [54–60]. These $\alpha$ emitters are in different isospins and mass numbers as well as around different protons and neutrons closed shells. We want to reveal some new behaviors of $\alpha$-particle preformation factors of extremely neutron-deficient nuclei near self-conjugate doubly magic nucleus $^{100}\text{Sn}$ for understanding the roles of proton-neutron correlation and the single-particle orbitals occupied by protons and neutrons in the preformation of $\alpha$-cluster as well as the physical mechanism of superallowed $\alpha$ decay.

The GLDM can deal with proton radioactivity [61], cluster radioactivity [62], fusion [63], fission [64], and the $\alpha$ decay process [22, 54–60, 65] because of introducing the quasimolecular shape mechanism [54], which can describe the complex deformation process from the parent nucleus continuous transition to the appearance of a deep and narrow neck finally resulting in two tangential fragments, and adding the proximity energy, including an

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accurate radius and mass asymmetry. In previous works [54–60], the GLDM has been discussed in detail. The α decay half-life can be obtained by

$$T_{1/2} = \frac{\ln 2}{\lambda},$$

(1)

with the α decay constant $\lambda$ being expressed as

$$\lambda = P_\alpha \nu P,$$

(2)

where the assault frequency $\nu$ is obtained by using the classical method with the kinetic energy of the α-particle. The barrier penetrating probability $P$ is determined by tunneling the GLDM potential barriers [54–60] with the Wentzel-Kramers-Brillouin (WKB) approximation.

The experimental α-particle preformation factor $P_\alpha^{Exp}$ can be extracted from the ratios between the theoretical decay half-life $T_{1/2}^{Cal}$ calculated by assuming the α-particle preformation factor as a constant $P_\alpha = 1$ to experimental data [59, 66–69] and expressed as

$$P_\alpha^{Exp} = \frac{T_{1/2}^{Cal}}{T_{1/2}^{Exp}}.$$  (3)

To examine the experimental α decay half-life data, the analytic formula for estimating the α-particle preformation factor is also adopted, which is put forward in our previous work [60, 65]. It is expressed as

$$\log_{10} P_\alpha^{Exp} = a + bA^{1/6} \sqrt{Z + c} \frac{Z}{\sqrt{Q_\alpha}} - d\chi' - e\rho' + f \sqrt{l(l + 1)},$$

(4)

where $\chi' = Z_1 Z_2 \sqrt{A_1 A_2 / (A_1 + A_2) Q_\alpha}$ and $\rho' = \sqrt{A_1 A_2 / (A_1 + A_2)} Z_1 Z_2 (A_1^{1/3} + A_2^{1/3})$. $A$, $Z$, and $Q_\alpha$ represent mass number, proton number, and α decay energy of the parent nucleus. $A_1$, $Z_1$, $A_2$, and $Z_2$ denote the mass and proton numbers of the α-particle and daughter nucleus. $l$ is the angular momentum carried by the α-particle. The parameters values are listed in Ref. [60].

The calculated α decay half-lives for nuclei above doubly magic nuclei $^{100}$Sn and $^{208}$Pb are presented in Tables I and II, respectively. In these two tables, the first four columns represent the α transition, the experimental kinetic energy of the α-particle, the experimental α decay energy, and the minimum angular momentum carried by the α-particle. The fifth column is the experimental α decay half-life. The sixth column denotes the calculated α decay half-life $T_{1/2}^{Cal}$ within the GLDM with $P_\alpha = 1$. The seventh column gives the calculated α decay half-life $T_{1/2}^{Cal}$ within the GLDM with the estimated α-particle preformation factor from Eq. (4). The eighth column shows the extracted experimental α-particle preformation factor by using Eq. (3) with $T_{1/2}^{Cal}$ and $T_{1/2}^{Exp}$. The last two columns express the calculated correlation energy of the proton-neutron $E_{p-n}$ and two protons-two neutrons $E_{2p-2n}$ determined by Eqs. (6) and (7). From these two tables, it can be seen immediately that the calculated α decay half-lives $T_{1/2}^{Cal}$ can well reproduce the experimental data including the newly observed self-conjugate nuclei $^{104}$Te and $^{108}$Xe [34]. Note that the calculations provide supports for recent experimental observation data in Ref. [34]. To measure the agreements between the calculated α decay half-lives $T_{1/2}^{Cal}$ and experimental data $T_{1/2}^{Exp}$, the standard deviations are calculated by

$$\sigma = \sqrt{\frac{1}{n} \sum (\log_{10} T_{1/2}^{Cal} - \log_{10} T_{1/2}^{Exp})^2}.$$  (5)

For nuclei in Tables I and II, the results of standard deviations $\sigma_1 = 0.47$ and $\sigma_2 = 0.16$ are satisfactory manifesting that $T_{1/2}^{Cal}$ can well reproduce $T_{1/2}^{Exp}$ within factors of $10^{0.47} = 2.95$ and $10^{0.16} = 1.45$, respectively. It demonstrated that the GLDM can be applied to extract the experimental α-particle preformation factors for studying the structure information of nuclei in these two regions.

