

New Geiger-Nuttall law of odd-Z nuclei and long-lived island beyond the stable line (Postprint)

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Abstract

Recently, we have analyzed α -decay data of even-Z nuclei and proposed the new Geiger-Nuttall law in which the effects of quantum numbers of α -core relative motion are naturally embedded [Physical Review C 85, 044608 (2012)]. In this paper, we first test whether the new law, without any change of parameters, can be applied to the α -decays of odd-Z nuclei, which are more complicated than those of even-even nuclei. Then the nuclear shell effect around $N=126$ is analyzed for very proton-rich nuclei with $Z=85-92$ based on α -decay energy and half-life data. A long-lived island beyond the line of stability is proposed, where the half-lives of nuclei on this island are abnormally long. The mechanism of the appearance of the island and its significance to other mass ranges are discussed.

Full Text

Preamble

New Geiger-Nuttall Law for Odd-Z Nuclei and a Long-Lived Island Beyond the Stable Line

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Abstract

Recently, we analyzed α -decay data for even-Z nuclei and proposed a new Geiger-Nuttall law that naturally incorporates the effects of quantum numbers associated with α -core relative motion [Physical Review C 85, 044608 (2012)]. In this paper, we first test whether this new law, without any parameter adjustments, can be applied to α -decays of odd-Z nuclei, which are more complex than those of even-even nuclei. We then analyze the nuclear shell effect around $N=126$ for very proton-rich nuclei with $Z=85-92$ based on α -decay energy and half-life data.

A long-lived island beyond the stable line is proposed, where nuclei exhibit abnormally long half-lives. The mechanism for the appearance of this island and its significance for other mass ranges are discussed.

Keywords

New Geiger-Nuttall law, α -decay, Odd-Z nuclei, Long-lived island

Introduction

It is well known that β -decay dominates the stability of light and medium-mass nuclei, and nuclei near the β -stable line are either stable or have longer half-lives than those far from the stable line [1]. For light and medium-mass nuclei, half-lives also decrease along an isotopic chain from the stable line toward the nuclear drip line [1]. In these regions, even-even nuclei are typically more stable than neighboring odd nuclei, exhibiting longer half-lives because β -decay is the dominant process. However, for heavier nuclei beyond ^{208}Pb (the last currently known stable nucleus), α -decay [2-8] plays an increasingly important role [9-20] as both the strong interaction and Coulomb interaction progressively govern nuclear stability with increasing proton number. In some cases, spontaneous fission also becomes significant for heavy and superheavy nuclei.

The emergence of different decay modes can alter traditional views of nuclear stability derived from β -decay studies near the stable line. The competition between various decay modes will also be crucial for the possible existence of long-lived nuclei or long-lived islands beyond ^{208}Pb . The discovery of a long-lived heavy nuclide or a new long-lived element would significantly impact current nuclear physics research.

Recently, we proposed a new Geiger-Nuttall law [21] for even-Z nuclei that incorporates the effects of quantum numbers on α -decay half-lives. In this paper, we first extend our research to α -decay half-lives of odd-Z nuclei to test the reliability of this law for such systems. Second, we analyze the variation of total half-lives for $Z=85-91$ isotopic chains and explore the effect of the magic number $N=126$ on the stability of proton-rich nuclei far from the stable line. We identify a long-lived island for these isotopes with $110 \leq N \leq 126$. This abnormally long half-life behavior has not been observed in other mass ranges, and investigating its mechanism could prove valuable for future studies of other heavy nuclei far from stability.

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2 Methods and Results

We begin with an analytical formula for α -decay half-lives of even-even nuclei:

$$\log_{10} T_{1/2} = aZ_c Z_d \sqrt{\frac{\mu}{Q}} + b + c$$

where the three parameters are $a=0.39961$, $b=-1.31008$, $c=-17.00698$, determined from even-even nuclei [7,21]. $T_{1/2}$ (s) is the α -decay half-life and Q (MeV) is the corresponding decay energy. Z_c and Z_d are the charge numbers of the cluster and daughter nucleus, respectively. $\mu = A_c A_d / (A_c + A_d)$ is the reduced mass, with A_c and A_d being the mass numbers of the cluster and daughter nucleus. For α -decay, $Z_c=2$ and $A_c=4$. Details of this formula are given in previous publications [7,21]. This expression is called the original Geiger-Nuttall law [21] as it naturally realizes both the Geiger-Nuttall law and the unified Viola-Seaborg description of α -decay and cluster radioactivity [7,19].

The new Geiger-Nuttall law is proposed [21] with the following expression:

$$\log_{10} T_{1/2} = aZ_c Z_d \sqrt{\frac{\mu}{Q}} + b + c + S + P_l$$

In this formula, S represents the change in radial quantum number of the α -core relative motion, and l in the last term is the angular momentum quantum number of the α -particle [21]. These terms incorporate the effects of quantum numbers on decay half-lives [21]. Here $S=1$ for $N \neq 126$ and $S=0$ for $N=127$ [21]. For favored α -decay transitions between nuclear ground states, $l=0$ is usually dominant when the parent and daughter nuclei have the same spin and parity. The three parameters a , b , c have the same values as those in Eq.(1).

