第 35 卷 第 4 期
2018 年 12 月

原 子 核 物 理 评 论
Nuclear Physics Review

Vol. 35, No. 4
Dec., 2018

Article ID: 1007-4627(2018) 04-0455-08

Theoretical Descriptions of Decay Modes in $^{274-291}$Cn and $^{266-287}$Ds Superheavy Nuclei

ZHAO Tianliang, BAO Xiaojun†

(*Department of Physics, Collaborative Innovation Center for Quantum Effects, and Key Laboratory of Low Dimensional Quantum Structures and Quantum Control of Ministry of Education, Hunan Normal University, Changsha 410081, China*)

Abstract: The stability of superheavy nuclei (SHN) is controlled mainly by spontaneous fission and α decay processes. To investigate whether long lived SHN could really exist around ^{270}Ds, the competition between α decay and spontaneous fission in the region $104 \leqslant Z \leqslant 112$ are studied systematically. The α decay half-lives are investigated by employing a generalized liquid drop model (GLDM) and phenomenological analytical formula. Calculations of spontaneous fission half-lives for the same SHN are carried out based on the Wenzel-Kramers-Brillouin(WKB) approximation with both the shell effect and the isospin effect included. Decay modes are predicted for the unknown nuclei $^{274-276,279}$Cn and $^{267-269}$Ds.

Key words: superheavy nuclei; half-life; α decay; spontaneous fission

CLC number: O571.2 **Document code:** A **DOI:** 10.11804/NuclPhysRev.35.04.455

http://www.npr.ac.cn

1 Introduction

The stability of the superheavy nuclei (SHN) has been a long standing fundamental question in nuclear physics[1−3]. α decay and spontaneous fission are dominant decay modes of nuclei in the SHN region, and they can be taken as the limiting factor that determines the stability of SHN[4−7]. However, the unambiguous identification of the new isotopes still poses a problem because their α decay chains terminate by spontaneous fission before reaching the known region of the nuclear chart. The understanding of the competition between α decay and spontaneous fission is crucial.

Recently, the measured α decay energies have provided confirmation of the special stability of the deformed shell at $Z = 108$ and $N = 162$[8] predicted by theory[9]. Still heavier and more neutron rich SHNs are expected to be spherical and even more strongly stabilized by $N = 184$ shell effects[2−3]. The experimental data on the synthesis of SHN by hot fusion reaction[6] are shown for nuclei with $Z = 106 \sim 116$ and $N = 165 \sim 177$, which fall into transitional region of deformation. By analyzing the experimental data of α decay and spontaneous fission[10], we found that the two decay modes are strong competition in transitional region of deformation. The study of deformation transition region is of great significance. On one hand, considering that for transitional region nuclei their α decay half-lives and/or spontaneous fission half-lives have not yet been measured, it is interesting to make reliable theoretical predictions for the decay properties and examine which decay mode is the dominant one[11]. On another hand, it is shown theoretically that for SHN with $Z < 110$, the formation cross section of cold fusion reactions is larger than the one of hot fusion reactions, while for SHN with $Z \geqslant 112$, the situation is quite the opposite[12−13]. Therefore, $Z = 110$ and 112 are an ideal nuclear region to investigate the role of there factors in the process of the SHN synthesis.

The many publications have given not only α decay half-lives[14−19], but also spontaneous fission half-lives in the region of even-even SHN[20−31]. Compared with the theoretical results of competition between α decay and spontaneous fission for even-even SHN, those of even-odd nuclei seem to be rare[32−35]. In addition, although the competition between α decay and spontaneous fission has been studied in a series of papers, α decay half-lives of SHN are calculated within

Received date: 12 Sep. 2018; **Revised date:** 5 Dec. 2018

Foundation item: National Natural Science Foundation of China (11705055, 11475050); Hunan Provincial Natural Science Foundation of China (2018JJ3324); Excellent Youth Fund of Hunan Provincial Education Department (17B154)

Biography: ZHAO Tianliang(1995–), male, Handan, Hebei Province, Postgraduate, working on nuclear astrophysics; E-mail: zhaotianliang@smail.hunnu.edu.cn.

† **Corresponding author:** BAO Xiaojun, E-mail: baoxiaojun@hunnu.edu.cn.

different theoretical models or empirical formulas using Q_α values from different mass tables. Actually, it is anticipated that them majority of SHN would α decay and/or spontaneous fission, but predictions vary from model to model, primarily due to our inability to make accurate predictions for spontaneous fission half-lives. In the present work, spontaneous fission half-lives are calculated by an empirical formula derived from a dynamical approach for spontaneous fission defined essentially by the shape, the height of fission barrier, the fissionability parameter, and even-odd corrections. We approximate the fission barrier by a one dimensional inverted harmonic oscillator, as suggested by Hill and Wheeler[36]. It is our hope by this approach to develop an alternative method for calculating the spontaneous fission half-lives of heavy and SHN that are not yet observed. The α decay half-lives of the SHN are studied within a phenomenological analytical formula and the generalized liquid drop model (GLDM)[37–40]. The intention of our present work is to compare the α decay half-lives and spontaneous fission half-lives of various isotopes of the SHN Z=110, 112. It aims at the predictions of decay modes of yet unknown nuclei $^{274-276,279,287-291}$Cn and $^{267-269}$Ds.