Furthermore, in Tables I and II, we can see that the extracted experimental α-particle preformation factors $P_\alpha^{Exp}$ of nuclei near $^{100}$Sn are larger than $P_\alpha^{Exp}$ of nuclei near $^{208}$Pb, and in particular, larger than $P_\alpha^{Exp}$ of analogous nuclei just above $^{208}$Pb. The analogous nuclei refer to the two nuclei with the same valence proton and valence neutron located above doubly magic cores $^{100}$Sn and $^{208}$Pb, respectively. The valence protons $N_p$ and valence neutrons $N_n$ are defined as $N_p = Z - Z_0$ and $N_n = N - N_0$ with $Z_0 = 50$ and $N_0 = 126$, being the magic numbers of protons and neutrons in the corresponding nuclear region. For example, $^{104}$Te is analogous to $^{212}$Po because they both have two valence protons and two valence neutrons outside of the doubly magic nuclei $^{100}$Sn and $^{208}$Pb, respectively.

The extracted experimental α-particle preformation factors $P_\alpha^{Exp}$ for nuclei above $^{100}$Sn and for analogous nuclei just above $^{208}$Pb are shown as functions of valence protons and valence neutrons in Fig. 1 (a), (b), and (c), respectively. In this figure, one can see that the $P_\alpha^{Exp}$ of nuclei above $^{100}$Sn are significantly larger than those of analogous nuclei just above $^{208}$Pb.

Furthermore, Fig. 1 (a) shows the variations of $P_\alpha^{Exp}$ for Te ($Z = 52$) and Po ($Z = 84$) isotopes, whose valence protons are $N_p = Z - Z_0 = 2$, against valence neutrons $N_n$. It is clearly seen that for Te isotopes the $P_\alpha^{Exp}$ exhibits an increasing trend when the nucleus moves towards the $N = Z$ line, but the $P_\alpha^{Exp}$ of Po isotopes do not show similar patterns due to the large asymmetry between neutrons and protons. Fig. 1 (b) displays the variations of $P_\alpha^{Exp}$ for Xe ($Z = 54$) and Ru ($Z = 86$) isotopes, whose valence protons are $N_p = Z - Z_0 = 4$, against valence neutrons $N_n$. We can find that for Xe isotopes the $P_\alpha^{Exp}$ also increases as the nucleus moves towards the $N = Z$ line. However, the $P_\alpha^{Exp}$ of Ru isotopes still do not show a similar trend of change. Fig. 1 (c) plots the $P_\alpha^{Exp}$ as functions of valence protons $N_p$ for $N = 58$ and $N = 134$ isotopes, whose valence neutrons are $N_n = N - N_0 = 8$. 


It is calculated by using the nuclear mass data in the evaluated atomic mass table AME2016. But this phenomenon has not occurred in the analogous taken from the evaluated nuclear properties table NUBASE2016. It is indicated that the doubly magic nucleus.

The $P_{\alpha}^{\text{Exp}}$ of $N = 58$ isotones also show an increasing tendency as the nuclei move towards the $N = Z$ line, but this phenomenon has not occurred in the analogous $N = 134$ isotopes just above $^{208}\text{Pb}$. It is indicated that the $P_{\alpha}^{\text{Exp}}$ is enhanced when a nucleus moves towards the $N = Z$ line, and result in the superallowed $\alpha$ decay near doubly magic nucleus $^{100}\text{Sn}$. In recent work, Clark et al. adopted a very different model and studied the $\alpha$-particle preformation factors of nuclei in these two regions [31]. A similar conclusion was obtained though the $\alpha$-particle
preformation factors of nuclei near doubly magic nuclei $^{100}$Sn and $^{208}$Pb are in orders of $10^{-2}$ and $10^{-3}$, respectively.

![Figure 1](image1.png)

**FIG. 1.** (Color online) The variations of extracted experimental $\alpha$-particle preformation factors $P^{\alpha}_{\exp}$ from Eq. (3) against $N_0$ for nuclei above $^{100}$Sn (left) and for nuclei above $^{208}$Pb (right), respectively.

![Figure 2](image2.png)

**FIG. 2.** (Color online) The correlation energy of the proton-neutron $E_{p-n}$ and two protons-two neutrons $E_{2p-2n}$ of nuclei above $^{100}$Sn (denoted as solid symbols) and those of analogous nuclei just above $^{208}$Pb (denoted as open symbols).

