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Stability of super heavy nuclei associated with the updated nuclear data*

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Abstract: The stability of super heavy nuclei (SHN) from Z=104 to Z=126 is analyzed systematically, associated with the following theoretical mass tables: FRDM2012 [At. Data Nucl. Data Tables 109-110(2016)], WS2010 [Phys. Rev. C 82, 044304(2010)], WS-LZ-RBF [J. Phys. G: Nucl. Part. Phys. 42, 095107(2015)] and the updated experimental data AME2016 [Chinese Physics C 41, 040002(2017)]. The nucleus with the biggest mean binding energy in each isotopic chain shows systematic regular behavior, indicating that the mean binding energy is a good criterion to classify SHN by their stability. Based on binding energy, the α-decay energy Q_α, two-proton separation energy S_{2p}, and two-neutron separation energy S_{2n} are extracted and analyzed. It is found that N=152 and N=162 are sub-magic numbers, $N = 184$ is a neutron magic number, and $Z = 114$ is a proton magic number, which may provide useful information for the synthesis and identification of SHN.

Keywords: super heavy nuclei, mean binding energy, α-decay energy

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1 Introduction

The existence of the island of super heavy nuclei (SHN) has attracted considerable attention since the 1960s [1]. In the last three decades, SHN with Z = 107–112 have been successfully synthesized by using cold fusion reactions at the GSI laboratory [2, 3], while SHN with $Z = 113-118$ have been synthesized by using hot fusion reaction at Dubna and RIKEN [4–10]. Investigations of the properties of these nuclei and exploring the position of the island of stability of SHN are extremely fascinating, and can help us to understand new nuclear features as well as the mass and charge limitations.

It is well known that the binding energy plays an important role in nuclear stability. With rapid development in theoretical methods, many models can reproduce the measured nuclear mass systematically to an excellent precision. These models include the Hartree-Fock-Bogoliubov (HFB) mass model [11, 12], the finite-range droplet model (FRDM) [13] and the Weizsäcker-Skyrme (WS) model [14–16]. The models have different prediction abilities, but in general, with the growing understanding of nuclear properties, the precision of the theoretical predictions has been continuously improved. Recently, a WS-type model which considers isospin, mass and deformation dependence, as well as mirror nuclei constraints and residual corrections, has been further developed. Strutinsky's method [17] is employed to deal with the shell and pairing effects simultaneously [18], which has greatly improved the precision of the theoretical calculation. More precise estimations for nuclear mass can be very helpful to explore the magic numbers for SHN. However, modern theoretical models disagree on the positions of the magic numbers. In Refs. [19, 20], Z=114 and N=184 are predicted to be the shell closures by the macroscopic-microscopic method (MMM) and its modification [21–24]. Z=124, 126 and N=184 were predicted to be the magic numbers by Skyrme-Hartree-Fock and Z=120, N=172 and Z=120, N=184 were predicted by the relativistic mean field model [25–29]. In short, different models give different properties of SHN, and even the same model with different interactions might give different predictions.

The mean binding energy (B_{bind}), the α-decay energy (Q_α), and the nucleon separation energy are the fundamental physical quantities which define a SHN. The nucleus with the maximum B_{bind} or the minimum Q_α of an isotopic chain is the most stable against α decay in

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that chain. The nucleon separation energy can provide us with useful information on the evolution of isotopic chains or isotonic chains as well as being a key input for theoretical studies on the origin of the heavy nuclei. So the motivation of this work is to explore the island of stability or the doubly magic nuclei in terms of these physical quantities for super heavy nuclei (SHN) from $Z=104$ to $Z=126$ associated with the updated experimental data AME2016, as well as the newest theoretical predictions.

