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# Double magic nuclei with Z > 82 and N > 126

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The 'island of stability' of superheavy nuclei due to shell effects is explored and the $\alpha$ decay half-lives of these nuclei are predicted. The calculations of the binding energies within a new macroscopic-microscopic model (MMM) are performed and compared with the experimental data for heavy nuclei from Md to the Z=118 element. The agreement is excellent. The data show that the $^{270}$Hs is a deformed double sub-magic nucleus beyond $^{208}$Pb. The features of $\alpha$ decay energies and one proton separation energies from the MMM reveal that the next double magic nucleus after $^{270}$Hs should be $^{298}$114. The potential energy surfaces calculated within the constrained relativistic mean field theory confirm that the $^{270}$Hs is a deformed double magic nucleus and $^{298}$114 is a spherical double magic nucleus. The $\alpha$ decay half-lives are determined using a generalized liquid drop model and the $Q_\alpha$ of the MMM for Hs and Z=114 isotopes respectively.

The existence of an 'island of stability' of superheavy nuclei (SHN) is predicted in the remote corner of the nuclear chart around the superheavy elements 114 to 126 due to shell effects. The recent discovery of new elements with atomic numbers Z $\geq$ 110 has brought much excitement to the atomic and nuclear physics communities. The experimental efforts have been focused on the direct creation of superheavy elements in heavy ion fusion reactions, leading to the production of elements up to proton number Z=118 up to now [1–7]. The half-life of the new synthesized isotope $^{287}$114 ( several seconds) is several times shorter than that of the previously observed heavier isotope $^{289}$114 ( $T_\alpha \approx 20$ s), formed in the reaction $^{48}$Ca + $^{244}$ Pu [6, 7]. Such a trend is expected to be associated with a decrease of the neutron number. The observed radioactive properties of the new nucleus $^{287}$114, together with the data obtained earlier for the isotope $^{289}$114 and the products of its $\alpha$-decay (namely, the isotopes $^{283}$Cn and $^{285}$Cn) can be considered as experimental proof of the approach of the 'island of stability' of superheavy elements around Z=114.

Theoretically it had been concluded that the existence of the heaviest nuclei with Z > 104 was primarily determined by the shell effects in 1960s [8–10]. These early calculations predicted that the nucleus with Z=114 and N=184 is the center of an island of long-lived SHN. Recently, the detailed spectroscopic studies were performed [11, 12] for nuclei beyond fermium (Z=100), with the aim of understanding the underlying single-particle structure of superheavy elements. A study of the Nobelium isotope $^{254}$No was accomplished [13], finding three excited structures, two of which are isomeric and one of these structures is firmly assigned to a two-proton excitation. These states are highly significant as their location is sensitive to single-particle levels above the gap in shell energies predicted at Z=114, and thus provide a microscopic benchmark for nuclear models of the superheavy elements. The microscopic models are, however, still uncertain when extrapolating in Z and the mass number A. In particular, there is no consensus among theorists with regard to what should be the next doubly magic nucleus beyond $^{208}$Pb (Z=82, N=126). In the SHN the density of single-particle energy levels is fairly large, so small energy shifts, such as those, for instance, due to poorly known parts of nuclear interaction, can be crucial for determining the shell stability. So an alternative choice is to develop the theoretical calculations in taking into account all the recent experimental data to give reliable predictions for the properties of the SHN.

Very recently, the macroscopic-microscopic method (MMM) was developed, the isospin and mass dependence of the model parameters being investigated with the Skyrme energy density function [14]. A very good improvement is that the macroscopic and microscopic parts in the proposed mass formula are closely connected to each other through the coefficient $a_{sym}$ of the symmetry energy. It is a main advantage to provide reasonable mass extrapolations for exotic and heavy nuclei. The number of model parameters (13 independent parameters) is considerably reduced as to be compared with the finite-range droplet model (FRDM) in which the number of parameters is about 40 [15]. The root-mean-square (rms) deviation with respect to 2149 measured nuclear masses is reduced to 0.441 MeV (the corresponding result with FRDM is 0.656 MeV), which should be one of the best results actually. Another most impressed improvement is that the rms deviation of $\alpha$-decay energies of 46 SHN is reduced to 0.263 MeV (the corresponding result with FRDM is 0.566 MeV), which allows us to give reliable predictions of $\alpha$-decay half-lives for SHN. It is meaningful to use the present data from the MMM to explore the features of SHN around the proposed 'island