For investigating the effects of proton-neutron interaction and two protons-two neutrons interaction on the $\alpha$-particle preformation, we calculate the correlation energy of the proton-neutron $E_{p-n}$ and two protons-two neutrons $E_{2p-2n}$ using

$$E_{p-n} = B(A,Z) + B(A-2,Z-1)$$

$$- B(A-1,Z-1) - B(A-1,Z),$$

(6)

$E_{2p-2n}$ is the binding energy of a nucleus with the mass number $A$ and proton number $Z$. The results of $E_{p-n}$ energy and $E_{2p-2n}$ energy are plotted in Fig. 2. In this figure, the $E_{p-n}$ energy and $E_{2p-2n}$ energy of nuclei above doubly magic nuclei $^{100}$Sn are larger than those of analogous nuclei just above $^{208}$Pb. This, in turn, leads to that the $P^{\alpha}_{\exp}$ of nuclei near $^{100}$Sn are enhanced significantly. The results of $E_{p-n}$ energy and $E_{2p-2n}$ energy are plotted in Fig. 2. In this figure, the $E_{p-n}$ energy and $E_{2p-2n}$ energy of nuclei above $^{100}$Sn are strengthened when compared to analogous nuclei just above $^{208}$Pb. For $Z = 52$ isotopes, the $E_{p-n}$ energy and $E_{2p-2n}$ energy increase rapidly in $N_n = 2$. Similarly, for $Z = 54$ isotopes, the $E_{p-n}$ energy and $E_{2p-2n}$ energy rise fast in $N_n = 4$. However, the $E_{p-n}$ energy and $E_{2p-2n}$ energy of analogous nuclei just above $^{208}$Pb are changed slowly. Therefore, it demonstrated that the $\alpha$-particle is more to form in self-conjugate nuclei and result in the superallowed $\alpha$ decay. In addition, the $E_{2p-2n}$ energy increases an increased tendency, the same as $P^{\alpha}_{\exp}$ when the nucleus moves towards the $N = Z$ line implying that the two protons-two neutrons interaction play a more significant role than one proton-one neutron interaction in $\alpha$-particle preformation.

The extracted experimental $\alpha$-particle preformation factors $P^{\alpha}_{\exp}$ for nuclei above $^{100}$Sn and $^{208}$Pb are shown as functions of $\frac{N_0N_0}{Z_0+Z_0}$ in Fig. 3 (a) and (b), respectively.

![Figure 3](image3.png)

**FIG. 3.** (Color online) The variations of extracted experimental $\alpha$-particle preformation factors $P^{\alpha}_{\exp}$ from Eq. (3) against $N_0N_0$ for nuclei above $^{100}$Sn (left) and for nuclei above $^{208}$Pb (right), respectively.

$$E_{p-n} = B(A,Z) + B(A-4,Z-2)$$

$$- B(A-2,Z-2) - B(A-2,Z),$$

(7)

Eqs. (6) and (7) were proposed in Ref. [71] and used to determine the experimental pairing energy of the nucleons [72]. $B(A,Z)$ is the binding energy of a nucleus with the mass number $A$ and proton number $Z$. The results of $E_{p-n}$ energy and $E_{2p-2n}$ energy are listed in the last two columns of Tables I and II. In these two tables, it can be found that the $E_{p-n}$ energy and $E_{2p-2n}$ energy of nuclei above doubly magic nuclei $^{100}$Sn are larger than those of analogous nuclei just above $^{208}$Pb. This, in turn, leads to that the $P^{\alpha}_{\exp}$ of nuclei near $^{100}$Sn are enhanced significantly. The results of $E_{p-n}$ energy and $E_{2p-2n}$ energy are plotted in Fig. 2. In this figure, the $E_{p-n}$ energy and $E_{2p-2n}$ energy of nuclei above $^{100}$Sn are strengthened when compared to analogous nuclei just above $^{208}$Pb. For $Z = 52$ isotopes, the $E_{p-n}$ energy and $E_{2p-2n}$ energy increase rapidly in $N_n = 2$. Similarly, for $Z = 54$ isotopes, the $E_{p-n}$ energy and $E_{2p-2n}$ energy rise fast in $N_n = 4$. However, the $E_{p-n}$ energy and $E_{2p-2n}$ energy of analogous nuclei just above $^{208}$Pb are changed slowly. Therefore, it demonstrated that the $\alpha$-particle is more to form in self-conjugate nuclei and result in the superallowed $\alpha$ decay. In addition, the $E_{2p-2n}$ energy increases an increased tendency, the same as $P^{\alpha}_{\exp}$ when the nucleus moves towards the $N = Z$ line implying that the two protons-two neutrons interaction play a more significant role than one proton-one neutron interaction in $\alpha$-particle preformation.

