Research on some superheavy nuclei *

DONG Tie-Kuang(董铁矿)[1] REN Zhong-Zhou(任中洲)[1,2;1)] XU Chang(许昌)[1]

1 (Department of Physics, Nanjing University, Nanjing 210008, China)

2 (Center of Theoretical Nuclear Physics, National Laboratory of Heavy-Ion Accelerator at Lanzhou, Lanzhou 730000, China)

Abstract Studies on some superheavy nuclei are performed. The α decay energies are calculated by an improved local binding energy formula, and the α decay half-lives are calculated by the Viola-Seaborg formula. Good agreements between theoretical and experimental results are reached.

Key words superheavy element, alpha decay energy, half-life

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1 Introduction

The research of superheavy nuclei is a hot point of nuclear physics from both experimental and theoretical point of view[1—14]. The elements with Z=110-112 have been discovered GSI in Germany[2] by the cold fusion reaction using ^{208}Pb and ^{209}Bi targets. Then the hot fusion reactions with ^{48}Ca-projectiles are used at Dubna to synthesize the elements from Z=114 to Z=118[8]. The element Z=113 has also been synthesized at RIKEN in Japan[9]. In 2000, GAN et al. successfully synthesized a new isotope ^{259}Db[10] in Lanzhou, and then they discovered the new isotope ^{265}Bh[11, 12] at the same facility. Theoretical studies play important roles on the rapid progress in experiments. Before the experiments are performed it is necessary to estimate the production cross sections of superheavy nuclei by some nuclear reaction models, where the binding energies are important input parameters. The binding energies and/or α decay energies also paly important roles in identifying the newly synthesized nuclei. It is because α decay is found, at least up to now, to be one of the main decay modes in the superheavy region. Therefore, to calculate reliably the binding energies and the α decay half-lives is useful for experiments. Very recently, we proposed a local binding energy formula for heavy and superheavy nuclei with $Z \geqslant 90$ and $N \geqslant 140$[15]. Then we improved this formula[16] by including the different strengths of the pairing correlation among different nucleons, such as pp, nn, and np correlations. The macroscopic-microscopic model[17] is also used to calculate the binding energies of superheavy nuclei. The α decay half-life is another important quantity of superheavy nucleus which is very sensitive to the α decay energy. The relationship between the α decay energy and half-life can be well described by the Viola-Seaborg formula[18]. In 2005, we renewed the parameters of this formula[19] by considering some newly measured data. A more microscopic model about α decay half-life is the cluster model. This model has been proposed by Xu and Ren[20—23] to investigate α decay half-lives extensively. For simplicity, in this paper we play emphasis on the local binding energy formula and the Viola-Seaborg formula.

This paper is organized as follows. Section 2 is the outline of the local binding energy formula and the Viola-Seaborg formula. Numerical results are shown and discussed in Section 3. A summary is given in Section 4.

2 Theoretical models

Before the numerical results are presented, it is necessary to outline the theoretical models we used for the consistency of this paper. In 2005, in order

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1) E-mail: zren@nju.edu.cn

to reproduce the existing experimental binding energies of heavy and superheavy nuclei, and to predict reliably the binding energies of unknown superheavy nuclei, we proposed a local binding energy formula for heavy and superheavy region. The formula is written as follows[15]

$$B(Z,A) = a_{\rm v} A - a_{\rm s} A^{2/3} - a_{\rm c} Z^2 A^{-1/3} - a_{\rm a} (\frac{A}{2} - Z)^2 A^{-1} + a_{\rm p} \delta A^{-1/2} + a_6 |A-252| / A - a_7 |N-152| / N, \quad (1)$$

where two terms are added to describe the shell effects at $N = 152$. The binding energies and the α decay energies of heavy and superheavy nuclei can be reproduced very well. Then an improved version of this formula[16] was proposed by considering the different strengths of proton-proton, neutron-neutron, and proton-neutron pairing correlations, and by introducing a new term to describe the proton-neutron correlations near the Fermi level. The formula reads

$$B(Z,A) = a_{\rm v} A - a_s A^{2/3} - a_{\rm c} Z^2 A^{-1/3} - a_{\rm a} (\frac{A}{2} - Z)^2 A^{-1} + a_{\rm p} A^{-1/2} + a_6 |A-252| / A - a_7 |N-152| / N + a_8 |N-Z-50| / A. \quad (2)$$

The parameters of this formula are obtained by fitting the binding energies of 117 nuclei with $Z \geqslant 90$ and $N \geqslant 140$. The best fit parameters are shown as follows:

$$\begin{cases} a_{\rm v} = 15.8032 \text{ MeV} \\ a_{\rm s} = 17.8147 \text{ MeV} \\ a_{\rm c} = 0.71478 \text{ MeV} \\ a_{\rm a} = 97.6619 \text{ MeV} \\ a_6 = 5.33 \text{ MeV} \\ a_7 = 21.0 \text{ MeV} \\ a_8 = -15.25 \text{ MeV} \end{cases},$$

and the coefficients of the pairing energy are

$$a_{\rm p} = \begin{cases} 12.66 \text{ MeV}, & \text{even} - \text{evennuclei} \\ 3.0 \text{ MeV}, & \text{even} - \text{oddnuclei} \\ 0 \text{ MeV}, & \text{odd} - \text{evennuclei} \\ -8.0 \text{ MeV}, & \text{odd} - \text{oddnuclei} \end{cases}. \quad (3)$$