We emphasize that the last two terms in Eq.(2) originate from the quantum number effects of the α -decay process; a detailed explanation is provided in Ref.[21]. Because the α -particle moves around the core before decay, its motion is described by three quantum numbers n , l , m in a central potential [21]. When nuclei cross a magic number such as $N=126$, the quantum numbers can differ, and S represents the change in radial quantum number. The quantity l in the last term is the angular momentum carried by the α -particle during the decay process [21]. For favored decays, the angular momentum l is zero.

We use both Eq.(1) and Eq.(2) to calculate α -decay half-lives of odd- Z isotopes with $Z=85-91$ for favored transitions. The numerical results for $Z=85$ and $Z=87$ using both equations are shown in Figs.1 and 2.

The deviations of the logarithm of α -decay half-lives for At and Fr isotopes are displayed in Figs.1 and 2, where results from Eq.(1) are denoted as “original law” and those from Eq.(2) as “new law.” Fig.1 clearly shows that the deviation between calculations using the original law and experimental data is abnormally large for $N=126$. In contrast, the deviation between calculations using the new

law and experimental data is reasonable. Figs.1 and 2 demonstrate the same effect, similar to the case of even-Z nuclei, clearly showing that the new law is valid for odd-Z isotopes without any additional adjustments. The improvement achieved by the quantum effect S is also remarkable for odd-Z nuclei.

Therefore, Figs.1 and 2 demonstrate good agreement between the new law and experimental data, although the deviation between the original law and experimental data is extraordinarily large for N=126 nuclei. These results are similar to those for even-Z nuclei, and we will not repeat the discussions further. For odd-Z isotopes, small staggered effects appear in the figures due to differences between odd-A and odd-odd nuclei.

[Figure 1: see original paper] (Color online) Logarithms of the ratios between experimental α -decay half-lives and theoretical ones for At isotopes calculated with the original law (Eq.(1)) and the new law (Eq.(2)). The original law and new law converge in the range N=128.

When performing numerical calculations for odd-A and odd-odd nuclei, we directly use Eq.(2) derived from even-even nuclei without introducing any additional adjustments for odd nuclei. Even so, the new law can reproduce experimental data within a factor of 3, demonstrating its correctness. One should note that perfect agreement corresponds to a logarithm value of zero for the ratio between experimental and calculated half-lives. In Figs.1 and 2, some points from the new law are above zero and others below zero, which represents the correct trend of the new law.

The numerical results for Z=85–91 isotopes using Eq.(2) are also listed in Tables 1 and 2.

[Figure 2: see original paper] (Color online) Logarithms of the ratios between experimental α -decay half-lives and theoretical ones for Fr isotopes calculated with the original law (Eq.(1)) and the new law (Eq.(2)). The original law and new law converge in the range N=128.

The staggered effects seen in Figs.1 and 2 may arise from the influence of odd nucleons. shows experimental decay energies (Q(MeV)) and logarithms of α -decay half-lives for Z=85 and Z=87 isotopes calculated with the new Geiger-Nuttall law ($\lg T_{\text{theo}}$) and experimental values ($\lg T_{\text{expt}}$). shows the same for Z=89 and Z=91 isotopes.

In Table 1, the first column denotes the parent nucleus, the second column represents the α -decay energy, and the third and fourth columns represent the logarithms of experimental and theoretical α -decay half-lives, respectively. Experimental data are taken from the nuclear mass table by Audi et al. [22,23]. In Tables 1 and 2, some nuclei are missing from the isotopic chains because no α -decay data exist or because the data are uncertain due to very small α -decay branching ratios [22,23].

Hindered transitions of odd-Z isotopes with changes in angular momentum or parity, such as N=127, are not included in this paper; we addressed these for

even- Z cases in our previous work [21]. Columns 5–8 have similar meanings to columns 1–4. The results for odd- Z nuclei with Eq.(2) are not as perfect as those for even-even nuclei in our previous publication, which is expected because ground-state transitions of even-even nuclei are simple and can be easily treated theoretically. For odd- Z nuclei, the odd nucleon can complicate α -decay transitions, introducing inaccuracies in both experimental measurements and theoretical calculations compared to even-even nuclei [22–24]. Although we introduce no additional adjustments for odd- Z nuclei in this paper, the results with Eq.(2) are good, confirming the validity of the new Geiger-Nuttall law for odd- Z nuclei. The good agreement between data and theoretical results is clearly evident in Tables 1 and 2.