The extracted experimental $\alpha$-particle preformation factors $P^{\alpha}_{\exp}$ for nuclei above $^{100}$Sn and $^{208}$Pb are shown as functions of $\frac{N_0N_0}{Z_0+Z_0}$ in Fig. 3 (a) and (b), respectively. In Fig. 3 (b), one can see that the closer the $\frac{N_0N_0}{Z_0+Z_0}$ is to the zero, representing the proton and/or neutron num-
bers approaches the closed shells, the smaller $P_{\text{Exp}}^\alpha$ is. When the $\frac{N_p N_n}{Z_p + N_0}$ is far from zero, the $P_{\text{Exp}}^\alpha$ will increase. This indicates that the closer the proton and/or neutron number is to the magic number, the more difficult it is for an $\alpha$-particle to form inside its parent nucleus. And we can find that the $P_{\text{Exp}}^\alpha$ is linearly dependent on the $\frac{N_p N_n}{Z_p + N_0}$ for nuclei above 208Pb. It is consistent with the conclusions deduced by adopting the different models, in which the $\alpha$-particle preformation factors are extracted from the ratios between theoretical $\alpha$-decay half-lives calculated by adopting the different models to experimental data [15, 73, 74], or calculated using the differences of binding energy between the $\alpha$ decaying parent nucleus and its neighboring nuclei within the cluster-formation model [75]. It is shown that the nuclear shell effects and the nucleons configuration play key roles in $\alpha$-cluster preformation for $\alpha$-particle emitters around doubly magic 208Pb. However, in Fig. 3 (a) this phenomenon is broken in the 100Sn region. The $P_{\text{Exp}}^\alpha$ of nuclei above 100Sn are linearly dependent on $\frac{N_p N_n}{Z_p + N_0}$ and show a new behavior. When the nucleus is close to the shell closures, the $P_{\text{Exp}}^\alpha$ of the nucleus near 100Sn does not decrease like that of the nucleus near 208Pb, but it increases. In addition, we can find that the maximum values of $P_{\text{Exp}}^\alpha$ in Fig. 3 (a) correspond to 104Te, 108Xe, and 114Ba. In particular along the $N = Z$ line, the $P_{\text{Exp}}^\alpha$ is significantly enhanced, which results in the $P_{\text{Exp}}^\alpha$ of nuclei above 100Sn are not linearly dependent on $\frac{N_p N_n}{Z_p + N_0}$.

In summary, we systematically studied the $\alpha$-particle preformation factors $P_{\text{Exp}}^\alpha$ of nuclei above doubly magic nuclei 100Sn and 208Pb, which are extracted from the ratios between the theoretical $\alpha$-decay half-lives within the GLDM to experimental data. The results show that the $P_{\text{Exp}}^\alpha$ of nuclei near self-conjugate doubly magic 100Sn are larger significantly than those of analogous nuclei just above 208Pb, and they will be enhanced when the nucleus moves towards the $N = Z$ line. The correlation energy of proton-neutron $E_{p-n}$ and two protons-two neutrons $E_{2p-2n}$ of nuclei near 100Sn are also larger than those of analogous nuclei just above 208Pb. It is indicated that the interactions between protons and neutrons occupying similar single-particle orbitals could enhance the $P_{\text{Exp}}^\alpha$ and result in the superallowed $\alpha$ decay near doubly magic nucleus 100Sn. Furthermore, as the nucleus moves towards the $N = Z$ line, the $E_{2p-2n}$ energy shows an increased tendency which is the same as that of $P_{\text{Exp}}^\alpha$, while $E_{p-n}$ energy doesn’t appear this pattern, indicating $E_{2p-2n}$ energy plays a more important role than $E_{p-n}$ energy in $\alpha$-particle preformation of superallowed $\alpha$ decay.

The linear relationship between the $P_{\text{Exp}}^\alpha$ and the product of valence protons and valence neutrons $\frac{N_p N_n}{Z_p + N_0}$ for nuclei above 208Pb is broken in the 100Sn region because the $P_{\text{Exp}}^\alpha$ is enhanced when the nucleus near 100Sn moves towards the $N = Z$ line. Besides, the calculated $\alpha$ decay half-lives can well reproduce experimental data including the newly observed self-conjugate nuclei 108Xe and 104Te. This work also provides evidence of the significant role of proton-neutron interaction on the $\alpha$-particle preformation, which will shed some new light on $\alpha$ decay and $\alpha$-particle preformation factors researches of nuclear physics in the future.

This work is supported by National Natural Science Foundation of China (Grants No. 12175170, No. 11675066, No. 11665019).

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