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New Perspective on Properties of Superheavy Nuclei*

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Abstract: Status of theoretical studies on superheavy nuclei is simply reviewed. We investigate the influence of nuclear deformation on half-lives of α-decay for long lifetime nuclei beyond ^{208}Pb. The range of the validity of relativistic mean-field model is analyzed and discussed. The conservation of parity in α-decay, cluster-radioactivity, and spontaneous fission of nuclei is stressed. New views on the properties of superheavy nuclei are presented.

Key words: long lifetime heavy nuclei; nuclear deformation; α-decay; spontaneous fission

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1 Introduction

Experimental methods of nuclear physics play an important role for the identification of new chemical elements in nature. A hundred years ago two elements with $Z=84$ (Po) and $Z=88$ (Ra) were identified due to their strong α radioactivity by M. Curie and P. Curie. Up to date about thirty elements were identified by the observation of α-decay chains from an unknown nuclide to a known nuclide[1-6] which includes the named superheavy elements with $Z=107$--110 (Bh-Ds) and the unnamed ones with $Z\geqslant 111$[1,2]. In China two new nuclides ^{259}Db and ^{265}Bh were synthesized by Gan et al[7,8].

Theoretically it was predicted that there exists a superheavy island in the chart of nuclides in 1960s. It was thought that some superheavy nuclei could be stable for spontaneous fission or have very long half-lives of spontaneous fission. Their half-lives for α-decay (or β-decay) are long enough to observe their existence and to investigate their properties. The half-lives of superheavy nuclei from various models range from μs (10^{-6} s) to 10^4 a. These will be tested by future experiments.

One guess on the cause of the existence of long-lived superheavy nuclei in 1960s is that there is a spherical shell closure at $Z=114$ and $N=184$. It is well known that there are spherical magic numbers **2**, **8**, **20**, **28**, **50**, **82** for protons and **2**, **8**, **20**, **28**, **50**, **82**, **126** for neutrons. The nuclei with magic numbers are more stable than neighboring nuclei according to spherical shell model. It is considered that next double magic nucleus is $Z=114$ and $N=184$ according to some theoretical calculations. Recently there are suggestions from mean-field calculations that $Z=120$, $N=172$, $N=184$, … may be spherical magic numbers for superheavy nuclei.

Although the isotopes with magic proton number are more stable than neighboring isotopes, a different situation can happen for an open-shell nu-

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cleus if there are many valence nucleons outside closed shells. Bohr and Mottelson have pointed out that for configurations with particles outside closed shells, the nucleus can gain energy by deformation[9]. The number of stable nuclides on an isotopic chain of even-Z rare-earth isotopes is as high as 5—6 where many rare-earth nuclei are deformed in their ground states. Beyond the doubly-magic nucleus ^{208}Pb some heavy nuclei such as ^{232}Th, ^{235,236,238}U, ^{244}Pu and ^{247}Cm have very long half-lives of α decay. It is found that there is deformation in their ground states ($\beta_2 \approx 0.26$—0.30)[10]. For heavier nuclei with $Z \approx 100$ and $N \approx 152$ it is known that there is quadrupole deformation $\beta_2 \approx 0.3$ in their ground states and the deformation also leads to the appearance of deformed subshell $N=152$ around $Z=100$. The nuclei with $N=152$ is more stable to spontaneous fission than expected (the branch ratio of spontaneous fission is very smaller than that of α decay). They also have longer half-lives of α decay than expected. For superheavy nuclei with $Z \approx 108$ and $N \approx 162$ various calculations show that there is a deformed subshell and the nuclei in this mass range can have longer half-lives of α decay than expected. Up to now it is unclear whether there is deformed subshell for superheavy nuclei with $Z=114$ or $Z=120$. Some mean-field calculations suggest there is deformation or superdeformation in the ground states of some nuclei on $Z=110$—120 isotopic chains[11-14]. This will be tested by future experiments.

Studies on superheavy nuclei provide an opportunity to see where is the end of the periodic table of chemical elements, to search the long-lived superheavy elements, and to test various nuclear models which are built based on the properties of nuclei near the stable line. In this article we discuss some important problems on current researches of superheavy nuclei. This paper is organized in the following way. Section 2 is an analysis on the experimental half-lives of nuclei. We discuss in Section 3 the parity conservation and octupole deformation of even-even nuclei in the present relativistic mean-field (RMF) model with the σ, ω, and ρ mesons. Section 4 is a short review on spontaneous fission of nuclei. Section 5 is a summary.

2 Long Lifetime Nuclei beyond ^{208}Pb

As we stated in the introduction, ^{232}Th, ^{235,236,238}U, ^{242}Pu, ^{247}Cm are long lifetime nuclei beyond ^{208}Pb. Why these nuclei have abnormally long half-lives of α-decay? We give a detailed explanation in this section.

We list the ground state properties of long-lifetime nuclei beyond ^{208}Pb in Table 1 where the number of long-lifetime nuclides ranges from 1 to 4 for an isotopic chain (the longest-lifetime nuclide of an isotopic chain is included). In Table 1 the first column is the nuclide and the second column is the half-life of the ground state where the half-lives are taken from Refs. [15,16]. The third column is the α-decay energy[15,16]. The spin and parity of the ground states of parent nuclei and daughter nuclei are given in columns 4 and 5[15,16]. The quadrupole deformation parameter of even-even nuclei is listed in column 6 where the data are from Ref. [10]. In the last column we give the branch ratio of α-decay from the ground state of the long-lived nuclide.[15,16].