2 Theoretical framework

2.1 α decay half-lives

The half-life of a parent nucleus decaying via α emission can be calculated by means of the Wenzel-Kramers-Brillouin(WKB) barrier penetration probability. The decay constant is simply defined as $\lambda = P_\alpha \nu_0 P$ and half-lives can be obtained by T=ln2/λ.

To calculate the absolute α decay width, the α preformation factor P_α is indispensable based on the Gamow picture, which measures the probability that an α particle is present in the decaying nucleus. However, development on the microscopical description of the α cluster preformation factor is still slow due to the complexity of the nuclear many-body problem. Recently an analytic formula is proposed for the preformation factor[41–42]:

$$P_\alpha = \exp[a + b(Z-Z_1)(Z_2-Z) + c(N-N_1)(N_2-N) + \mathrm{d}A], \tag{1}$$

where Z, N, and A are the charge, neutron, and mass number of the parent nucleus, respectively, which provided general guidance for the microscopic study on the α particle preformation factor. The preformation factor P_α will be addressed in detail in Refs. [41–42].

The assault frequency ν_0 is calculated phenomenologically which will be addressed in detail in Ref. [43],

$$\nu_0 = \frac{1}{2R}\sqrt{\frac{2E_\alpha}{M}}. \tag{2}$$

The barrier penetrability probability P is calculated with the action integral[44]:

$$P = \exp\left[-\frac{2}{\hbar}\int_{R_{\rm in}}^{R_{\rm out}}\sqrt{2\mu[V(r)-Q_\alpha]}\mathrm{d}r\right], \tag{3}$$

where $R_{\rm in}$ and $R_{\rm out}$ are the two turning points of the WKB action integral. The following approximations are used here:

$$R_{\rm in} = R_1 + R_2, \quad R_{\rm out} = e^2 Z_1 Z_2/Q_\alpha, \tag{4}$$

where R_1, R_2 are the radius of α cluster and daughter nucleus, respectively. Q_α is the α decay energy.

The $V(r)$ has been studied in Ref. [45], where the potential $V(r)$ has been determined within a liquid drop model including proximity effects between the α particle and the daughter nucleus. The excellent agreement with the experimental data indicates the GLDM is a useful tool to investigate α decay half-lives[46].

A phenomenological formula is presented for the α decay half-lives, it is constructed in a conventional way by considering the penetrability of a charged particle in a spherical Coulomb potential. We obtained the following explicit form from Refs. [55–56]:

$$\log_{10}T_{1/2} = aZ_\alpha Z_{\rm d}\sqrt{\frac{A_{\rm d}A_\alpha}{(A_{\rm d}+A_\alpha)Q_\alpha}} + b\sqrt{\frac{A_{\rm d}A_\alpha}{(A_{\rm d}+A_\alpha)}Z_\alpha Z_{\rm d}(A_{\rm d}^{1/3}+A_\alpha^{1/3})} + c, \tag{5}$$

The parameters a, b and c can be addressed in detail in Ref. [57].

2.2 Spontaneous fission half-lives

It is well known that the isospin effect, $I = (N-Z)/A$, also plays an important role in spontaneous fission half-lives. Considering the dependence of half-lives on the shell correction and the isospin effect, the modified formula can be written as[46]

$$\log_{10}[T_{1/2}(yr)] = c_1 + c_2\left[\frac{Z^2}{(1-kI^2)A}\right] + c_3\left[\frac{Z^2}{(1-kI^2)A}\right]^2 + c_4E_{\rm mic} + h_i. \tag{6}$$

This semiempirical formula is similar to the Swiateck's formula, so we call it a modified Swiateck's formula. The parameters are: c_1=1174.353 441, c_2=−47.666 855, c_3=0.471 307, c_4=3.378 848. The fixed value of k is 2.6[44]. The h_i is the blocking effect of unpaired nucleon. For the even-even nuclei blocking factor $h_{\rm ee}$=0. The odd-N $h_{\rm eo}$=2.609 374 and odd-Z $h_{\rm oe}$=2.619 768 nuclei are obtained by fitting the experimental half-lives of spontaneous fission 12 odd-N and

http://www.npr.ac.cn

12 odd-Z nuclei, respectively. We put the blocking factor h_{oo} of odd-odd nuclei as equal to the sum of the blocking factor of even-odd and odd-even nuclei. Finally, we get only 6 adjustable parameters (c_1, c_2, c_3, c_4, h_{eo}, h_{oe}) to describe spontaneous fission for all four classes of nuclei[48].