The standard and the average deviations of the binding energies for the 117 nuclei by this improved formula are, respectively,

$$\sqrt{\sigma^2} = [\sum_{i=1}^{117} (B^i_{\rm exp.} - B^i_{\rm cal.})^2 / 117]^{1/2} = 0.105 \text{ MeV}, (4)$$

and

$$\langle \sigma \rangle = \sum_{i=1}^{117} |B^i_{\rm exp.} - B^i_{\rm cal.}| / 117 = 0.086 \text{ MeV}. \quad (5)$$

The Viola-Seaborg formula is a simple but widely used formula in identifying the newly synthesized nuclei. The Viola-Seaborg formula was proposed by Viola and Seaborg[18] in 1966. This formula can be seen as a generalization of the Geiger-Nuttall law. The formula reads

$$\log_{10} T_\alpha = (aZ + b) Q_\alpha^{-1/2} + (cZ + d) + h_{\rm log}. \quad (6)$$

Very recently, we renewed the parameters of this formula[19] by considering some new data of α decay energies and half-lives in the 2003 nuclear data table compiled by Audi et al.[24]. The parameters we obtained are $a = 1.64062$, $b = -8.54399$, $c = -0.19430$, $d = -33.9054$, and

$$h_{\rm log} = \begin{cases} 0 & , Z \text{ even}, N \text{ even} \\ 0.8937 & , Z \text{ even}, N \text{ odd} \\ 0.5720 & , Z \text{ odd}, N \text{ even} \\ 0.9380 & , Z \text{ odd}, N \text{ odd} \end{cases}. \quad (7)$$

3 Numerical results and discussions

With the above formulas we calculate the α decay energies and half-lives for heavy and superheavy nuclei. Considering the limit of the length of this paper we will only give the results of proton-rich nuclei from Z=102 to Z=109. Table 1 shows the α decay energies and half-lives from No to Rf, and Table 2 shows the results from Db to Mt. From these tables one can see that the α decay energies can be reproduced very well. Most of the deviations between theoretical and experimental α decay energies are less than 0.2 MeV. For only three nuclei ^{256}No, ^{257}No, and ^{258}Lr the deviations are slightly larger than 0.3 MeV. It is interesting to note that two of these three nuclei are $N = 155$ isotones. Very recently, Asai et al.[29] have reported that the ground-state configuration of ^{257}No is different from that of lighter $N = 155$ isotones ^{253}Cf and ^{255}Fm. According to the single particle nuclear shell model, the total energy of a nucleus is the sum of the single particle energies of nucleons, and the single-particle energies are determined by the quantum numbers of their orbits. When the valence nucleon occupies a new orbital the energy level may change sharply. Hence, the α decay energy will change sharply, since the α decay energy is the difference between the binding energies of the parent, the daughter, and the α particle. However, for other

Table 1. Theoretical and experimental α decay energies (in MeV) and half-lives (in second) for nuclei from Z=102 to Z=104 with the neutron number near N=152. Theoretical α decay energies are used to calculate the half-lives (T_α(Cal)) by the Viola-Seaborg formula.

Nucl.	Q_α(Cal)	Q_α(Exp)	T_α(Cal)	T_α(Exp)	Ref.
^{251}No	8.643		15.3	0.916	[24]
^{252}No	8.493	8.550	5.84	≈ 3.64	[24]
^{253}No	8.290	8.421	0.21×10^{3}		
^{254}No	8.096	8.226	0.122×10^{3}	0.567×10^{2}	[24]
^{255}No	8.164	8.442	0.557×10^{3}	0.305×10^{3}	[24]
^{256}No	8.238	8.581	40.1	≈ 2.91	[24]
^{257}No	8.066	8.466	0.121×10^{4}		
^{253}Lr	8.912	8.937	2.50	0.644	[24]
^{254}Lr	8.713		23.7	17.105	[24]
^{255}Lr	8.521		41.4	25.882	[25]
^{256}Lr	8.595		55.5	31.765	[24]
^{257}Lr	8.714		10.1	≈ 0.646	[24]
^{258}Lr	8.545	8.900	80.3	$4.1\sim4.32$	[24]
^{259}Lr	8.383		1.160×10^{2}	7.949	[24]
^{253}Rf	9.522		0.202	$\approx 0.26\times10^{-1}$	[24]
^{254}Rf	9.336		0.855×10^{-1}		
^{255}Rf	9.140	9.058	2.47	3.154	[25]
^{256}Rf	8.952	8.930	1.14	2.016	[24]
^{257}Rf	9.071	9.044	3.95	5.34/4.43	[26]
^{258}Rf	9.195		0.219	0.923×10^{-1}	[24]
^{259}Rf	9.028		5.30	3.04	[24]

Table 2. Same as Table 1 but for nuclei from Z=105 to Z=109.