It is seen from Table 1 that many nuclides have very long half-lives. The half-lives of ^{232}Th, ^{235,236,238}U, ^{244}Pu, and ^{247}Cm can compare with the life-time of the earth. At first let us focus on even-even nuclei in Table 1. It is known experimentally that there is prolate deformation in the ground states of above nuclei. The quadrupole deformation parameters in these nuclei are approximately $\beta_2 = 0.26$—0.29[10]. For odd-A and odd-odd nuclei in Table 1, it is known from the spin and parity of their ground state that they are also well deformed and their deformation parameters are close to those of neighboring even-even nuclei[17]. For example Bohr and Mottelson pointed out there is deformation for ^{237} Np and its deformation parameter $\beta_2 \approx$

Table 1 Ground state properties of long-lived heavy nuclei beyond ^{208}Pb and the ground state spin and parity of their daughter nuclei (J^{π}_{d})

Nuclei	$T_{1/2}$/a	Q_{α}/MeV	J^{π}_{p}	J^{π}_{d}	β_2	α decay/(%)
^{232}Th	1.405×10^{10}	4.082	0^+	0^+	0.261	100
^{231}Pa	3.276×10^{4}	5.150	$(3/2)^-$	$(3/2)^-$		100
^{234}U	2.455×10^{5}	4.858	0^+	0^+	0.272	100
^{235}U	7.038×10^{8}	4.678	$(7/2)^-$	$(5/2)^+$		100
^{236}U	2.342×10^{7}	4.573	0^+	0^+	0.282	100
^{238}U	4.468×10^{9}	4.270	0^+	0^+	0.286	100
^{237}Np	2.144×10^{6}	4.958	$(5/2)^+$	$(3/2)^-$		100
^{239}Pu	2.411×10^{4}	5.245	$(1/2)^+$	$(7/2)^-$		100
^{240}Pu	6.564×10^{3}	5.256	0^+	0^+	0.289	100
^{242}Pu	3.733×10^{5}	4.985	0^+	0^+	0.292	100
^{244}Pu	8.000×10^{7}	4.666	0^+	0^+	0.293	100
^{243}Am	7.370×10^{3}	5.439	$(5/2)^-$	$(5/2)^+$		100
^{245}Cm	8.500×10^{3}	5.623	$(7/2)^+$	$(5/2)^+$		100
^{246}Cm	4.760×10^{3}	5.475	0^+	0^+	0.298	100
^{247}Cm	1.560×10^{7}	5.353	$(9/2)^-$	$(7/2)^+$		100
^{248}Cm	3.400×10^{5}	5.162	0^+	0^+	0.297	92
^{247}Bk	1.380×10^{3}	5.890	$(3/2)^-$(#)	$(5/2)^-$		100
^{249}Cf	3.510×10^{2}	6.296	$(9/2)^-$	$(7/2)^+$		100
^{250}Cf	1.310×10^{1}	6.128	0^+	0^+	0.299	100
^{251}Cf	9.000×10^{2}	6.176	$(1/2)^+$	$(9/2)^-$		100
^{252}Cf	2.645×10^{0}	6.217	0^+	0^+	0.304	97
^{252}Es	1.300×10^{0}	6.790	5^-	6^+		76
^{253}Es	0.056×10^{0}	6.739	$(7/2)^+$	$(7/2)^+$		100
^{254}Es	0.756×10^{0}	6.616	7^+(#)	2^-		100
^{257}Fm	0.275×10^{0}	6.864	$(9/2)^+$(#)	$(7/2)^+$(#)		100
^{258}Md	0.141×10^{0}	7.271	$(8)^-$(#)	7^+(#)		100

0.25 (see Ref. [17]: On ^{237}Np, 266-267; On ^{235}U, 273—274, and Fig. 5-14; On the Nilsson Levels with $N>126$, 225, Fig. 5-5). It is concluded from Table 1 that the long-lifetime nuclei (and the longest lifetime one) have significant deformation in their ground state. Is this an accident coincidence between the longest-lifetime nuclei and nuclear deformation of ground state? We think that this is not an accident coincidence. It shows that deformed heavy nuclei can have very long half-lives. In general deformation can increase the stability of nuclei for open-shell nuclei[9]. The half-lives of nuclei are determined by decay energies and by the ground state properties. When there are enough valence neutrons and protons, deformation can lead deeper binding of nucleons than expected[9]. The half-lives of nuclei can become longer due to this. When nuclear half-lives are determined by α-decay, the influence of deformation becomes very important because the half-lives of α-decay are very sensitive to the variation of decay energy. A small decrease of decay energy can lead to a large increase of half-life because there is an exponential relationship between the half-life and decay energy

$\log_{10}(T_{1/2}) \sim E_\alpha^{-1/2}$.