2 Mean binding energy of even-even isotopic chains from $Z=104$ to 126

The mean binding energy is a good criterion to classify SHN by their stability. Figure 1 gives $B_{\rm bind}$ for a set of even-even nuclei of isotopic chains from $Z=104$ to $Z=126$ based on the four data tables FRDM2012 [32], WS2010 [15], WS-LZ-RBF [31], and AME2016 [30]. For these isotopic chains, the nuclei with the maximal $B_{\rm bind}$ are shown in Table 1. The numbers of the first column are proton numbers from 104 to 126, and the numbers of the rest of the columns are the neutron numbers of the most stable nuclei, which come from the three models by comparing $B_{\rm bind}$, corresponding to the proton number of the first column. The nucleus with the maximum $B_{\rm bind}$ in each of the isotopic chains from WS-LZ-RBF is more consistent with the experimental data than the other two theoretical calculations, indicating that the WS-LZ-RBF model is better able to reproduce the experimental data than the other two models.

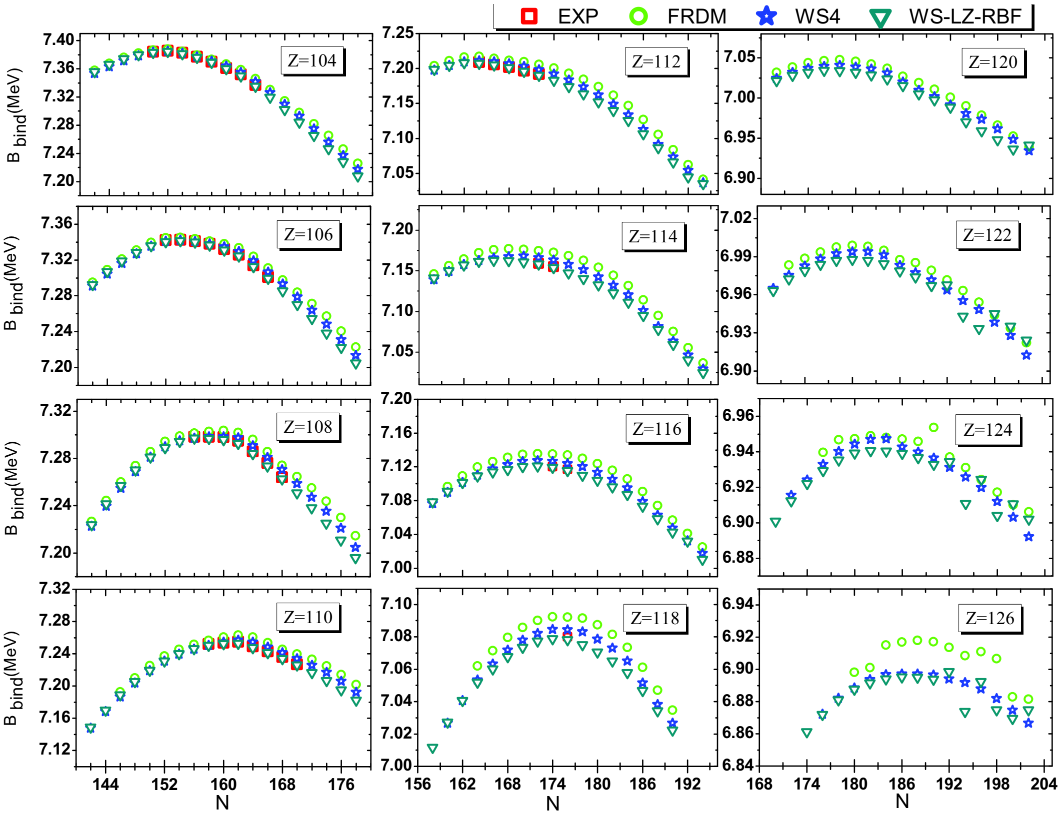

Fig. 1. (color online) The mean binding energy $B_{\rm bind}$ of isotopic chains from $Z=104$ to $Z=126$. The red squares show the experimental data. The green circles, blue stars and dark cyan triangles show the theoretical results calculated from FRDM (2012), WS4, and WS-LZ-RBF, respectively.