3 Numerical results and discussions

3.1 Spontaneous fission half-lives

The spontaneous fission half-lives are calculated by the present formula [Eq.(6)] with increasing neutron number for different SHN from Z=104 to Z=112 are shown in Fig. 1. For comparison in Fig. 1 is also given spontaneous fission half-lives from Z=104 to Z=112 with the theoretical prediction results from macroscopic-microscopic model (MMM)[21−22], the self-consistent Hartree-Fock-Bogoliubov (HFB) method[27] with the finite-range and density-dependent Gogny force with the D1S parameter set (GHFB) and the SkM* Skyrme energy density functional (SHFB)[28]. Unfortunately, the macroscopic-microscopic[21−22] and microscopic[27−28] calculations were performed only for even-even SHN, and as we have also considered the even-odd nuclei in this work. The even-odd nuclei are found to have considerably prolonged half-lives based on the experimental results relative to their even-even nuclei neighbours. According to theoretical calculation, the hindrance factor (HF) is typically on the order of 10^5[49]. Here, we use the average hindrance factor to deal with the influence of odd N on the spontaneous fission half-life, *i.e.*, $10^5 = \frac{T_{1/2}(A,N)}{\sqrt{T_{1/2}(A-1,N-1)\times T_{1/2}(A+1,N+1)}}$.

To compare the reliability of using different methods to calculate the spontaneous fission half-lives. We list in Table 1 for spontaneous fission half-lives experiments and calculations by different models. It can be found that the method used herein may be better for the description of spontaneous fission half-life. By comparison of our spontaneous fission half-lives with

http://www.npr.ac.cn

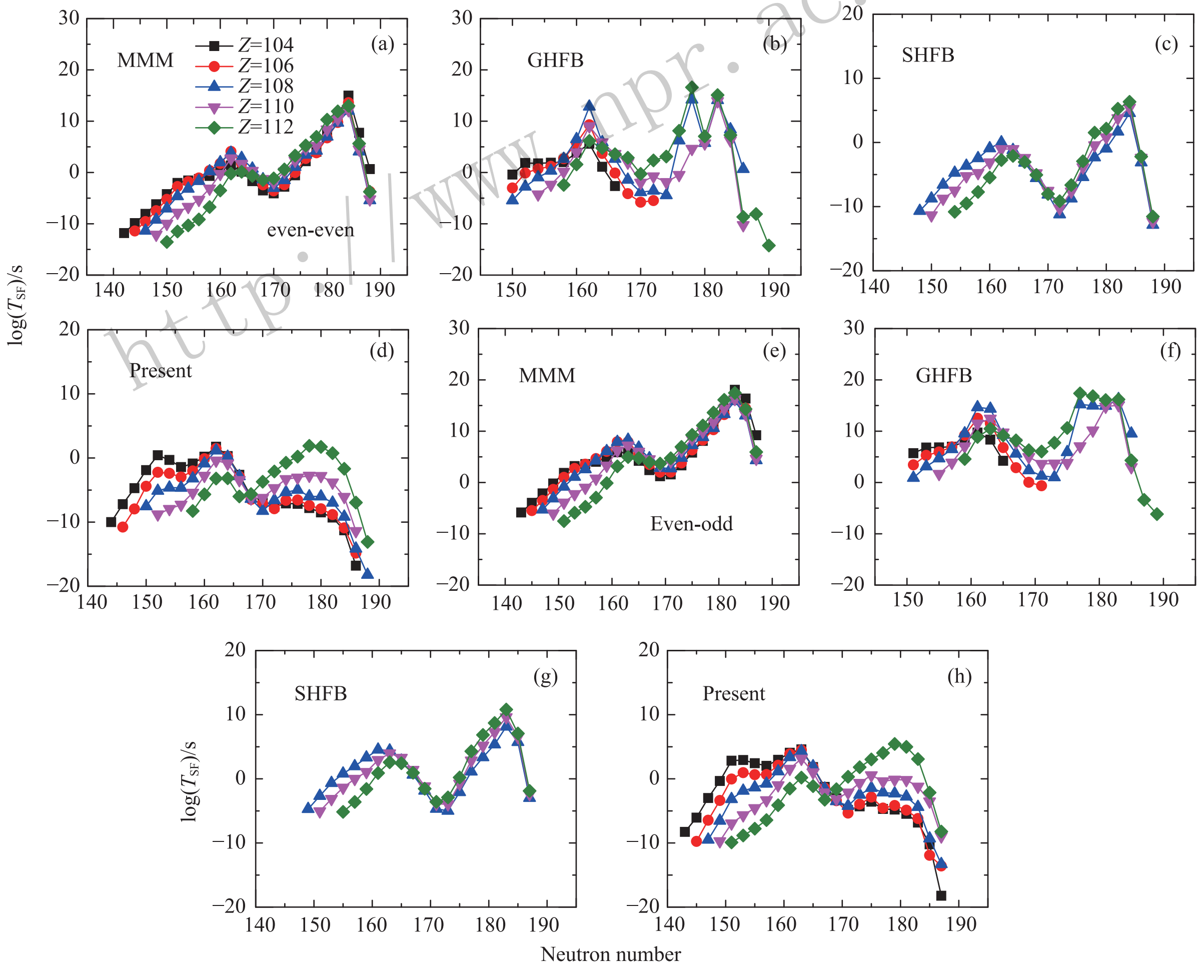


Fig. 1　(color online) Dependence of the logarithm of the calculated spontaneous fission half-lives, given in seconds, on the neutron number N, for superheavy nuclei $Z = 104 \sim 112$.