It is also seen from Table 1 that some odd-A and odd-odd nuclei have long half-lives. In some cases they have the longest half-life on an isotopic chain. Importantly some odd-N nuclei on an even-Z isotopic chain have longer half-lives of α-decay than the neighboring even-N nuclei. Some odd-N nuclei on an odd-Z isotopic chain also have longer half-life than the neighboring even-N nuclei on this chain. This is an interesting phenomenon when the half-life is determined by α-decay. It is related to both the blocking effect of odd-nucleon and the selection rule of favored α-decay on spin and parity. Let us take ^{235}U of Table 1 as an example to see this interesting phenomenon. Although the α-decay energy of ^{235}U is between the decay energy of ^{234}U and the decay energy of ^{236}U, the half-life of ^{235}U is much longer than those of ^{234}U and ^{236}U. Usually the blocking effect of an odd nucleon leads to the variation of the half-life with a few times. Only in some special cases the blocking effect of an odd-nucleon can lead to the variation of the half-life with 10—100 times because of the selection rule of angular momentum and parity in α decay. Here the decay of ^{235}U belongs to one of the special cases where the spin and parity of parent and daughter nuclei are different. Because the ground-state spin and parity of ^{235}U ($J_p^\pi=(7/2)^-$) are different from those of ^{231}Th ($J_d^\pi=(5/2)^+$), the α-decay to the ground state of ^{231}Th is an unfavored transition and this transition only occupies a small component in all modes of α-decay from ^{235}U to various states of ^{231}Th (5%)[18]. Because there is deformation in this mass range, there are many Nilsson levels in the energy spectrum of ^{231}Th. The most important branch in all α-transitions[18] is a favored transition (55%) which occurs between the ground state of ^{235}U ($J_p^\pi=(7/2)^-$) and the excited state of ^{231}Th ($J_{d^*}^\pi=(7/2)^-$) where the excited energy of this state is 0.205 MeV. The decay half-life of ^{235}U is mainly determined by this favored transition. The effective decay energy to this excited state of ^{231}Th is $Q_\alpha^*=4.678-0.205=4.473$ MeV. This leads to that the half-life of ^{235}U is abnormally longer than those of ^{231,236}U. Therefore deformation plays an important role for the abnormally long half-life of ^{235}U. The above argument on the long half-life of ^{235}U is also valid for other nuclei with odd-nucleon where the spin and parity of parent and daughter nuclei are different. For example ^{247}Cm in Table 1 is the longest lifetime nuclide on $Z=96$ isotopic chain. It has a much longer half-life than those of ^{246}Cm and ^{248}Cm. The favored transition (branch ratio: 71%) in all α-transitions of ^{247}Cm is to the excited state of ^{243}Pu with $J_{d^*}^\pi=(9/2)^-$ and with excited energy $E^*=0.402$ MeV[18]. This leads to that ^{247}Cm is the longest lifetime nuclide on $Z=96$ isotopic chain. ^{249,251}Cf have longer half-lives than those of ^{250,252}Cf due to the same cause where ^{251}Cf is the longest lifetime nuclide on $Z=98$ isotopic chain. Therefore deformation plays a crucial role for the long half-life of some odd-A and odd-odd nuclei in this mass range. In the lower part of Table 1 the ground-state spin and parity of some nuclei are unknown and their estimated values by Audi et al[15] are listed with a symbol #. Although we only listed the long lifetime nuclei on $Z=90$—101 isotopic chains in Table 1, the conclusion here can be valid for other mass range such as superheavy nuclei.

It is also known from nuclear data tables[15] that there exist isomers near these long lifetime nuclides. Nuclear deformation leads the splitting of a spherical level into many Nillson levels. Therefore various configurations of nuclei become close in energy and these provide an opportunity for shape coexistence in low excited spectrum. The existence of isomers shows again the importance of deformation in this mass range and shape coexistence leads to the deep binding of many nuclei in general. But for few nuclei it could also lead to the weak binding of a nucleon outside a deformed subshell. The prolate deformation dominates the ground state of these nuclei. This is consistent with previous conclusions.

Nuclear deformation also leads to an exotic phenomenon for the nuclide ^{235}U[17]. On the one hand it has a very long half-life of α decay due to the negative parity in its ground state. This means it is very stable for α decay. On the other hand it is very unstable for artificial fission. A low-energy neutron can leads its fission. This can be associated with the influence of nuclear deformation. There is an isomer with a very low excitation energy for ^{235}U[18]. The properties of this isomer are $E^* = 0.077$ keV, $J^\pi = (1/2)^+$, $T_{1/2} = 26$ min. The spin and parity of both ground state and the isomer state is consistent with quadrupole deformation $\beta_2 \approx 0.25$ for ^{235}U[17]. When we see the variation of the last neutron separation energy with neutron number for odd-N nuclei on U isotopic chain, the separation energy decreases with the increase of neutron number for mass range from ^{231}U to ^{239}U. This is drawn in Fig. 1, from which it is seen that there is a sudden decrease of neutron separation energy at ^{235}U[15]. The possible cause is that deformation leads to a subshell at $N = 142$[17] and the 143th neutron in the ground state of ^{235}U is weakly bound. This can also be seen from the lower part of Fig. 1 that $N = 142$ can be approximately considered as a deformed subshell. There is a very low isomer in ^{235}U ($E^* = 0.077$ keV). The two Nilsson levels with $N = 143$ $J^\pi = (7/2)^-$ and with $N = 145$ $J^\pi = (1/2)^+$ are very close in energy in this mass range. Therefore two neutrons in the ground state of ^{236}U are not weakly bound due to strong configuration mixing of the two levels from pairing interactions. When two neutrons are added on ^{236}U, ^{238}U is formed and it is again normally bound. Because the single particle levels in ^{235}U are dense due to deformation and the last neutron is very weakly bound, a low-energy neutron can lead to the occurrence of artificial fission in ^{235}U.

When ^{235}U is in its ground state, its half-life for α decay is very long. But it is very unstable for artificial fission. This is due to the exotic effect of nuclear deformation. ^{235}U is also very stable for spontaneous fission because its half-life of spontaneous fission ($T_{sf} = (1.8-3.5) \times 10^{17}$ a) is much longer than that of α decay ($T_\alpha = 7.04 \times 10^8$ a). We will discuss this in Section 4 in detail.