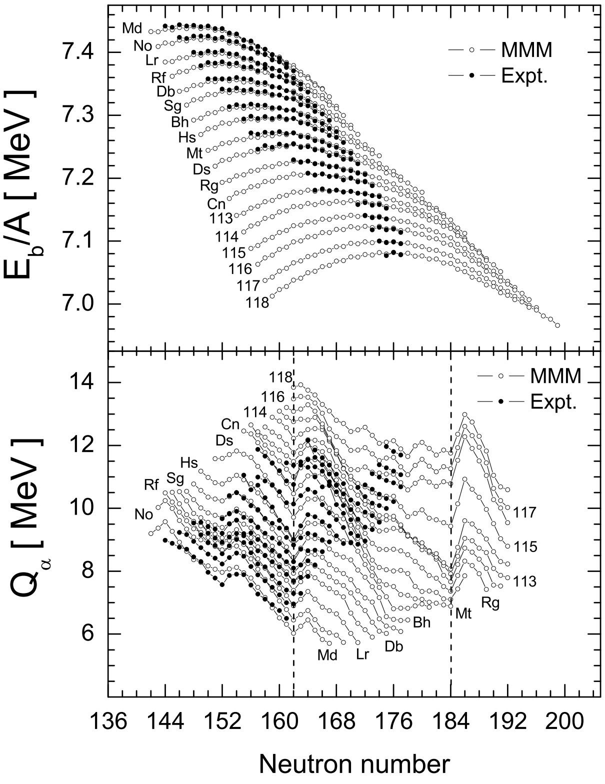

FIG. 1: Comparison of the experimental binding energy E$_b$/A (upper panel) and $\alpha$-decay energies $Q_\alpha$ (lower panel) with the theoretical results. The vertical dotted lines indicate the magic neutron numbers in the lower panel.

of stability'.

First, we compared the binding energy of the MMM with the up-to-date nuclear data [16, 17]. As shown in the upper panel of Fig.1, the agreement between the MMM [14] calculations and the experimental results [16, 17] is excellent for all the known nuclei from Md to Z=118 isotopes. This gives us full confidence to explore the $\alpha$-decay energies coming from the binding energy : $Q = E_b^D + E_b^\alpha - E_b^P$, where $E_b^D$, $E_b^\alpha$ and $E_b^P$ are the binding energies of daughter nucleus, $\alpha$ particle and parent nucleus, respectively. The MMM $\alpha$-decay energies and the experimental values are shown in the lower panel of Fig.1. The agreement between the two data is good. The lowest $\alpha$ decay energies are located at N = 162 and 184. If we check the results more carefully, one observes that from Md to Hs isotopes the shell effect at neutron number N=162 is increasing, then decreasing, and nearly disappearing after the Z=115 isotopes. For N=184, the shell effects increase from the Ds to Z=114 isotopes, then decrease till the isotope Z=118. From Md to Z=114 isotopes, N=162 is the magic neutron number and from Ds to Z=118 isotopes N=184 is the magic neutron number. It is interesting to explore the proton magic number from the systematic properties of the SHN.

The one proton separation energy and $\alpha$-decay energy of the MMM [14] and experimental data [16, 17] are shown in Fig.2 for N=162 and N=184 isotones to find the proton magic number. $S_{1p}$ generally decreases with increasing Z with obvious even-odd effect from the upper panel. With careful observation it can be found that at Z = 108, and 114 the values of $S_{1p}$ are above the general trend, indicating that these nuclei are more stable. The results obtained by the MMM and the experimental data show clearly that the proton number Z=108 is a magic proton number for N=162 isotones and the calculated one proton separation energy of the MMM confirmed that Z=114 is a proton magic number for N=184 isotones. The $\alpha$-decay energies for N=162 and 184 isotones are shown in the lower panel of Fig.2. Again we find the kinks of $\alpha$-decay energy curves at Z=108 and 114. The conclusions that both $^{270}$Hs and $^{298}$114 are double magic nuclei after $^{208}$Pb are verified again and it is very interesting to study the ground state deformations of the two nuclei.