Table 1 The first column show charge and mass numbers. The other columns given theoretical and experimental spontaneous fission half-lives.

Nucleus	$\log T_{\rm SF}$/s				
	Exp.[48]	MMM	GHFB	SHFB	Present
^{282}Cn	−3.04	−1.15	−0.27	−8.03	−3.70
^{284}Cn	−0.94	0.60	2.36	−9.15	−2.10
^{270}Ds	−1.04	−0.27	3.94	−3.10	−2.77
^{264}Hs	−2.64	−1.67	0.35	−3.64	−4.66
^{258}Sg	−2.44	−2.74	−0.11		−2.23
^{260}Sg	−2.09	−1.79	0.70		−2.40
^{262}Sg	−1.76	−1.07	1.20		−2.99
^{264}Sg	−1.37	0.37	2.68		−2.02
^{266}Sg	−0.30	1.76	5.75		−0.12
^{253}Rf	−4.26	−0.21			−0.34
^{254}Rf	−4.54	−4.22	−0.41		−1.89
^{255}Rf	0.52	1.87	5.72		2.82
^{256}Rf	−2.15	−2.04	1.85		0.43
^{258}Rf	−1.79	−1.56	1.77		−0.31
^{259}Rf	1.68	3.59	6.84		2.43
^{260}Rf	−1.64	−1.27	1.90		−1.41
^{262}Rf	0.38	−0.67	2.03		−0.87

other calculated values, those of Refs. [21–22] (Fig. 1(a,e)), shows that those values are larger than ours by up to about 4-9 orders of magnitude. Also the results (Fig. 1(b,f)) of Ref. [27] are very different from ours. For nuclei with neutron number N close to the magic value $N=162$, the spontaneous fission half-lives of Ref. [27] are larger than ours by up to more than 9 orders of magnitude. There is a relatively good consistency between our calculated results and those obtained in the SHFB[28].

It is known that the spontaneous fission half-life is very sensitive to changes of various quantities appearing in the calculations. This is due to fission barrier height, its width and generally shape, effective inertia appear in the exponent in spontaneous fission tunneling probability P. However, different models give different estimates for the barrier heights, the width of the barriers and the inertial parameter[21–22, 27–28]. For example, a 10% error in either the height of the barrier or in the inertia, or a 5% error in the width of the barrier, corresponds to an error of approximately 10^2 in the calculated spontaneous fission half-life. The total uncertainty from all three sources of error could be as large as 10^{10}[20].

Although there are significant differences in the spontaneous fission half-lives from one model to another, we can obtain the general trend from Fig. 1. It can be seen that a significant increase of stability may be expected in the regions around the magic nuclei. One can see a clear effect of the N=162 shell in the spontaneous fission half-life, for all Z=104∼112 and all models. Due to shells at N=162 neutrons and Z=108 protons were predicted by macroscopic-microscopic model[21–22] as well as self-consistent mean field[27–28]. For Z=104 and 106, also the effect of the lower shell at N=152 is visible in our calculation results. If the neutron number exceed N=162, this will lead to a decrease of the shell effect and to loss of stability. From Fig. 1 it is seen clearly that the extra stability effect of neutron shell at N=162 slowly disappears with the increase of neutron number. Note that for $N\geqslant 172$, the spontaneous fission half-lives rise again, so two additional neutrons in ^{284}Cn, compared with ^{282}Cn, increase fission half-lives by two orders of magnitude. A similar effect is observed from ^{286}Fl to ^{288}Fl[6]. This increase is related to the increase in neutron number toward the N=184 spherical shell closure.

3.2 Predictions of α decay chains in $^{274-291}$Cn and $^{266-287}$Ds

If spontaneous fission half-lives are generally larger than the corresponding α decay half-lives. This indicates that the dominant decay mode of these nuclei is α decay. Our calculated spontaneous fission half-lives of SHN based on the WKB approximation with both the shell effect and the isospin effect included, which works well for the mass region from ^{232}Th to ^{286}Fl[48]. In order to study the influence of the uncertainty of spontaneous fission half-lives on the decay mode. The comparison of spontaneous fission half-lives from Z=104 to Z=112 with the theoretical prediction results from macroscopic-microscopic model[21–22], the self-consistent Hartree-Fock-Bogoliubov (HFB) method[27–28]. Within the GLDM and the new formula evaluating the half-lives of α decay. We study the α decay and spontaneous fission half-lives in chains of $^{277,281-285}$Cn and $^{269-271}$Ds SHN. We list numerical results about the decay modes for these SHN in Table 2. By comparing the half-lives of α decay with those of spontaneous fission, one can identify the decay mode of each nucleus, we find that these studied α decay chains are terminated by the spontaneous fission of corresponding nuclei such as $^{281-285}$Cn and ^{270}Ds. These results are found to be in good agreement with the observed decay modes[10].