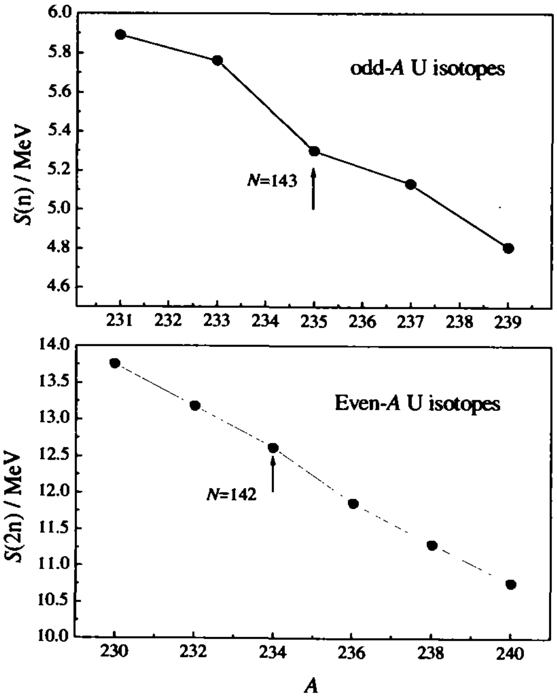

Fig. 1　The variation of the one-neutron separation energy in odd-A U isotopes and the variation of the two-neutron separation energ in even-A U isotopes. A deformed subshell effect appears at $N = 142$.

3　Parity Conservation and Octupole Deformation of Even-even Nuclei in RMF Model

Because there is rare discussion on the odd-multipolarity deformations of even-even nuclei in the published RMF articles, we discuss in this section whether there exist the odd-multipolarity deformations in present RMF model with σ, ω, and ρ mesons. We concentrate our discussions on the octupole deformation which was believed to be the most important one of the odd-multipolarity deformations in nuclei. As the octupole deformation of even-even nuclei is directly related to the asymmetry of space reflection, the existence of static octupole deformation means the non-conservation of parity in nuclei.

In 1956 Lee and Yang[19,20] pointed out that experimental data do indicate parity conservation in strong and electromagnetic interactions to a high degree of accuracy. For the processes related to weak interactions they found there is no experimental evidence of parity conservation. They predicted that there exists the violation of the symmetry of space reflection in β-decay of a nucleus. This is also called as the parity non-conservation of the weak interaction in physics. It was first predicted by Lee and Yang in 1956 and confirmed by Wu et al[21]. In order to explain the parity non-conservation in β-decay, Lee and Yang introduced the axial-vector term (i. e. γ_5 matrix) in the Lagrangian density of the weak interaction[20,21]. Therefore the appearance of the γ_5 matrix in the Lagrangian density is a necessary condition to explain the parity violation in β-decay[20,22]. This is widely accepted and it becomes a part of the Standard Model in nuclear physics and particle physics.

For the strong interactions and the electromagnetic interaction, it is generally believed that parity conserves and there is no parity-violating term in the Lagrangian density or the Hamiltonian. Since 1956 experimental physicists spent much time to try to find the violation of parity conservation in strong interactions (such as nuclear spectrum and nuclear reactions) but they found that parity is conserved to a good precision (10^{-7}) in strong interactions and in the electromagnetic interaction. For an atomic nucleus which is a quantum many-body system with a definite number of protons and neutrons, Mayer and Jensen[23] discussed the problem of the parity and pointed out that the ground states of all nuclei with an even-number of protons and of neutrons have zero angular momentum and even parity. Bohr and Mottelson[24,25] discussed the problem of the parity in nuclei clearly and pointed out that the ground-state rotational band of even-even nuclei is 0^+, 2^+, 4^+, … if there is the symmetry of space reflection and of time reversal. The ground-state rotational band of even-even nuclei will be $0^\pm$, $1^\pm$, $2^\pm$, $3^\pm$, $4^\pm$, … (parity doublets) if parity does not conserve. They stressed that a parity-violating deformation can appear if there is a parity-violating mean-field[25] potential like the term pseudo-scalar interaction. They further pointed out[25] that the absence of parity doublets shows the invariance of space reflection of the intrinsic motion. Bohr and Mottelson[24] concluded from the analysis of experimental data of α-decay and γ-decay that the parity selection rules are obeyed to a high degree of accuracy. It is also pointed out in other textbooks that parity conserves for a nucleus[26,27].

The relativistic many-body problem of nuclei was developed by Serot and Walecka[28]. They found a theoretical description of the relativistic many-body problem within the framework of quantum hadron dynamics (QHD)[28]. The model (QHD-II)[28] contains fields for baryons and four kinds of mesons: the neutral scalar meson(σ), the neutral vector meson(ω), the isovector-vector meson(ρ), and the isovector pseudoscalar meson(π). Of courses the photons are included because there are electromagnetic interactions between protons. A local Lagrangian density with the nucleons, the mesons σ, ω, ρ, π and photons can be constructed[28]. The local Lagrangian density of the RMF model is written as follows[28,29]:

$$\mathcal{L}_{\mathrm{RMF}} = \mathcal{L}_{\sigma\omega\rho} + \mathcal{L}_{\pi}, \tag{1}$$

where the Lagrangian density of the π meson is

$$\mathcal{L}_{\pi} = \frac{1}{2}(\partial_\mu \pi^a \cdot \partial^\mu \pi^a - m_\pi^2 \pi^a \cdot \pi^a) - \frac{f_\pi}{m_\pi}\bar{\Psi}\gamma_5\gamma_\mu \partial^\mu \pi^a \cdot \tau^a \Psi . \tag{2}$$