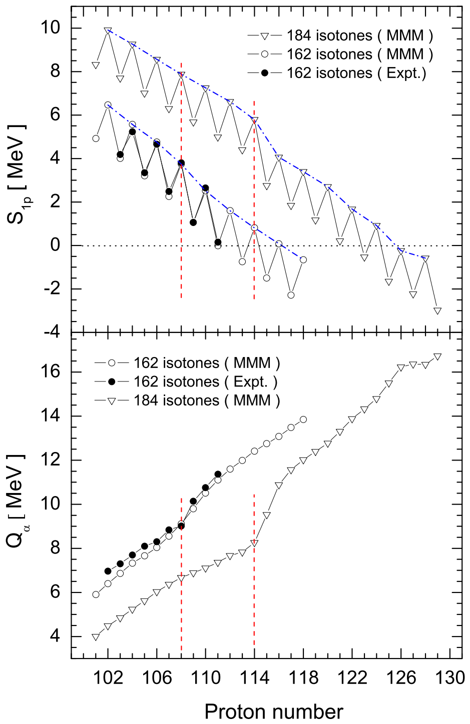

FIG. 2: (Color online). Comparison between the experimental one proton separation energies (upper panel) and $\alpha$-decay energies (lower panel) with the theoretical results for N=162 and N=184 isotones.

In fact, most of superheavy nuclei found experimentally are known to be deformed. It is worthy to investigate the potential energy surfaces in order to see the validity of the lowest equilibrium deformation. It is well known that the relativistic mean field calculation gives

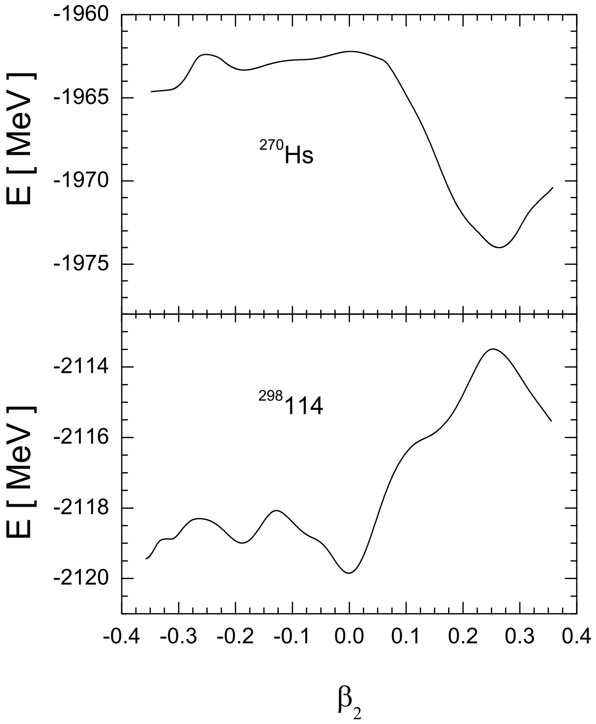

FIG. 3: Potential energy calculated in the constrained relativistic mean field (CRMF) theory with effective interaction NL3 for $^{270}$Hs (upper panel) and $^{298}$114 (lower panel) respectively.

a good description of the structure of nuclei throughout the periodic table [18–20]. In this paper, the potential energy surfaces of possible double magic nuclei are obtained by using the deformation-constrained relativistic mean field theory [21] and the pairing correlations are coped with the Barden-Cooper-Schrieffer (BCS) approximation [22]. The deformation parameter $\beta_2$ is set to the expected deformation to obtain high accuracy and reduce the computing time. The potential energy surfaces have been calculated for $^{270}$Hs and $^{298}$114 with the successful parameter set NL3 [23].

In Fig.3, the potential energies of the nuclei $^{270}$Hs and $^{298}$114 are presented versus the deformation. For nucleus $^{298}$114, there is a local spherical minimum ($\beta_2 \sim 0$). For nucleus $^{270}$Hs, the spherical minimum has completely disappeared while a well-deformed local minimum appears at $\beta_2 \sim 0.26$. So we can draw the conclusion that the nucleus $^{270}$Hs is a deformed double sub-magic nucleus and $^{298}$114 is a spherical double magic nucleus.