As can be seen from the Table 2, the decay modes obtained on the basis of the spontaneous fission half-lives calculated by different theoretical models are generally similar. This seems to be the effect of shells, mainly of that at $N=162$, to which spontaneous fission half-lives is more sensitive than α decay half-lives.

http://www.npr.ac.cn

Table 2 The first column show charge and mass numbers. The other columns given theoretical and experimental decay modes.

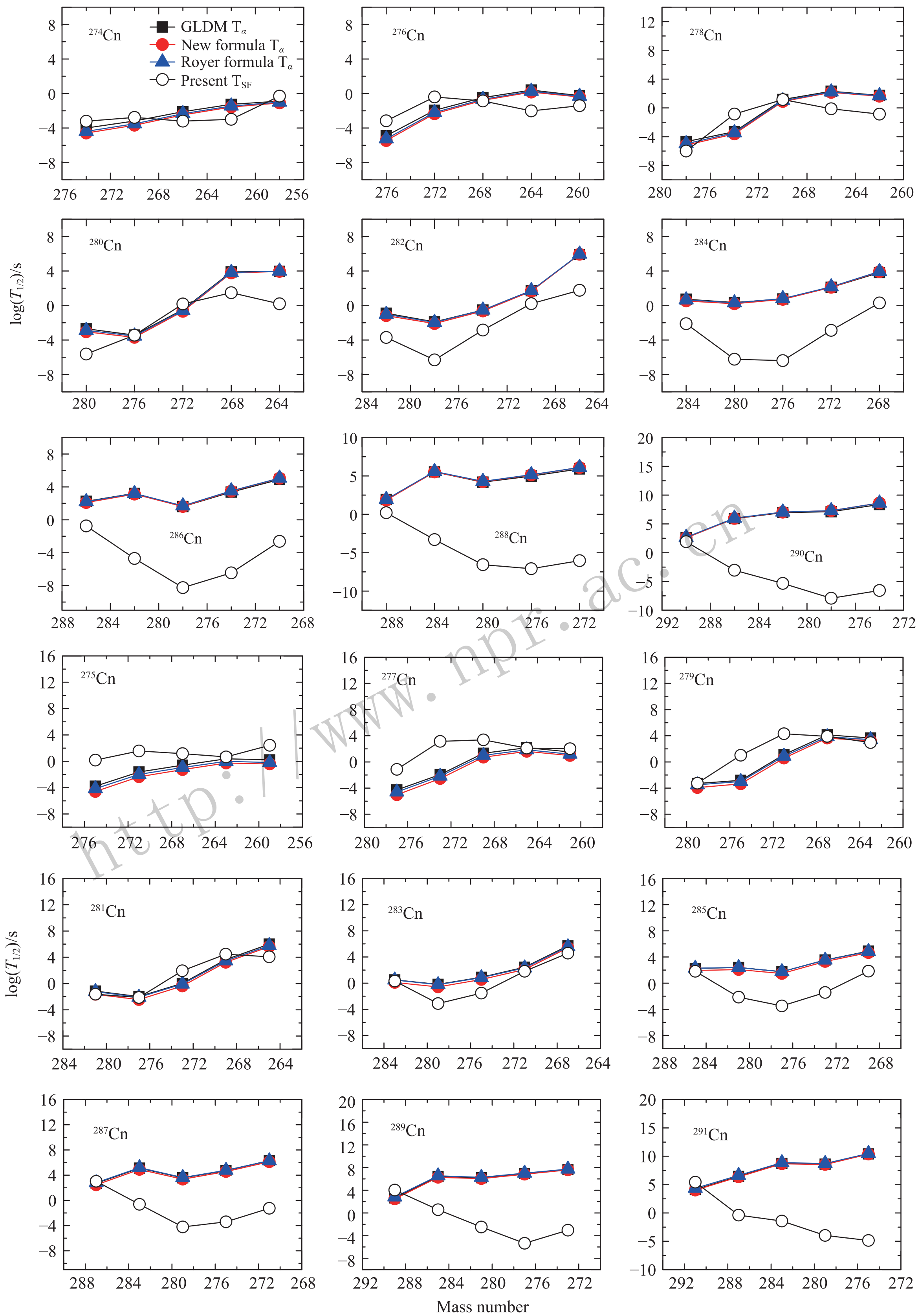
Nucleus	Decay mode				
	Ref. [21–22]	Ref. [27]	Ref. [28]	Present	Exp.
^{285}Cn	α	α	SF	α/SF	α
^{281}Ds	α/SF	α/SF	SF	SF	SF
^{284}Cn	α/SF	α	SF	SF	SF
^{283}Cn	α	α	SF	α/SF	α
^{279}Ds	α	α	α/SF	SF	SF
^{282}Cn	α/SF	α/SF	SF	SF	SF
^{281}Cn	α	α	α/SF	α/SF	α
^{277}Ds	α	α	α	α/SF	α
^{273}Hs	α	α	α	α	α
^{269}Sg	α	α		α/SF	α
^{265}Rf	α/SF	α		SF	SF
^{277}Cn	α	α	α	α	α
^{273}Ds	α	α	α	α	α
^{269}Hs	α	α	α	α	α
^{265}Sg	α	α		α/SF	α
^{261}Rf	α	α		α/SF	α
^{271}Ds	α	α	α	α	α
^{267}Hs	α	α	α	α	α
^{263}Sg	α	α		α/SF	α
^{259}Rf	α	α		α	α
^{270}Ds	α	α	α/SF	α/SF	α
^{266}Hs	α	α		α/SF	α
^{262}Sg	α/SF	α		α/SF	SF
^{269}Ds	α	α	α	α	α
^{265}Hs	α	α	α	α	α
^{261}Sg	α	α		α	α
^{257}Rf	α	α		α	α