The Lagrangian density $\mathcal{L}_{\sigma\omega\rho}$ for interacting nucleons, σ, ω and ρ mesons, and photons[28,29]

$$\begin{aligned}\mathcal{L}_{\sigma\omega\rho} = {} & \bar{\Psi}(\mathrm{i}\gamma^\mu \partial_\mu - \mathrm{M})\Psi - \mathrm{g}_\sigma \bar{\Psi}\sigma\Psi - \\ & g_\omega \bar{\Psi}\gamma^\mu \omega_\mu \Psi - g_\rho \bar{\Psi}\gamma^\mu \rho_\mu^a \tau^a \Psi + \\ & \frac{1}{2}\partial^\mu\sigma\,\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_2\sigma^3 -\end{aligned}$$

$$\frac{1}{4}g_3\sigma^4 + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 -$$
$$\frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu -$$
$$\frac{1}{4}R^{a\mu\nu}\cdot R^a_{\mu\nu} + \frac{1}{2}m_\rho^2\rho^{a\mu}\cdot\rho^a_\mu -$$
$$\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - e\bar{\Psi}\gamma^\mu A^\mu\frac{1}{2}(1-\tau^3)\Psi, \quad (3)$$

$$\Omega^{\mu\nu} = \partial^\mu\omega^\nu - \partial^\nu\omega^\mu, \quad (4)$$
$$R^{a\mu\nu} = \partial^\mu\rho^{a\nu} - \partial^\nu\rho^{a\mu}, \quad (5)$$
$$F^{\mu\nu} = \partial^\mu A^\nu - \partial^\nu A^\mu, \quad (6)$$

where the meson fields are denoted by σ, ω_μ and ρ^a_μ and their masses are denoted by m_σ, m_ω and m_ρ respectively. The nucleon field and rest mass are denoted by Ψ and M. A_μ is the photon field which is responsible for the electromagnetic interaction, $e^2/4\pi = 1/137$. The effective strengths of the coupling between the mesons and nucleons are, respectively, g_σ, g_ω and g_ρ. g_2 and g_3 are the nonlinear coupling strengths of the σ meson. c_3 is the self-coupling term of the ω field. The isospin Pauli matrices are written as τ^a, τ^3 being the third component of τ^a.

For the mesons in the Lagrangian density of the RMF model (Eqs. (1—3)), the most important meson is the π meson[28,29]. It carries the quantum number $J=0$, $T=1$ and $P=-1$[28,29]. The equations of motion for the fields are easily obtained from the variational principle[28,29]. In order to describe the ground state properties of even-even nuclei we need static solution of the above Lagrangian. For this case the meson field and photon fields are assumed to be classical fields and they are time independent (c-numbers). The nucleons move in classical fields as independent particles (mean-field approximations). The Dirac field operator can be expanded in terms of single particle wave functions $\Psi = \sum_i \phi_i a_i$ where a_i is a particle creation operator[28,29] and ϕ_i is the single particle wave function. It is useful to stress that nuclear density distributions can be measured directly by electron scattering or by other methods. Up to now the density distributions with symmetry of space reflection are obtained experimentally for even-even nuclei.

In order to obtain the coupled RMF equations of even-even nuclei (the Hartree approximation) from Eq. (1) Serot and Walecka made two important assumptions[28]. They assumed that there are good parity and invariance of time reversal for even-even nuclei[28]. Ring also agreed that these assumptions are right[29]. Reinhard also admitted that nuclear states in the RMF model have definite parity[30]. The above two assumptions are the bases of the RMF formulations and are independent of the methods of numerical calculations. These two assumptions also agree with the experimental facts that there are the good parity and invariance of time reversal for even-even nuclei[24,25]. The π meson is dropped off as the mean-field of the π meson breaks the parity on the Hartree level[28–30]. Preston et al wrote that odd electric moments must vanish if theories are invariant under time reversal or if the system has a definite parity[31]. The RMF Lagrangian (Eq. (3)) is used for the calculations of even-even nuclei by all the persons who worked with the RMF model (Hartree-approximation plus σ, ω, and ρ mesons). This was well stated in the review articles[28–30]. The force parameters of the RMF model are obtained by fitting the ground state properties of even-even spherical nuclei and the properties of infinite nuclear matter. This confirms again that no parity-violating interaction is introduced in the RMF Lagrangian density (Eq. (3)) because parity is a good quantum number for spherical nuclei. Under these assumptions only three mesons σ, ω_0, and ρ_{00} enter the coupled RMF equations for spherical nuclei. Under these assumptions also the three mesons σ, ω_0, and ρ_{00} enter the coupled RMF equations for axial-deformed nuclei. These assumptions guarantee the same force parameters can be used both for spherical cases and deformed cases. When one of these basic assumptions breaks, the force parameters fitted from spherical nuclei can not be used for axial-deformed nuclei because the number of the mesons entering the RMF equations is larger than three. By the way the definitions of quantities such as the operators of electric multipole moments and the operator of particle number are based on the definite parity of nuclear wave function in the RMF model. For example the operator of particle number is related to the density distribution of nucleons in the mean-field model and the density distribution is related to the square of the single particle wave function. When the single particle wave function has a definite parity, the nuclear density is a scalar under space reflection.

In order to obtain the ground state of even-even nuclei by the self-consistent iteration of the RMF equations one usually starts from an initial wave function with zero angular momentum and even parity (0^+). Therefore one always gets a final converged solution with even parity if his numerical calculations are right. If there is no conservation of parity in the final solution, we have to ask which interaction leads to the violation of the symmetry of space reflection. One should notice that a small component of parity-violating strong interaction will leads to a huge effect of the parity-violating phenomenon in β decay. This is because the strong interaction is much stronger than the weak interaction in nature.

For the RMF calculation without constraint one minimizes a parity-conservation Hamiltonian $H_{\rm RMF}$ to obtain the ground state solution of a nucleus. For the constraint RMF calculation on quadrupole moments (Q_{20}) one minimizes a new Hamiltonian $H' = H_{\rm RMF} - \lambda_{\rm constr} \cdot Q_{20}$ (linear constraint or square constraint) to obtain the variation of the energy with quadrupole deformation parameter. For the constraint on quadrupole moments (Q_{20}) parity should conserve for both Hamiltonians. One must be very careful to carry out numerical calculations for new Hamiltonian because two Hamiltonians are not exactly equivalent. In order to get the right solution to describe the variation of the energy with deformation parameters the basic symmetry (such as the conservation of parity ...) of the old Hamiltonian $H_{\rm RMF}$ must be kept during each iteration process of the new Hamiltonian. Because there is no parity-violating interaction in the RMF Hamiltonian ($H_{\rm RMF}$), the solution with the conservation of parity from the new Hamiltonian(H') is a physical solution. Therefore the solution of the ground state of even-even nuclei in the present RMF model has even parity. The even parity must be kept for the whole energy curve of the new Hamiltonian (the variation of the energy with deformation parameter). An energy curve is interesting if the basic quantum numbers such as parity and angular momentum are same in each point of the curve (except energy).