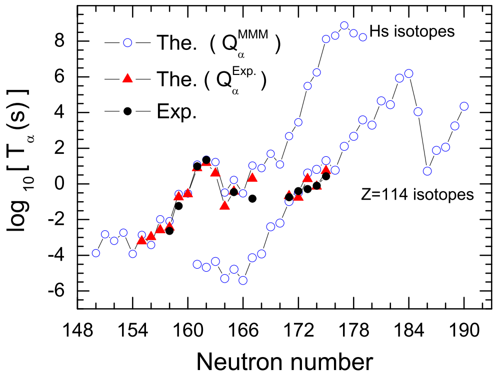

FIG. 4: (Color online). Comparison between the experimental $\alpha$-decay half-lives and the theoretical results.

The main decay mode of SHN is the $\alpha$ emission. Recently the $\alpha$-decay half-lives have been calculated within a tunneling effect through a potential barrier determined by a generalized liquid drop model ( GLDM ) [24, 25] and the Wenzel-Kramers-Brillouin (WKB) approximation. The penetration probability is estimated by

$$P = exp[-\frac{2}{\hbar}\int_{R_{\rm in}}^{R_{\rm out}} \sqrt{2B(r)(E(r)-E(sphere))}\, dr] \ , \tag{1}$$

Where two approximations ae used : $R_{\rm in} = R_d + R_\alpha$ and $B(r) = \mu$ where $\mu$ is the reduced mass, and $R_{out}$ is simply $e^2 Z_d Z_\alpha / Q_\alpha$.

The decay constant is :

$$\lambda = P_\alpha \nu_0 P, \tag{2}$$

where $P_\alpha$ is the $\alpha$ particle preformation factor and $\nu_0$ the assault frequency [25]. Then the half-life can be calculated by $T_\alpha = \frac{ln2}{\lambda}$. The $\alpha$-decay half-lives calculated by taking the experimental $\alpha$-decay energies and theoretical MMM ones are shown by small triangles and circles in Fig.4 respectively. The experimental $\alpha$-decay half-lives are also presented by black dots for comparison. The calculated $\alpha$-decay half-lives from experimental $Q_\alpha$ coincide with the experimental ones almost perfectly, implying that as long as we have the right $Q_\alpha$, the presently used method can give precise results for $\alpha$-decay half-lives. The calculated $\alpha$-decay half-lives with $Q_\alpha$ from MMM are reasonably consistent with the experimental data which tells us that the present method can be used to predict the $\alpha$-decay half-lives. The calculations of $\alpha$-decay half-lives for Hs and Z=114 isotopes are performed. The $\alpha$-decay half-life of the deformed double magic nucleus $^{270}$Hs calculated by a phenomenological formula is 22 s [3], 23.33 s by our calculations using the MMM $Q_\alpha$, and 15.14 s by using the experimental $Q_\alpha$ ( 9.02 MeV [3] ). For the spherical double magic nucleus $^{298}$114, the $\alpha$-decay half-life is 1537588 s ( about 18 days) with $Q_\alpha$ of MMM. It would not exist on earth at all if it was not constantly being produced.

The investigation of the properties of these nuclei is extremely intriguing for exploring the position of the predicted island of stability of the super heavy nuclei, and understanding some new, unexpected features of nuclear structure. There is unlikely super heavy nucleus existing in nature, and the extreme difficulties to synthesize the super heavy nuclei greatly restrict the experimental studies on it, so the theoretical studies are very important.

As a conclusion, a fundamental prediction of modern nuclear theory is the existence of an 'island of stability' among the largely unstable superheavy elements. Different models have predicted different magic numbers, and up to now, this island of stability has not yet been localized experimentally. The central goal of the present work is to find some decisive evidences for localizing this island. With this in mind, we investigate the position of the 'island of stability' in a way which is closely connected with the experimental data. The latest experimental average binding energies are compared with the recent calculations by the MMM for the heavy nuclei from Md to Z=118 elements, and the agreement with the available data is excellent. Both the two data show that the $^{270}$Hs is a double sub-magic nucleus after $^{208}$Pb. The features of $\alpha$ decay energies and one proton separation energies of the MMM reveal that the next double magic nucleus after $^{270}$Hs should be the $^{298}$114 nucleus. The potential energy surfaces are calculated within the CRMF theory and the results confirm that the $^{270}$Hs is a deformed double magic nucleus and the $^{298}$114 is a spherical double magic nucleus. The $\alpha$ decay half-lives are predicted within a generalized liquid drop model and the WKB method and the $Q_\alpha$ of the MMM for Hs and Z=114 isotopes respectively.

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