Examining the results for At ($Z=85$) isotopes in columns 1–4 of Table 1, we find that for many nuclei, calculated half-lives agree with data within a factor of 1–3 (corresponding to logarithmic deviations of 0–0.5), and only for a few nuclei does the agreement reach approximately a factor of 4–5 (logarithmic deviations of 0.6–0.7). For Fr isotopes in Table 1, calculated half-lives also agree well with data, confirming the validity of the new Geiger-Nuttall law for odd- Z nuclei. The numerical results for Ac ($Z=89$) and Pa ($Z=91$) isotopes listed in Table 2 further confirm the reliability of the new law for odd- Z isotopes through good agreement between calculated and experimental values. For nuclei on Pa isotopic chains, ^{231}Pa is special [22–24]: although its ground-state spin and parity match those of its daughter nucleus ^{227}Ac , the α -decay branching ratio to the ground state of ^{227}Ac is only about 11%, again illustrating the complexity of decays in odd- Z nuclei compared to even-even cases. For some proton-rich nuclei such as $^{208-210}, ^{212-213}, ^{217}\text{Ac}$, the α -decay branching ratios are unknown and we assume them to be 100% based on neighboring nuclei [22,23]. For $^{209-211}\text{Pa}$ and ^{205}Ac , experimental decay energies and half-lives are unknown; experiments on these nuclei will be conducted at the Institute of Modern Physics in Lanzhou, China. We estimate their decay energies (marked with asterisks in Table 2) based on trends and predict their half-lives using the new law with these estimated energies, which will be compared with future measured values.

Before concluding, it is interesting to discuss the stability of nuclei far from the stable line and investigate the effect of the $N=126$ shell closure on half-lives of proton-rich nuclei. According to modern physics and nuclear physics textbooks, the β -stable line lies approximately at $N=Z$ for very light nuclei and $N=1.54Z$ for heavy nuclei around ^{208}Pb . Heavy nuclei such as ^{208}Pb , ^{232}Th , and ^{238}U are stable or have very long half-lives because they lie near the stable line. Moving away from the stable line, nuclear half-lives decrease along an isotopic chain. This is well established for light and heavy nuclei with $Z \leq 82$. However, we observe that total nuclear half-lives with $N=126$ on $Z=85-92$ isotopic chains are extraordinarily long due to the sudden decrease in decay energies at the shell closure. This clearly demonstrates that the magic number $N=126$ persists in the proton-rich region with $Z=85-92$, although some magic numbers can disappear in light neutron-rich nuclei. The existence of the

$N=126$ magic number in this region leads to the appearance of a long-lived island for $Z=85-92$ nuclei, which we illustrate for some odd- Z nuclei in Fig.3.

[Figure 3: see original paper] (Color online) Variation of experimental total half-lives for $Z=85-91$ isotopes toward the proton-rich side. Total half-lives on an isotopic chain become shorter with decreasing neutron number when moving away from the stable line. A long-lived island appears for nuclei with $N=126$.

Fig.3 shows that total nuclear half-lives for $Z=85-91$ decrease rapidly from $N=138$ to $N=128$ when moving from the stable line toward the proton-rich side. The shortest half-life occurs around $N=128$ for each isotopic chain due to maximum decay energies for ground-state α -transitions. Nuclear half-lives then increase rapidly from $N=128$ to $N=126$, reaching a local maximum around $N=125$ or $N=126$. Afterward, nuclear half-lives decrease very slowly, forming an island with longer half-lives beyond the traditional stable line. While even-even nuclei are more stable than neighboring odd- A nuclei, and odd- A nuclei are more stable than neighboring odd-odd nuclei when β -decay dominates, the situation differs for α -decay. For α -decay, odd- A nuclei on an isotopic chain can have longer half-lives than neighboring even-even nuclei due to the quantum blocking effect of the odd nucleon. Similarly, odd-odd nuclei on an odd- Z chain can have longer half-lives than neighboring odd- A nuclei due to the same effect. Therefore, research on α -decay in heavy-mass regions can change traditional views of nuclear stability derived from studies near the stable line. Similar phenomena regarding half-lives of even and odd nuclei are observed for spontaneous fission half-lives of heavy nuclei.

Regarding the scope of this island, current nuclear data do not reveal the upper proton number limit. We suggest conducting more experiments on $Z=92-94$ chains to explore this upper limit. Future work should investigate the mechanism of such islands and search for new islands far from the stable line, as they are directly related to the existence of magic numbers and the saturation of nuclear forces near the drip line. This could aid in the search for other spherical islands beyond ^{208}Pb .

3 Conclusion

In summary, we calculate half-lives of $Z=85-91$ nuclei using the new Geiger-Nuttall law and test its validity for odd- Z isotopic chains. We find that the new law can be applied to odd- Z nuclei without introducing additional parameters. A new island with abnormally long half-lives manifests for $Z=85-92$ isotopes with $N=126$ due to spherical shell closure. This represents the first island with abnormally long half-lives beyond the stable line. The mechanism for the appearance of this island could be used to explore other long-lifetime islands beyond the stable line and is useful for investigating the variation of magic numbers for nuclei far from stability.

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