Only for the lightest isotopes, spontaneous fission half-lives are shorter than α decay half-lives for all SHNs investigated. The decay modes of practically all synthesized nuclei up to the ^{277}Cn are well explained by model calculations reflecting the effect of the deformed shells Z=108 and N = 162. The spontaneous fission half-life relative to the half-life of α decay, more sensitive to rely on magic number, is mainly due to the following two aspects. It is well known that the shell effect on the α decay is related to the Q_α value. For the α decay of the nuclei being not close to the shell closures, a parent nucleus and its daughter nucleus sharing the same odevity of both the proton and neutron numbers, the shell correction and pairing correction energies to their masses could be canceled to a large extent leading to a small correction to a Q_α value[50]. As for the spontaneous fission, with the increase of the neutron number, the shell correction increases gradually, and the fission probability decreases gradually. The effect of shell effect on the fission probability increases gradually, so it is not like the case of α decay, the shell correction and pairing correction energies to fission barrier could not be canceled.

For some nuclei belonging to α decay chains with deviations as shown in Table 2, the half-lives from the different theoretical models are uncertain by a few times possibly from following reasons. On the one hand, for odd isotope ^{283}Cn, transitions to excited states of the daughter nuclei have been observed[6]. However, it should be noted that these events comprise only a small part. So we may assume that the experimentally observed main decay modes are also connected with transitions between ground states. On the other hand, the limited knowledge of the spontaneous fission half-lives of even-odd (^{281,283}Cn) nuclei in the superheavy mass region, in the present calculations we have accounted for the hindrance factor by always fitting (or choosing) average value. However, the hindrance factor is typically on the order of 10^5 but varies in magnitude between 10 and 10^{10}[49]. Therefore, it is very important to study the spontaneous fission half-lives of the odd-A nuclei based on the microscopic model[51] and the macroscopic microscopic model[52–53].

Fig. 2 and Fig. 3 represent the comparison between the α decay and spontaneous fission half-lives for even-even and even-odd SHN with $Z = 104 \sim 112$. The calculations on the α decay half-lives within new formula and GLDM have been performed by using the theoretical Q_α values[54]. Our computed α decay half-lives for all isotopes with $Z = 104 \sim 112$ are in close agreement with the values calculated using the new analytical formula. The α decay half-lives calculated by using the Royer's formula[44] have been given for comparison. As the isotopes with greater the spontaneous fission half-lives than α decay half-lives survive fission and could be detected through α decay in the laboratory, a comparison of the α half-lives with the corresponding spontaneous fission half-lives leads us to predict the mode of decay and thereby identify the nuclei that will survive fission. From Fig. 2 and Fig. 3 it

http://www.npr.ac.cn



http://www.npr.ac.cn

Fig. 2 (color online) The comparison of the calculated α decay half-lives with the corresponding spontaneous fission half-lives of the isotopes $^{274-291}$Cn and their decay products.