This is well known in the non-relativistic calculations with harmonic potential plus various potentials. One obtains the quadrupole deformation and hexadecapole deformation with a potential

$$V = \frac{1}{2}\hbar\omega_0(\varepsilon_2, \varepsilon_4)\rho^2(1 + c_1\varepsilon_2 Y_{20} + c_2\varepsilon_4 Y_{40} + c_3 L\cdot S + c_4 L^2), \qquad (7)$$

where Y_{lm} is the spherical harmonic function. c_1, c_2, c_3, and c_4 are constants. ε_2 and ε_4 are quadrupole and hexadecupole deformations, respectively. The conservation of parity was kept for the calculations of even-even nuclei with the above potential. In order to obtain the solution with octupole deformation one has to introduce a parity-violating potential Y_{30}. As realistic two-body interactions from the low energy data of two nucleon systems conserve parity, the important deformation besides quadrupole deformation is the hexadecupole deformation in the ground state of even-even nuclei. The effective mean-field interaction should be the main part of the sum of realistic two-body interactions. This is written in textbooks and in papers[25,26].

There were some wrong statements on the constraint mean-field calculations in some references (we do not cite these references in this paper). It was written that all other deformations in constraint calculations are included automatically if one made a constraint on the quadrupole moments (Q_{20}) on the old Hamiltonian (H_{MF}). This is wrong because the symmetry of the old Hamiltonian (H_{MF}) must be kept for the constraint calculations. If there is no parity-violating interaction in the old Hamiltonian of even-even nuclei, there is no odd-multipolarity deformation in the correct solution of the constraint mean-field calculations. Even if there exists the configuration without the symmetry of space reflection in even-even nuclei, the present RMF model can not describe this configuration because there is no parity-violating interaction in the present RMF model (Hartree approximation $+\sigma$, ω, and ρ). Parity conservation of even-even nuclei is also an important assumption of the RMF model when the π meson is dropped off from the RMF Lagrangian density.

There is no parity-violation interaction in the present RMF model with nucleons, the mesons σ, ω, and ρ, and photons. Any small component of the parity-violating strong interactions in a relativistic Lagrangian will destroy the widely accepted β decay theory which is controlled by the parity-violating weak interactions in the Standard Model. This is because the strength of strong interactions is much stronger than the weak interaction and the β decay is directly related to the atomic nucleus.

Although there were studies on the possibility of octupole deformation in the ground state of nuclei since 1960s, it was concluded that the octupole deformation in the ground state of even-even nuclei is approximately zero [32-34]. Up to date there is no clear experimental evidence on the existence of the octupole deformation in the ground states of even-even nuclei and in the superdeformed rotational band of even-even nuclei (lowly excited states) or low-excited isomeric states. This is also why the octupole deformation is not included in the ground states of nuclei[35,36] even if it is easy to introduce the parity-violating potential Y_{30} in non-relativistic calculations.

We believe that parity conservation is true in various nuclear processes which are governed by strong interactions and electromagnetic processes. Even if there exists the configuration without the symmetry of space reflection in a very rare case, the present RMF model can not describe this configuration because there is no parity-violating interaction in the present RMF model and the conservation of parity of even-even nuclei is a basic assumption of the present RMF model with the σ, ω, and ρ mesons. In the following RMF calculations we restrict the calculations of even-even nuclei to the axial deformation with even-multipolarity deformations. This is the natural space of the standard RMF model. Lalazissis et al[37] also restricted the deformed RMF calculations to these cases when they calculated the energy surface of ^{192}Hg and ^{194}Hg. In the standard RMF model, one can not obtain static octupole deformation of even-even nuclei because there is no parity-violating term Y_{30} in the RMF Lagrangian and parity conservation of even-even nuclei is a basic assumption in the RMF model.

The variation of energy with quadrupole deformation parameter β_2 for a superheavy nucleus ^{290}114 is drawn in Fig. 2. The minima of Fig. 2 correspond to different solutions. This clearly exhibits the shape coexistence of a superheavy nucleus. It is seen from Fig. 2 that there is a solution with superdeformation. This solution is the lowest in energy and it can be the ground state of this nucleus. This is a theoretical prediction in the RMF model with TMA force. It is one of the various possible shapes in the ground state of superheavy nuclei. Whether this prediction is right for ^{290}114 will be tested by future experiments of superheavy nuclei. There are two ways to test this prediction. One is to measure the rotational band and another is to search the isomers in this nucleus[38]. If this prediction is right, it will promote the synthesis of superheavy nuclei because the reaction cross-section can be increased due to deformation. The half-lives of superheavy nuclei can be also longer than expected. If it is wrong, it does not matter because it only shows that the superdeformed solution in the RMF model is not an unphysical solution. This is also helpful to improve the RMF model and to cure the deficiency of the model. The path of development of physics is based on both successful and unsuccessful explorations from theoretical and experimental physicists.

