α decay energies and half-lives from a macroscopic-microscopic model *

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Abstract α decay energies of 323 heavy nuclei with $Z \geqslant 82$ are evaluated with a macroscopic-microscopic model. In this model, the macroscopic part is treated by the continuous medium model and the microscopic part consists of shell and pairing corrections based on the Nilsson potential. α decay half-lives are calculated by Viola-Seaborg formula. The results of α decay energies and half-lives are compared with experimental values and satisfactory agreement is found. The recoiling effect of the daughter nucleus on α decay half-life is also discussed.

Key words macroscopic-microscopic model, continuous medium model, α decay energy, α decay half-life

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1 Introduction

α decay is an important decay mode in which a nucleus emits an α particle via quantum tunneling effect. Many medium and heavy nuclei have α radioactivity. The study of α decay may provide us much with information about nuclear structure. In particular, α decay is nowadays a very important and indispensable way to identify superheavy nuclei. Therefore many articles were devoted to the study of α decay in heavy and/or superheavy nuclei recently.

For an estimation of α decay half lives, one may use the well known Viola-Seaborg formula in which the half life is related to the decay energy and the proton number Z of the decaying nucleus[1]. With the α decay energies obtained from the relativistic mean field (RMF) calculations, the decay half lives of many superheavy nuclei were calculated by the Viola-Seaborg formua[2—4]. A generalized Viola-Seaborg formula was proposed to incorporate the further hindrance of α decay in odd-A or odd-odd nuclei induced by the centrifugal barrier due to the non-zero orbital angular momentum[5]. Very recently, this formula was used to calculate α decay life times of some superheavy nuclei which may be synthesized in future experiments at HIRFL, Lanzhou[6].

Besides the investigations by using empirical formulae, α decay can be studied microscopically based on the Gamow picture in which the preformed α particle penetrates the potential barrier between the α and the daughter nucleus. Xu and Ren developed a density-dependent cluster model which reproduced the experimental α decay half lives within a factor of 3 for many nuclei[7]. A calculation with the deformation and orientation-dependent double-folding potential was also achieved by the same authors[8]. Zhang and collaborators studied α decay of superheavy nuclei with a generalized liquid drop model and the WKB approximation. Their results are in reasonable agreement with experimental α decay life times[9—11]. Pei et al. calculated α decay half lives of even-even heavy and superheavy nuclei by using an effective potential which is based on the Skyrme-Hartree-Fock model and obtained good agreement with the data[12].

The continuous medium model was proposed in 1980's as one of the macroscopic models[13]. In this model, the energy of a nucleus is expressed as a functional of the proton and neutron densities. In order

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to give an adequate description of the nuclear binding energies, the microscopic corrections, i.e., the shell and pairing corrections were included[14]. Peng et al. readjusted the parameters of this macroscopic-microscopic (MM) model with respect to the masses of heavy and superheavy nuclei with $Z \geqslant 82$[15]. Two new parameter sets were suggested and they can both reproduce the experimental masses of known heavy nuclei well. In this work we'll study the α decay properties of heavy and superheavy nuclei using this macroscopic-microscopic model with new parameter sets. Namely, we first calculate the α decay energies of heavy and superheavy nuclei ($Z \geqslant 82$) based on the binding energies given by the MM model. Then we evaluate α decay half lives with the Viola-seaborg formula and compare the calculated results with the experiment.

The article is organized as follows. In Sec. 2, the macroscopic-microscopic model is sketched and the methods to calculate α decay energy and half-life are shown.The results and discussions are presented in Sec. 3. Finally a summary is given in Sec. 4.

2 Formalism

2.1 The macroscopic-microscopic model

In the present macroscopic-microscopic model, the macroscopic part of the binding energy was evaluated by the continuous medium model[13] which is based on the energy density functional method. The shell and pairing corrections are calculated from the single particle scheme of the Nilsson potential and the BCS approach[14]. Next we give briefly the formalism of the continuous medium model.