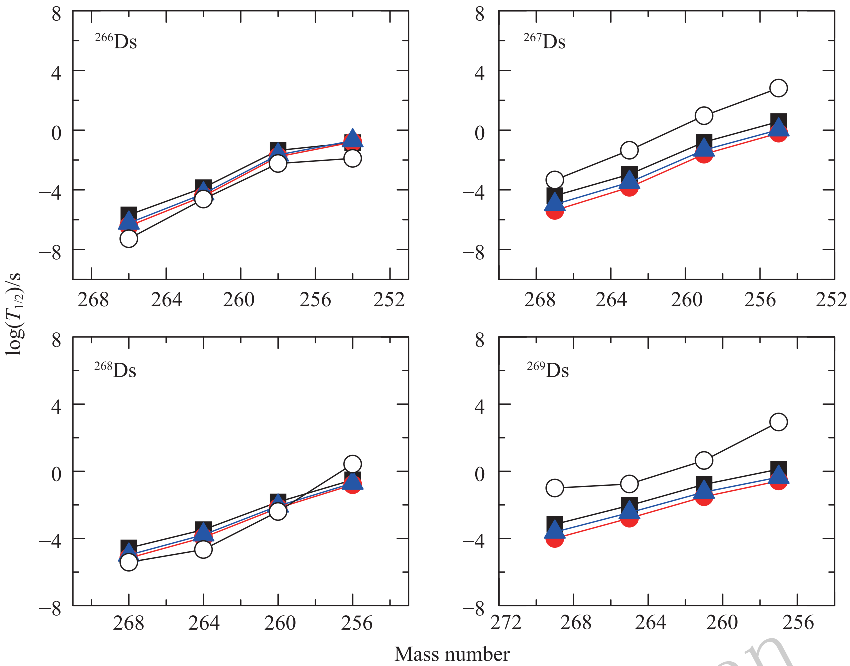


Fig. 3　(color online) The same as Fig. 2, but for $^{266-269}$Ds and their decay products.

can be seen that the SHN $^{274-276,279,286-291}$Cn and $^{267-269}$Ds have shorter half-lives of the α decay than those of the spontaneous fission. These isotopes can be identified in the laboratory via α decay. The most important characteristics limiting the experimental studies of SHN nuclei is not only there decay modes and half-lives but available projectile-target combinations and the corresponding evaporation residue cross sections. The evaporation residue cross sections for synthesizing these nuclei $^{274-276,279}$Cn and $^{267-269}$Ds are predicted within dinuclear system model[12–13]. Therefore, we presume that our study will give motivation to future experiments involving the synthesis of SHN.

4 Summary

In this work we gave a systematic overview of the available experimental data and the calculated decay modes around ^{270}Hs. The spontaneous fission half-lives of SHN are calculated based on the WKB approximation with both the shell effect and the isospin effect included, which works well for the mass region from ^{232}Th to ^{286}Fl. The α decay half-lives are obtained by the a new analytical formula and the generalized liquid drop model (GLDM). The competition between α decay and spontaneous fission is discussed. For the observed α decay chains of $^{277,281-285}$Cn and $^{269-271}$Ds, the calculated results are found to be in good agreement with the experimental data. Decay mode of the isotopes of $^{274-276,279}$Cn and $^{267-269}$Ds are predicted, presuming that this might help to discriminate between all the possible future experiments.

References:

[1] MYERS W D, SWIATECKI W J. Nucl Phys A, 1966, **81**: 1.

[2] SOBICZEWSKI A, GAREEV F A, KALINKIN B N. Phys Lett, 1966, **22**: 500.

[3] ĆWIOK S, DOBACZEWSKI J, HEENEN P H. *et al*. Nucl Phys A, 1996, **611**: 211.

[4] HOFMANN S. Radiochim Acta, 2011, **99**: 405.

[5] MORITA K, MORIMOTO K，KAJI D. *et al*. J Phys Soc Jpn, 2007, **76** 045001.

[6] OGANESSIAN Y T. J Phys G: Nucl Part Phys, 2007, **34**: R165.

[7] OGANESSIAN Y T. Radiochim Acta, 2011, **99**: 429.

[8] DVORAK J, BRUCHLE W, CHELNOKOV M. *et al*. Phys Rev Lett, 2006, **97**: 242501.

[9] BARAN A, POMORSKI K, LUKASIAK A, *et al*. Nucl Phys A, 2016, **361**: 83.

[10] HOFMANN S. J Phys G: Nucl Part Phys, 2015, **42**: 114001.

[11] ANGHEL C I, SILISTEANU I. Phy Rev C, 2017, **95**: 034611.

[12] BAO X J, GAO Y, LI J Q, *et al*. Phys Rev C, 2015, **92**: 034612.

[13] BAO X J, GAO Y, LI J Q, *el al*. Phys Rev C, 2016, **93**: 044615.

[14] XU C, REN Z Z. Phy Rev C, 2006, **74**: 014304.

[15] POENARU D N, PLONSKI I H, GREINER W. Phy Rev C, 2006, **74**: 014312.

[16] PEI J C, XU F R, LIN Z J, *et al*. Phys Rev C, 2007, **76**: 044326.

[17] ISMAIL M, ELLITHI A Y, BOTROS M M. *et al*. Phys Rev C, 2010, **81**: 024602.

[18] WANG Y Z, WANG S J, HOU Z Y, *et al*. Phys Rev C, 2015,

http://www.npr.ac.cn

92: 064301.

[19] GHODSI O N, DAEI-ATAOLLAH A. Phys Rev C, 2016, **93**: 024612.

[20] FISET E O, NIX J R. Nucl Phys A, 1972, **193**: 647.

[21] SMOLAŃCZUK R, SKALSKI J, SOBICZEWSKI A. Phys Rev C, 1995, **52**: 1871.

[22] SMOLAŃCZUK R. Phys Rev C, 1997, **56**: 812.

[23] SWIATECKI W. Phys Rev, 1955, **100**: 937.

[24] XU C, REN Z Z. Phys Rev C, 2005, **71**: 014309.

[25] XU C, REN Z Z, GUO Y Q. Phys Rev C, 2008, **78**: 044329.