Nucl.	Q_α(Cal)	Q_α(Exp)	T_α(Cal)	T_α(Exp)	Ref.
^{256}Db	9.550		0.408	2.5	[27]
^{257}Db	9.407	9.230	0.443	$1.53\sim1.63$	[24]
^{258}Db	9.529		0.465	7.03	[24]
^{259}Db	9.655	9.620	0.903×10^{-1}	0.51	[24]
^{260}Db	9.494	9.380	0.585	$1.52\sim1.68$	[24]
^{261}Db	9.337		0.699	$1.8\sim2.20$	[24]
^{258}Sg	9.867		0.139×10^{-1}	$>0.165\times10^{-1}$	[24]
^{259}Sg	9.991	9.830	0.509×10^{-1}	0.644	[24]
^{260}Sg	10.121	9.920	0.301×10^{-2}	0.95×10^{-2}	[24]
^{261}Sg	9.961		0.611×10^{-1}	≈ 0.23	[24]
^{262}Sg	9.810		0.197×10^{-1}	$>0.364\times10^{-1}$	[24]
^{263}Sg	9.648		0.428	$1.0\sim1.43$	[24]
^{260}Bh	10.437	10.364	0.863×10^{-2}	0.35×10^{-1}	[28]
^{261}Bh	10.568	10.560	0.177×10^{-2}	0.137×10^{-1}	[24]
^{262}Bh	10.412	10.300	0.994×10^{-2}		
^{264}Hs	10.721	10.591	0.411×10^{-3}	$\approx 1.08\times10^{-3}$	[24]
^{265}Hs	10.566	10.590	0.769×10^{-2}	$\approx 0.21\times10^{-2}$	[24]
^{266}Hs	10.418	10.336	0.228×10^{-2}	0.23×10^{-2}	[1]
^{267}Hs	10.260		0.451×10^{-1}	0.32×10^{-1}	[24]
^{264}Mt	11.306		0.315×10^{-3}		
^{265}Mt	11.162		0.286×10^{-3}		
^{266}Mt	11.010	10.996	0.149×10^{-2}		
^{267}Mt	10.864		0.141×10^{-2}		

two $N = 155$ isotones, ^{260}Db and ^{262}Bh, the deviations are very small. The ground-state configurations for other $N=155$ isotones and neighboring nuclei are useful for clarifying this problem. Another possible interpretation is the Z-dependence of the $N = 152$ shell gap. Very recently, the result of the in-beam γ-ray spectroscopy of ^{245,246}Pu has been measured[30]. It is found that the $N=152$ shell gap was very small for Pu isotopes[30] compared with neighboring nuclei. But for Rf, Db, Sg, and Bh isotopes near $N=154$, the α decay energies are reproduced very well. Therefore, we can not draw firm conclusion about the discontinue change of the α decay energies near $N = 155$. The systematic deviations between experiment and theory mean that detailed studies in this region from both experimental and theoretical points of view are needed.

Now let's compare the experimental and theoretical α decay half-lives. From Tables 1 and 2, one can see that the calculated α decay half-lives are very close to experimental ones. On the whole, experimental half-lives can be reproduced within a factor of 4. For only few nuclei the deviations are slightly larger than a factor of 10. The largest value of the ratio between theoretical and experimental half-life is 18.6 for ^{258}Lr.

It is interesting to note that the α energy and half-life of the newly discovered nucleus ^{260}Bh are reproduced quite well by combining the improved binding energy formula with the Viola-Seaborg formula. The α decay energy of this nucleus is obtained by the relation[31]: $Q_\alpha = [A_\mathrm{p}/(A_\mathrm{p}-4)]E_\alpha + (65.3\,Z_\mathrm{p}^{7/5} - 80.0\,Z_\mathrm{p}^{2/5})\times10^{-6}$MeV, where Z_p and A_p are the proton and mass numbers of the parent nucleus, respectively. By this formula we obtain the α decay energy of this nucleus $Q_\alpha = 10.364$ MeV, from the measured kinetic energy of the α particle E_α=10.16 MeV. The deviation between the theoretical and experimental value is 0.073 MeV. Please note that our result is also close to the estimated value 10.470 MeV by Audi et al.. It means that the improved binding energy formula has a strong predictive ability.

4 Summary

In summary, we calculate the α decay energies and half-lives of heavy and superheavy nuclei from No (Z=102) to Mt (Z=109) by combining the improved binding energy formula with the Viola-Seaborg formula. Good agreements are achieved. The possible reasons for the discontinue change of α decay energy near $N = 155$ are discussed. The α decay energy and half-life of the newly synthesized nucleus ^{260}Bh are reproduced very well. The good agreement between the formulas and experiment shows that the improved binding energy formula is useful for the future research of superheavy region.

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