In the continuous medium model, the energy of a nucleus is expressed as a functional of the neutron and proton densities:

$$E[\rho_{\rm N},\rho_{\rm Z}]= \int\left[-a_1+\frac{a_3(\rho_{\rm N}-\rho_{\rm Z})^2}{\rho_0^2}+\frac{sa_3(\rho_{\rm N}+\rho_{\rm Z}-\rho_0)^2}{\rho_0^2}\right]\rho_0{\rm d}V+ \int\left[a_4-\frac{a_6(\rho_{\rm N}-\rho_{\rm Z})^2}{\rho_0^2}+\frac{sa_6(\rho_{\rm N}+\rho_{\rm Z}-\rho_0)^2}{\rho_0^2}\right]|\nabla\rho_0|{\rm d}V+ \frac{e^2}{2}\iint\frac{\rho_{\rm Z}(\boldsymbol{r}_1)\rho_{\rm Z}(\boldsymbol{r}_2)}{|\boldsymbol{r}_1-\boldsymbol{r}_2|}{\rm d}V_1{\rm d}V_2 , \tag{1}$$

where $\rho_{\rm N}$ and $\rho_{\rm Z}$ stand for the neutron and proton densities and satisfy

$$\int\rho_{\rm N}{\rm d}V=N, \qquad \int\rho_{\rm Z}{\rm d}V=Z. \tag{2}$$

ρ_0 is a reference density which is taken as the Fermi form:

$$\rho_0=\frac{t}{4\pi a^3}\frac{1}{1+e^{(r-R)/a}} . \tag{3}$$

In Eq. (1), the first, the second, and the third integrals give the volume energy, the surface energy, and the coulomb energy respectively. In the volume and the surface parts, the isospin dependence and the effect from the fluctuation of the densities from the reference one are included.

a_1, a_3, a_4, a_6, a and s are the parameters of the model which are fixed by reproducing the experimental masses of known nuclei. In Ref. [15], these parameters are fixed by fitting the masses of 714 heavy nuclei with $Z \geqslant 82$[16]. The results are a_1 = 16.0337 MeV, a_3 = 27.0787 MeV, a_4 = 14.8896 MeV, a_6/a_3 = 0.55, a = 0.522225 fm and s = 0.464563. With this parameter set, the MM model reproduces the masses of these nuclei satisfactorily with a root mean square deviation about 0.8 MeV. In the following, we shall use these parameters to calculate the binding energies of heavy and superheavy nuclei.

2.2 α decay energy, half-life and the recoil effect

In the process of an α decay,

$$^{A}_{Z}{\rm X}\rightarrow^{A-4}_{Z-2}{\rm Y}+^{4}_{2}{\rm He} , \tag{4}$$

the released energy Q_α is shared by the α particle (the kinetic energy $E_{\rm k}$) and the daughter nucleus. From the binding energies of the parent nucleus ($\Delta W_{\rm x}$), the daughter nucleus ($\Delta W_{\rm y}$) and the α particle (ΔW_α), we may get[17]:

$$Q_\alpha=\Delta W_{\rm y}+\Delta W_\alpha-\Delta W_{\rm x} . \tag{5}$$

Due to the recoiling effect, the kinetic energy of the α particle is always smaller than the decay energy[17]:

$$Q_\alpha=\left(1+\frac{m_\alpha}{m_\gamma}\right)E_{\rm k} , \tag{6}$$

where m_γ is the mass of the daughter nucleus. Under the approximation $\frac{m_\alpha}{m_\gamma}\approx\frac{4}{A-4}$, Eq. (6) is rewritten as:

$$Q_\alpha=\frac{A}{A-4}E_{\rm k} , \tag{7}$$

if we ignore the influence of the recoil energy of the daughter nucleus,

$$Q_\alpha=E_{\rm k} , \tag{8}$$

In 1911, Geiger and Nuttall found out a relationship between α decay energy Q_α and α decay half-life T_α:

$$\log_{10}T_\alpha=A+BQ_\alpha^{-1/2} , \tag{9}$$

where A and B are the parameters depending on the charge number of decaying nucleus. In 1966, Viola and Seaborg generalized the law of Geiger and

Nuttall and proposed the well known Viola-Seaborg relationship[1]:

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

where Z is the proton number of the decaying nucleus, a, b, c, d are the parameters which may be obtained by fitting, $h_{\log}$ is the hindrance factor for odd-A or odd-odd nuclei. In the present study, we adopt the parameters a, b, c, d given by Sobiczewski et al.[18]:

$$\begin{aligned} a &= 1.66175, & b &= -8.5166 \ , \\ c &= -0.20228, & d &= -33.9069 \ , \end{aligned} \qquad (11)$$

and the hindrance parameter by Viola and Seaborg[1]:

$$h_{\log} = \begin{cases} 0 \ , & \text{even } Z \text{ and } N \\ 1.066 \ , & \text{even } Z \text{ and odd } N \\ 0.772 \ , & \text{odd } Z \text{ and even } N \\ 1.114 \ , & \text{odd } Z \text{ and } N \end{cases} . \qquad (12)$$

3 Results and discussions

3.1 α decay energies and half-lives

We calculate α decay energies Q_α and half-lives T_α of 323 heavy nuclei ($Z \geqslant 82$), and compare them with the experimental data which are taken from Ref. [19—21]. The results are summarized in Table 1. The deviations of the calculation from the experiment for α decay energies are shown in Fig. 1.

Table 1. Summary of the ratio between the experimental and calculated α decay half-lives and the root mean square deviations of α decay energies σ_{Q_α}. The results marked with "*" are calculated with experimental α decay energies.

nuclei	$T_\alpha^{\exp}/T_\alpha^{\text{cal}}$				σ_{Q_α}/MeV
	$\leqslant 10$	$10 \sim 100$	$100 \sim 1000$	$\geqslant 1000$	
all nuclei(323)	265*	54*	4*	0*	
	82.0%*	16.7%*	1.2%*	0%*	
	129	79	44	71	0.7238
	40.0%	24.5%	13.6%	22.0%	
even-even nuclei(116)	48	28	15	25	0.6666
	41.4%	24.1%	12.9%	21.6%	
even-odd nuclei(82)	35	21	7	19	0.7680
	42.7%	25.6%	8.5%	23.2%	
odd-even nuclei(65)	23	15	11	16	0.7249
	35.4%	23.1%	16.9%	24.6%	
odd-odd nuclei(60)	23	15	11	11	0.7654
	38.3%	25.0%	18.3%	18.3%	

From Table 1, it's found that the deviation of α decay energies with experimental data is about 0.72 MeV for all 323 nuclei, and only 0.67 MeV for 116 even-even nuclei. We may find in Fig. 1 that the calculated Q_α agree well with the data. However, for the nuclei with mass number around 210 there seems to be a bit larger deviation.

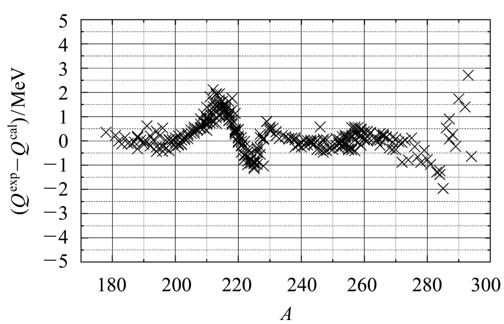

Fig. 1. Deviations of the calculated α decay energies from the experimental values.

We also calculated the α decay half lives with the experimental Q_α values. It turns out that for 265 nuclei among the 323 (82%), the α decay half-lives are of the same order of magnitude compared with the experimental values. As for the estimation according to the calculated Q_α values, the corresponding percentage is 40% and there are about 22% of nuclei whose α decay half-lives differ by more than 3 orders of magnitude from the experimental values.

Figure 2 presents the statistics of the deviation of the calculated α decay half-lives from the experimental data. Generally speaking, our results agree well with the experiment, especially for even-even and even-odd nuclei. However, the results with the calculated Q_α seem not so good as those by using the experimental Q_α. This is due to the following reasons: (i) the parameters of the Viola-Seaborg formula were adjusted to T_α with the experimental Q_α; (ii) there are sizable deviations between the calculated α decay energies with the experimental values as discussed above. The latter indicates that the present MM model needs to be modified more carefully in order to give a better description of nuclear masses. Meanwhile we may find that even if we calculate the α decay half-lives with experimental Q_α, there is also 18% of nuclei for which the deviations of the α decay life times from the experiment are beyond one order of magnitude. This reveals the shortage of the

Viola-Seaborg formula.