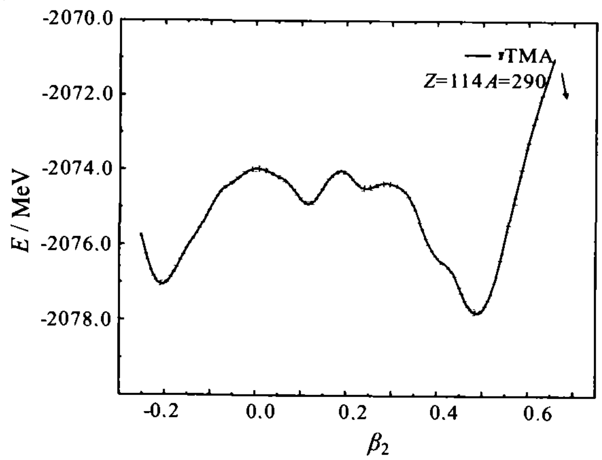

Fig. 2 The variation of the energy of the nucleus $^{290}114$ with the quadrupole deformation parameter β_2 in the constraint RMF model with TMA. The ground state of $^{290}114$ can correspond to a configuration with superdeformation deformation. The superdeformation is suitable for nuclear stability from the point of view of energy.

Up to date we do not know whether the RMF model can be applied for calculations of static fission barrier in heavy and superheavy nuclei. Someone called the maximum height of the energy curve (such as in Fig. 2) as the height of fission barrier. We are not sure whether this is right for the RMF model. In the mean-field model there is a very basic assumption on the existence of a single mass center of a nucleus and this mass center is the central point of the mean-field. The space coordinates of all nucleons and the motions of particles are defined with reference to this central point. The mean-field is also defined with reference to this central point. On the one hand fission is a splitting of a nucleus (a single mass center) into two fragments or more fragments (two or more mass centers). The validity of the RMF model (a single mass center) for fission (two or more mass centers) is unknown. In principle the height of fission barrier is different for different mass and charge combination of two fragments. In the RMF calculation the charge and mass numbers of two fragments have not been taken into account. So we are not sure that the maximum height of the energy curve in the constraint RMF model is the fission barrier. On the other hand the force parameters of the RMF model are obtained by fitting the ground state properties of nuclei (binding energies and radii of some spherical nuclei). The nuclei near the barrier of fission lie in highly excited states. We do not know whether we can extrapolate the RMF model from the ground state to the highly excited states.

4 Parity Conservation in Spontaneous Fission of the Ground State of Nuclei

Fission is important for nuclear stability. For nuclear fission we should classify the two types of fission: (1) the artificial fission which is induced by photons, neutrons, and α particles; (2) the spontaneous fission. These two kinds of fission have different mechanisms in physics. Bohr and Wheeler[39] proposed a liquid drop model to explain artificial fission. For artificial fission one can trace the fission path where the nucleus is gradually excited to the highly-excited states with different symmetry and different shapes (or a formation of compound nucleus). One can see the variation of nuclear shape in highly excited states. When the excited energy is higher than the static fission barrier, various fission channels are gradually possible but some fission channels are observed due to the competition of the fission channels and of the symmetry (for real processes of fission different fission channels have different fission barriers due to the different combination of charge number and mass number of two fragments). The shell effect can influence the mass distributions of fragments. The parity of even-even nuclei does not conserve on the artificial fission path from the ground state of even-even nucleus to the highly excited states and to the appearance of two separate fragments due to the outside interaction. The exotic shape such as octupole deformation may appear near the outer barrier of artificial fission although the lowest-energy state (i. e. the ground state or the fission isomer in the superdeformed well) is symmetric for space reflection. Bohr and Mottelson pointed out the isomeric minimum of heavy nuclei is stable for octupole deformation because there is no parity-violating potential[25].

For spontaneous fission of even-even nuclei in the ground state it is a pure quantum tunnelling effect[40—43]. When an even-even nucleus is in its ground state, it has definite spin and parity. It can never increase its energy automatically without outside interactions (the conservation of the energy). Its parity does not change without outside interactions (conservation of parity). It is known from quantum mechanics that a microscopic particle has dual properties: wave and particle. It is due to the wave property of a microscopic particle that the quantum tunnelling effect can happen. Because the microscopic particle is a probability wave during spontaneous fission process (i. e. quantum tunnelling process), there is no meaning to talk about the shape of a microscopic particle (the kinetic energy of a particle is negative under the fission barrier according to classical mechanics). Therefore the spontaneous fission, α decay, cluster radioactivity (^{14}C, …) and proton emission belong to the same mechanism in physics: quantum tunnelling effect. The α decay, cluster radioactivity, and proton-emission are the extreme asymmetry spontaneous fission. The occurrence of asymmetry spontaneous fission in the ground state of even-even nuclei is independent of static octupole deformation (a spherical even-even nucleus can have α decay). It is well known that the parity conserves for α decays between the states of two even-even nuclei. For α decays one never talk about the path of the decay because it is a pure quantum tunnelling effect. Experiment physicists have never observed the shape of the α particle when it is in the intermediate tunnelling process of the decay. For spontaneous fission, α decay, cluster radioactivity, and proton emission, it is widely accepted that the barrier is mainly controlled by the Coulomb interaction (the strong interaction plays a partial role).

Spontaneous fission from the ground state of the even-even nuclei is a nuclear process which is governed by strong interactions and the Coulomb interaction. Parity should conserve in spontaneous fission. When Wheeler discussed the spontaneous fission, he pointed out that parity conserves in the process of the spontaneous fission[11]. Johansson stressed this again[43]. Vandenbosch and Huizenga clearly pointed out that both spin and parity should conserve in spontaneous fission of even-even nuclei and odd-A nuclei[44] where fission starts from the ground states of nuclei. The even parity is kept for even-even nuclei in spontaneous fission as the ground state of even-even nuclei has even-parity. Bohr and Mottelson also pointed out the isomeric minimum of heavy nuclei is stable for octupole deformation because there is no parity-violating potential[25]. Based on these we consider that parity should conserve for spontaneous fission from the ground state of even-even nuclei (even parity). The conservation of parity forbiddens the occurrence of static octupole deformation in spontaneous fission of even-even nuclei as the static octupole deformation is related to asymmetry of space reflection. It is well known that parity conservation is valid for α-decay and γ-transitions of nuclei. Parity conservation should be also valid for cluster radioactivity (^{14}C, ^{24}Ne, …). It is interesting to test experimentally the conservation of parity for cluster radioactivity of heavy nuclei in order to confirm the parity conservation in these process which are governed by strong interactions and the Coulomb interactions.