Table 1. The neutron number of the stable nucleus for isotopic chains $Z=104\sim126$ from the three theoretical models and experimental data.

models	104	106	108	110	112	114	116	118	120	122	124	126
FRDM	152	154	160	162	164	168	172	174	178	180	190	188
WS4	152	154	160	162	164	170	172	174	178	182	184	188
WS-LZ-RBF	152	154	156	162	164	166	172	174	176	180	182	186
EXP	152	154	156	162	164	172	174	176	–	–	–	–

For the isotopic chains of $Z=104$, 106, 110 and 112, the most stable nuclei are the same against the biggest $B_{\rm bind}$ from the three theoretical mass tables and the experimental data. The corresponding neutron numbers are 152, 154, 162 and 164, respectively. For $Z=108$ isotopes, the most stable nucleus associated with $B_{\rm bind}$ from FRDM and WS4 is ^{268}Hs, but the most stable nucleus from WS-LZ-RBF is ^{264}Hs, which is consistent with the results from experiment. This difference is mainly due to WS-LZ-RBF adopting the conventional Strutinsky method to first evaluate shell and pairing effects simultaneously, then including the RBF approach.

For the isotopic chain of $Z=114$, none of the theoretical calculations can reproduce the experimental results, and actually there is not enough experimental data to select the most stable nucleus. For the isotopic chains of $Z=116$ and $Z=118$, the three theoretical models predict the most stable nuclei are ^{288}116 and ^{292}118, respectively. These could be synthesized in near future experiments since they not only have relatively large predicted cross sections but also can be identified via α-decay chains [33].

3 Q_α of even-even nuclei for $Z=104$ to 126 isotopic chains

Nuclei with magic nucleon numbers should be relatively stable against α-decay, as they have smaller Q_α than that of neighboring nuclei. Figure 2 shows Q_α for even-even nuclei in the isotopic chains $Z=104\sim126$. When $Z=104,106,108$, $N=152,162,184$, the Q_α decreases sharply, implying the neutron magic number may be located at $N=152,162,184$ for those isotopes. For $Z=110,112,114$, however, neutron magic numbers only exist at $N=162$ and $N=184$. For $116\leqslant Z\leqslant120$, only $N=184$ shows an obvious sharp decrease. If we check the figure carefully, we find that $N=178$ also shows the similar, but weaker behavior, which indicates that $N=178$ may be a sub-magic number, but this phenomenon is inconspicuous.

Up to now, many models have shown that $Z=114$ is a proton magic number [19, 20, 25]. In this isotopic chain, it is shown that Q_α decreases with increasing neutron number up to $N=162$, after which Q_α increases rapidly. The increment is about 1 MeV between $N=162$ and $N=164$. Then it decreases again until $N=184$. When $N=186$ the Q_α increases sharply and then decreases with increasing neutron number. So it is clearly demonstrated that $N=162,184$ are neutron magic numbers against α-decay and that ^{276}114, ^{298}114 are double magic nuclei.

For the isotopic chain of $Z=118$, in the region of $N=168$ to 186, Q_α from WS-LZ-RBF decreases with increasing neutron number up to $N=184$. Q_α from WS4 decreases with increasing neutron number up to $N=178$