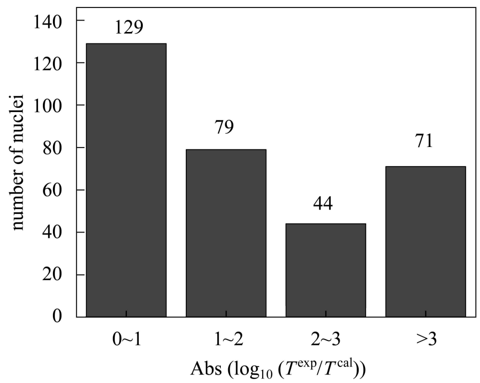

Fig. 2. Statistics of the ratio between the experimental α decay half-lives and our results.

Due to page limit, we give detailed results only for some superheavy nuclei with $Z_{\rm P} \geqslant 107$ in Table 2. For the heaviest nuclei, namely those with $Z_{\rm P} = 116$ and 118, the calculated half lives $T_\alpha^{\rm cal2}$ deviate from the experimental values by two to eight orders of magnitude. These large deviations mainly come from the errors of the calculated decay energies which are around 1 to 2 MeV. The calculated half lives for most of the other superheavy nuclei listed in Table 2 agree with the experimental values within one order of magnitude.

3.2 The recoiling effect on α decay half-life

The α decay energy Q_α consists of the kinetic energy $E_{\rm k}$ of the α particle and the recoiling energy $E_{\rm R}$ of the daughter nucleus. Usually only the kinetic energy $E_{\rm k}$ of the α particle is measured. One needs to transfer $E_{\rm k}$ to Q_α via Eq. (7). Next we examine the recoiling effect on the α decay half lives.

Table 2. The calculated α decay energies and half-lives compared with the experimental data for some superheavy nuclei with $Z_{\rm P} \geqslant 107$. $Z_{\rm P}$ and $A_{\rm P}$ are the charge and mass numbers of the parent nuclei, $Q_\alpha^{\rm exp}$ and $Q_\alpha^{\rm cal}$ are the experimental and theoretical decay energies in unit of MeV, $T_\alpha^{\rm cal1}$ and $T_\alpha^{\rm cal2}$ represent the calculated half-lives with $Q_\alpha^{\rm exp}$ and $Q_\alpha^{\rm cal}$ in units of second, and $T_\alpha^{\rm exp}$ is the experimental α decay half-life.