[26] KARPOV A V, ZAGREVAEV V I, MARTINEZ PALENZUELA Y, *et al.* Int J Mod Phys E, 2012, **21**: 1250013.

[27] WARDA M, EGIDO J L. Phys Rev C, 2012, **86**: 014322.

[28] STASZCZAK A, BARAN A, NAZAREWICZ W. Phys Rev C, 2013, **87**: 024320.

[29] CHOWDHURY P R, SAMANTA C, BASU D N. Phys Rev C, 2008, **77**: 044603.

[30] POENARU D N, GHERGHESCU R A, GREINER W. J Phys G: Nucl Part Phys, 2013, **40**: 105105.

[31] QIAN Y B, REN Z Z. Eur Phys J A, 2013, **49**: 5.

[32] SANTHOSH K P, SABINA S, JAYESH G J. Nucl Phys A, 2011, **850**: 34.

[33] SANTHOSH K P, PRIYANKA B, UNNIKRISHNAN M S. Phys Rev C, 2012, **85**: 034604.

[34] SANTHOSH K P, PRIYANKA B. J Phys G: Nucl Part Phys, 2012, **39**: 085106.

[35] QIAN Y B, REN Z Z. Phys Rev C, 2014, **90**: 064308.

[36] HILL D L, WHEELER J A. Phys Rev, 1953, **89**: 1102.

[37] ROYER G, REMAUD B. J Phys G, 1984, **10**: 1541.

[38] ROYER G, HADDAD F. Phys Rev C, 1995, **51**: 2813.

[39] ROYER G, ZBIRI K. Nucl Phys A, 2002, **697**: 630.

[40] BONILLA C, ROYER G. Acta Phys Hung A, 2006, **25(1)**: 11.

[41] ZHANG H F, ROYER G, LI J Q. Phys Rev C, 2011, **84**: 027303.

[42] ZHANG H F, DONG J M, ROYER G, *et al.* Phys Rew C, 2009. **80**: 037307.

[43] DONG J M, ZUO W, GU J Z, *et al.* Phys Rev C, 2010, **81**: 064309.

[44] ROYER G. J Phys G: Nucl Part Phys, 2000, **26**: 1149.

[45] BAO X J, ZHANG H F, ZHANG H F, *et al.* Nucl Phys A, 2014, **921**: 85.

[46] BAO X J, GUO S Q, LI J Q, *et al.* Phys Rev C, 2017, **95**: 034323.

[47] WANG M, WAPSTRA A H, KONDEV F G, *et al.* Chin Phys C, 2012, **36**: 1287-1602.

[48] BAO X J, GUO S Q, ZHANG H F, *et al.* J Phys G: Nucl Part Phys, 2015, **42**: 085101.

[49] RANDRUP J, TSANG C F, MOLLER P, *et al.* Nucl Phys A, 1973, **217**: 221.

[50] DONG J M, ZUO W, SCHEID W. Phys Rev Lett, 2011, **107**: 012501.

[51] PEREZMARTIN S, ROBLEDO L M. Int J Mod Phys E, 2009, **18**: 788-797.

[52] MPLLER P, SIERK A J, ICHIKAWA T, *et al.* Phys Rev C, 2015, **91**: 024310.

[53] JACHIMOWICZ P, KOWAL M, SKALSKI J. Phys Rev C, 2017, **95**: 014303.

[54] WANG N, LIU M, WU X, *et al.* Phys Lett B, 2014, **734**: 215.

[55] QI C, XU F R, LIOTTA R J, *et al.* Phys Rev Lett, 2009, **103**: 072501.

[56] NI D D, REN Z Z, DONG T K, *et al.* Phys Rev C, 2008, **78**: 044310.

[57] ZHAO T L, BAO X J, GUO S Q. J Phys G: Nucl Part Phys, 2018, **45**: 025106.

http://www.npr.ac.cn

理论预测超重核 $^{274-291}$Cn 和 $^{266-287}$Ds 的衰变模式

赵天亮，包小军†

（湖南师范大学物理系，长沙 410081）

摘要： 自发裂变和 α 衰变是影响超重核稳定性的两个主要因素。为了探索 ^{270}Ds 附近的长寿命的超重核，系统地计算了电荷数在 $104 \leqslant Z \leqslant 112$ 范围内的 α 衰变与自发裂变之间的竞争。采用推广的液滴模型和唯象的解析公式计算了 α 衰变半衰期。基于包括壳效应和同位旋效应的 WKB 近似方法估算了相同超重核的自发裂变半衰期，进而预测了未知超重核 $^{274-276,279}$Cn 与 $^{267-269}$Ds 的衰变模式。

关键词： 超重核；半衰期；α衰变；自发裂变

收稿日期： 2018-09-12； **修改日期：** 2018-12-05

基金项目： 国家自然科学基金资助项目 (11705055, 11475050)；湖南省自然科学基金资助项目 (2018JJ3324)；湖南省教育厅优秀青年基金资助项目 (17B154)

† **通信作者：** 包小军，E-mail: baoxiaojun@hunnu.edu.cn。