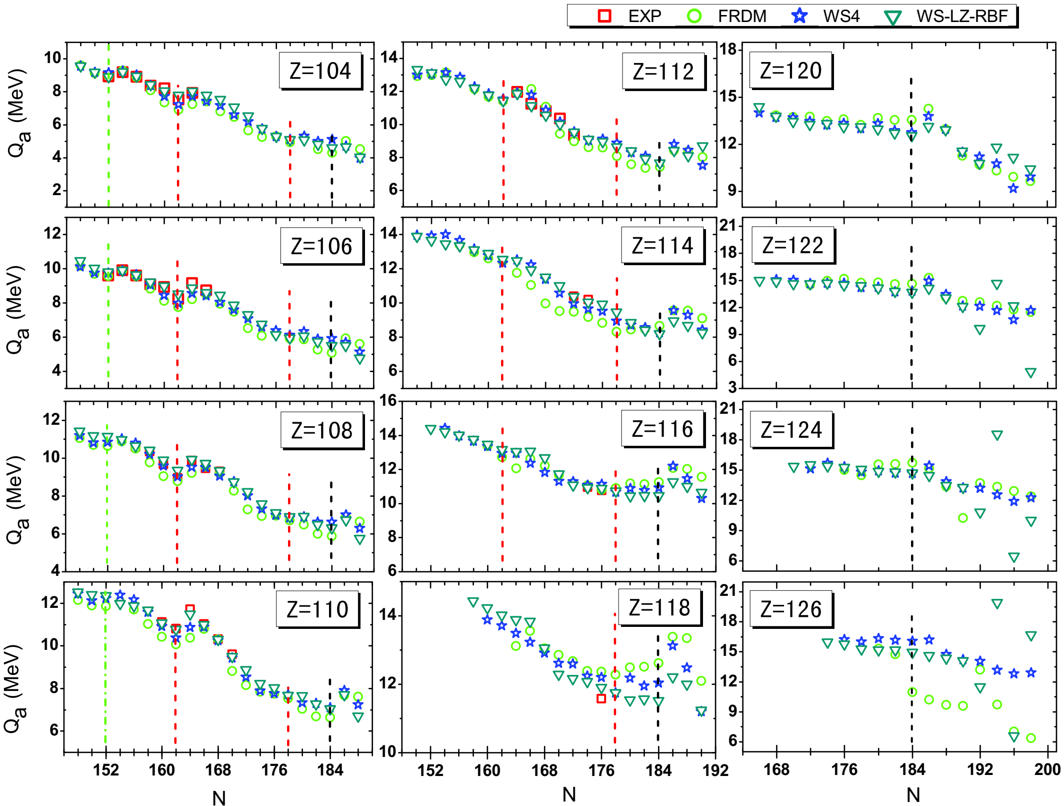

Fig. 2. (color online) The α-decay energy Q_α of even-even isotopic chains from $Z=104$ to $Z=126$ as a function of neutron number N. The red squares show the experimental data. The green circles, blue stars and dark cyan triangles show the theoretical results calculated from FRDM (2012), WS4, and WS-LZ-RBF, respectively.

and then increases sharply at $N=180$, after which it decreases up to $N=184$. Q_α from FRDM decreases up to $N=178$, and then increases slowly up to $N=184$, then at $N=186$ it increases dramatically (the increment is about 0.77 MeV, which is larger than the increment between $N=178$ and 184). Overall, although the shell effect of $N=178$ is weaker than $N=184$, we can infer that $N=178$ is a sub-magic neutron number for $Z=118$ isotopes. As far as we know, the new element $^{294}118$ has been synthesized by experiment, so we may predict that $^{296}118$ will be synthesized in the near future.

For $Z=120$ and 122, from Fig. 2, Q_α suddenly increases at $N=186$, but the experimental data is not available and the precision of the theoretical models is not high enough to draw any conclusions.

4 Two-neutron separation energy S_{2n} of the even-even isotopic chains from $Z=$ 104 to 126

Figure 3 shows the two-neutron separation energy S_{2n} of the even-even nuclei for isotopic chains from $Z=104$ to 126. There is a general tendency for S_{2n} to fall steadily as the neutron number N increases. There are sudden drops between $N=152$ and $N=154$ for the isotopic chains of $Z=104$ to $Z=108$, between $N=162$ and $N=164$ for the isotopic chains of $Z=110$ to $Z=114$, and between $N=182$ and $N=184$ for the isotopic chains of $Z=104$ to $Z=122$. All of these indicate that for the isotopes of $Z=104$ to 108 the sub-magic numbers are $N=152,162$, $N=162$ is a sub-magic number for $Z=110$ to 114, and $N=184$ is a neutron magic number for the isotopic chains of $Z=104$ to 122. The sub-magic number corresponds to the mean field associated with the shell structure undergoing a sharp change from a spherical to a deformed shape. However, for $^{260}108$, $^{274}112$, and $^{276}114$, the shell closures are not obvious. With careful observation of Fig. 3, one can find that for isotopic chains $Z=104\sim108$, between $N=174$ and $N=176$ the S_{2n} from FRDM has a larger decrement. However, the S_{2n} from the three theoretical models has larger decrement between $N=178$ and $N=180$. For $Z\geqslant110$, $N=174$ and $N=178$ do not show this phenomenon. Interestingly, Fig. 3 shows that magic number could be evolving. The $Z=104$ to 108 isotopic chains show the characteristics of $N=152$ as a sub-magic number and $N=184$ as a magic number. However, for the $Z=110\sim114$ isotopic chains, the sub-magic number $N=152$ is replaced by $N=162$. For the $Z=116\sim120$ isotopic chains, only $N=184$ is the neutron magic number.