The half-lives of nuclear spontaneous fission can be measured by experiments. Some data of the half-lives of spontaneous fission have been accumulated up to date. The half-lives of spontaneous fission of $Z=90$, 92, 94, 96, and 98 are listed in Table 2 where the data are from Ref. [44]. In Table 2 an average value of data from different groups is presented for a given nuclide.

Table 2 Half-lives of spontaneous fission of even-*Z* isotopic chains

Nuclei	T/a	Nuclei	T/a	Nuclei	T/a
^{230}Th	$\geqslant 1.5\times10^{17}$	^{232}Th	$\geqslant 1\times10^{20}$	^{232}U	$(8\pm5.5)\times10^{13}$
^{233}U	$(1.2\pm0.3)\times10^{17}$	^{234}U	1.6×10^{16}	^{235}U	$(1.8—3.5)\times10^{17}$
^{236}U	2×10^{16}	^{238}U	$(0.58—1.3)\times10^{16}$	^{236}Pu	3.5×10^{9}
^{238}Pu	$(5\pm0.6)\times10^{10}$	^{239}Pu	5.5×10^{15}	^{240}Pu	$(1.2—1.45)\times10^{11}$
^{242}Pu	$(6.5—7.45)\times10^{10}$	^{244}Pu	$(2.5\pm0.8)\times10^{10}$	^{240}Cm	1.9×10^{6}
^{242}Cm	7.2×10^{6}	^{244}Cm	1.4×10^{7}	^{246}Cm	$(1.66—2.0)\times10^{7}$
^{248}Cm	$(4.2—4.6)\times10^{6}$	^{250}Cm	2×10^{4}	^{246}Cf	$(2.1\pm0.3)\times10^{3}$
^{248}Cf	$(0.7—4.1)\times10^{4}$	^{249}Cf	$\geqslant 2\times10^{9}$	^{250}Cf	$(1.5\pm0.5)\times10^{4}$
^{252}Cf	$(6.6—8.5)\times10^{1}$	^{254}Cf	0.16		

It is found that ^{235}U has the longest half-life of spontaneous fission in available data of U isotopic chain. ^{239}Pu also has the longest half-life of spontaneous fission in available data of Pu isotopic chain. ^{249}Cf has the longest half-life of spontaneous fission in available data of Cf isotopic chain. This fact confirms that spontaneous fission is a quantum effect where even-odd effect in pairing correlations plays an important role. It also indicates that there are selection rules of parity and angular momentum in spontaneous fissions because the even-odd effect is very strong. If the parity and spin of the nuclear ground state does not conserve on the path of spontaneous fission, the blocking effect of odd-nucleon will be very small and the half-lives of odd-N nuclei in even-Z isotopic chain will be close to the neighboring even-even nuclei on this chain. **Therefore available data of spontaneous half-lives clearly show that the conservation of parity should be kept to describe spontaneous fissions where a quantum tunnelling effect happens.** One should also differentiate the artificial fission and spontaneous fission because they have different mechanism in physics.

Why an odd-A nucleus ^{235}U has the longest half-life of spontaneous fission on U isotopic chain ? Newton[42] and Wheeler[41] considered that both spin and parity of nuclei should conserve in the process of spontaneous fission. Johansson also stressed this[43]. Therefore odd nucleon has a blocking effect in spontaneous fission as compared with even-even nuclei. This leads to an increase of spontaneous fission barrier. Therefore the odd-A nuclei can have longer half-lives of spontaneous fission than those of neighboring even-even nuclei.

5 Summary

In this paper we have discussed the relationship between nuclear stability and nuclear deformation. It is found that the long-lived nuclides on $Z=90—101$ isotopic chains have significant deformation in their ground states. Therefore deformed heavy nuclei can have long half-lives. When the half-lives of nuclei are determined by α decay, some odd-N nuclei can have longer half-lives than those of even-N nuclei on an isotopic chain. Nuclear deformation can also lead that the half-life of an odd-A nuclide or an odd-odd nuclide is the longest one on an isotopic chain. Especially the very long lifetime of ^{235}U is analyzed and discussed. This analysis can be useful for future researches of superheavy nuclei where the half-lives are mainly determined by α decay and by spontaneous fission.

The conservation of parity is stressed in RMF model. The conservation of parity is also stressed in α-decay, cluster-radioactivity, and spontaneous fission of nuclei starting from nuclear ground state where they are governed by strong interactions and the Coulomb interactions. We clearly point out that one should notice the difference between artificial fission and spontaneous fission. For spontaneous fission of nuclei from the ground state one should keep the conservation of parity in theoretical calculations of the ground state of even-even nuclei or in description of spontaneous fission. The theoretical results with conservation of parity can be compared with experimental data and have meaning in physics. It is also proposed that an experiment to test the conservation of parity in cluster radioactivity such as ^{14}C or ^{24}Ne is useful for deep understanding of the role of parity in nuclear process.

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超重核性质的新观点*

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摘 要：简单回顾了超重核的理论研究现状，讨论了形变对长寿命重核 α 衰变半衰期的影响。分析了相对论平均场模型的有效范围。强调了 α 衰变、结团放射性和自发裂变中应保持宇称守恒。提出了一些新观点。

关 键 词：长寿命重核；核形变；α 衰变；自发裂变

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