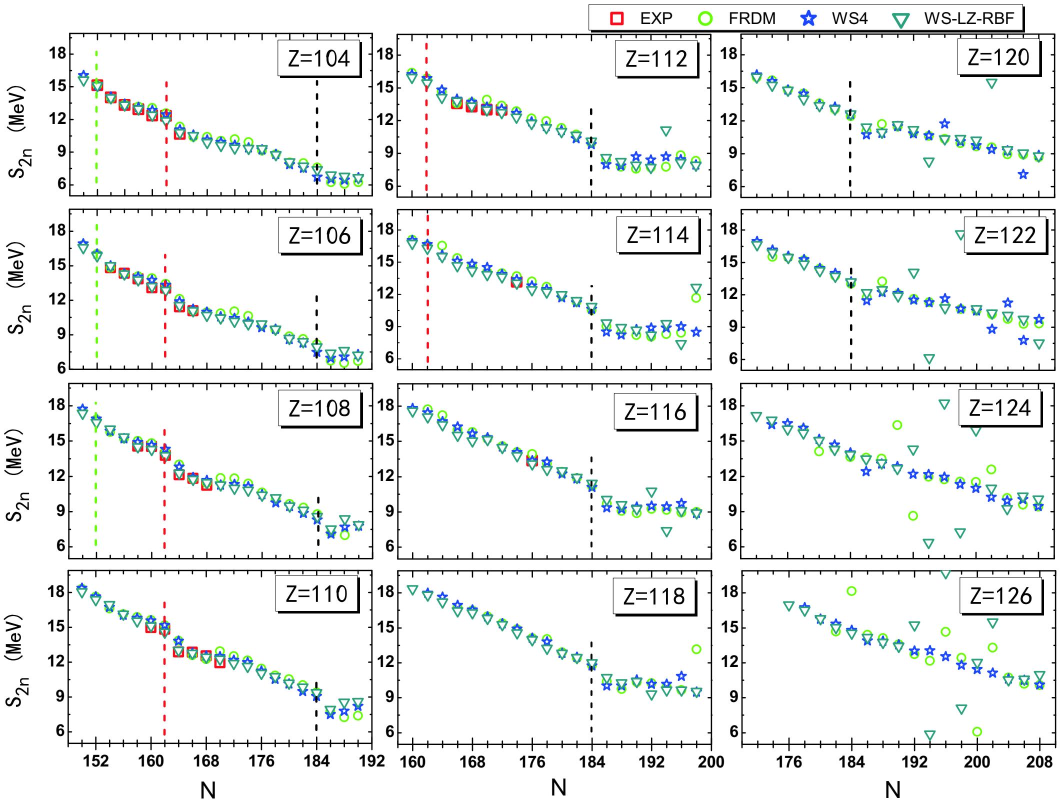

Fig. 3. (color online) Two-neutron separation energy S_{2n} of even-even nuclei isotopic chains $Z=104$ to $Z=126$ as a function of neutron number N. The red squares show the experimental data. The green circles, blue stars and dark cyan triangles show the theoretical results calculated from FRDM (2012), WS4, and WS-LZ-RBF, respectively.

5 Two-proton separation energy S_{2p} of the N=162, 176, 178 and 184 isotonic chains

Through the above analyses, $N=152$ and $N=162$ are neutron sub-magic numbers and $N=184$ is a neutron magic number. In order to find the proton magic number, the S_{2p} of the isotonic chains for N=162, 176, 178 and 184 are shown in Fig. 4. There is some irregular behavior when $Z=114$, and a sudden decrease in S_{2p} is evident. For N=178 and N=184, S_{2p} decreases with increasing Z up to Z=114. The sudden decrease of S_{2p} calculated with the macroscopic-microscopic models, including the FRDM and the WS series of models, indicates that $Z=114$ is a proton magic number. S_{2p} then decreases with increasing Z again. We can conclude that $Z=114$ is a proton magic number, so the predicted center of stability at the hypothetical doubly-magic spherical nucleus with $Z=114$ and $N=184$ is confirmed again.

For $N=162$ istones, the increased stability leads to a local minimum of S_{2p} at $Z=108$, then it decreases sharply at Z=110, with a decrement of more than 2.3 MeV. In Ref. [37], theoretical calculations predict ^{270}Hs to be a doubly magic deformed nucleus, decaying mainly by α-particle emission.

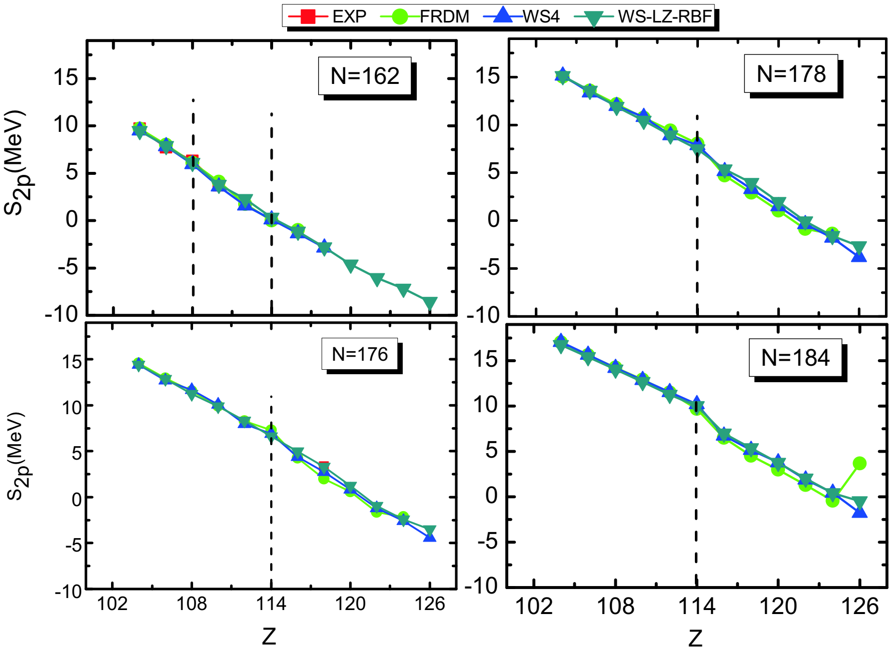

Fig. 4. (color online) The two-proton separation energy of the isotonic chains for N=162,176,178 and 184. The red squares, green circles, blue up-triangles and dark cyan down-triangles represent the two-proton separation energy calculated from experimental data, FRDM, WS4 and WS-LZ-FBF, respectively.

6 Summary

In this article, the mean binding energy, separation energy and α-decay energy of even-even nuclei with Z from 104 to 126 have been calculated using three theoretical mass tables and the updated experimental data. By analyzing these physical quantities, the following conclusions are drawn. (i) We get the most stable nucleus of the 12 even-even isotopic chains from Z=104∼126 by comparing the mean binding energy. The result shows that the WS-LZ-RBF model has the best ability to reproduce the experimental data. (ii) By analyzing the two-neutron separation energy S_{2n} and the α-decay energy Q_α, we confirm that N=152 and N=162 are neutron sub-magic numbers and N=184 is a neutron magic number, and we infer that $N=178$ may be a neutron sub-magic number. (iii) We find that the neutron magic number can evolve with increasing Z. For Z=104 to 108, N=152 and 162 are sub-magic numbers and N=184 is a magic number, but for $110\leqslant Z\leqslant 114$, N=152 does not show shell closure and only $N=162$ and 184 are magic numbers. For $Z\geqslant 116$, only $N=184$ is a magic number. (iv) By analyzing the two-proton separation energy of the isotone chains for $N=162,176,178$ and 184, we conclude that $Z=114$ is a proton magic number and confirm the doubly magic nuclei $^{270}_{108}$Hs and ^{298}114. (v) For the isotopes of Z=116 to 120, the sub-magic number N=178 should receive more attention in future work.

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