$Z_{\rm P}$	$A_{\rm P}$	$Q_\alpha^{\rm exp}$	$Q_\alpha^{\rm cal}$	$T_\alpha^{\rm exp}$	$T_\alpha^{\rm cal1}$	$T_\alpha^{\rm cal2}$	$\log(T_\alpha^{\rm exp}/T_\alpha^{\rm cal1})$	$\log(T_\alpha^{\rm exp}/T_\alpha^{\rm cal2})$
118	294	11.8100	12.4480	0.1800×10^{-2}	0.6377×10^{-3}	0.2441×10^{-4}	0.4506	1.8677
116	293	10.7100	8.0010	0.1070×10^{2}	0.9865	0.6784×10^{9}	1.0353	−7.8021
116	292	10.7100	9.3090	0.1200	0.8474×10^{-1}	0.1038×10^{4}	0.1511	−3.9370
116	290	11.6000	9.8660	0.1500×10^{-1}	0.5312×10^{-3}	0.1935×10^{2}	1.4509	−3.1107
115	287	10.7400	9.8360	0.3200×10^{-1}	0.2073	0.6616×10^{2}	−0.8115	−3.3154
114	289	9.7100	9.9440	0.3040×10^{2}	0.1446×10^{3}	0.2971×10^{2}	−0.6772	0.0100
114	288	10.0900	9.8330	0.2820×10	0.9779	0.5368×10	0.4600	−0.2796
114	287	10.2900	10.2180	0.5500×10	0.3163×10	0.4994×10	0.2403	0.0419
114	286	10.8500	10.3230	0.4000	0.9105×10^{-2}	0.2207	1.6428	0.2582
113	284	10.1500	11.3790	0.4800	0.4134×10	0.3097×10^{-2}	−0.9351	2.1902
113	283	10.2600	11.5480	0.1000	0.9374	0.5737×10^{-3}	−0.9719	2.2413
113	278	11.6800	12.5650	0.3440×10^{-3}	0.6336×10^{-3}	0.8334×10^{-5}	−0.2652	1.6157
112	285	8.6700	10.6340	0.9240×10^{3}	0.6602×10^{5}	0.9240×10^{-1}	−1.8540	4.0000
112	284	9.3000	10.6910	0.9800×10	0.4730×10^{2}	0.5679×10^{-2}	−0.6837	3.2369
112	277	11.4500	12.1070	0.2400×10^{-3}	0.9754×10^{-3}	0.3509×10^{-4}	−0.6090	0.8350
111	280	9.8700	10.6410	0.3600×10	0.5696×10	0.4882×10^{-1}	−0.1993	1.8677
111	279	10.5200	10.9090	0.1700	0.4528×10^{-1}	0.4786×10^{-2}	0.5745	1.5504
111	274	11.1500	11.9390	0.9260×10^{-2}	0.2775×10^{-2}	0.4704×10^{-4}	0.5234	2.2942
111	272	10.8200	11.7030	0.1500×10^{-2}	0.1740×10^{-1}	0.1525×10^{-3}	−1.0646	0.9928
110	281	8.8300	9.8050	0.9600×10^{2}	0.3604×10^{4}	0.3669×10	−1.5745	1.4178
110	273	11.2910	11.2670	0.1100×10^{-3}	0.5928×10^{-3}	0.6732×10^{-3}	−0.7315	−0.7867
110	271	10.9580	10.9970	0.6200×10^{-3}	0.3590×10^{-2}	0.2895×10^{-2}	−0.7627	−0.6692
110	270	11.2420	11.1550	0.1000×10^{-3}	0.6604×10^{-4}	0.1052×10^{-3}	0.1802	−0.0221
110	269	11.3450	11.1940	0.2700×10^{-3}	0.4460×10^{-3}	0.9934×10^{-3}	−0.2180	−0.5658
109	276	9.8500	10.0870	0.7200	0.1439×10	0.3222	−0.3007	0.3493
109	275	10.4800	10.3580	0.9700×10^{-2}	0.1372×10^{-1}	0.2821×10^{-1}	−0.1505	−0.4636
109	270	10.0300	10.3910	0.7160×10^{-2}	0.4595	0.5095×10^{-1}	−1.8074	−0.8522
109	268	10.2990	10.5890	0.7000×10^{-1}	0.8826×10^{-1}	0.1600×10^{-1}	−0.1007	0.6410
108	269	9.3540	9.7050	0.7100×10	0.1616×10^{2}	0.1543×10	−0.3571	0.6630
108	267	10.0760	9.9080	0.7400×10^{-1}	0.1474	0.4199	−0.2993	−0.7539
108	266	10.3810	10.1600	0.2300×10^{-2}	0.2020×10^{-2}	0.7575×10^{-2}	0.0563	−0.5177
108	265	10.5700	10.2730	0.1200×10^{-2}	0.7851×10^{-2}	0.4463×10^{-1}	−0.8158	−1.5704
108	264	10.5900	10.5140	0.1080×10^{-2}	0.6015×10^{-3}	0.9306×10^{-3}	0.2542	0.0646
107	272	9.1500	9.2160	0.9800×10	0.3380×10^{2}	0.2129×10^{2}	−0.5377	−0.3369
107	267	9.3700	9.2220	0.2200×10^{2}	0.3357×10	0.9290×10	0.8164	0.3744
107	266	9.4770	9.2950	0.1000×10	0.3588×10	0.1232×10^{2}	−0.5549	−1.0907
107	265	9.3800	9.5570	0.9400	0.3137×10	0.9599	−0.5234	−0.0091
107	264	9.6710	9.6730	0.4400	0.1001×10	0.9883	−0.3571	−0.3514
107	262	10.4200	10.0880	0.1020	0.1018×10^{-1}	0.7304×10^{-1}	1.0011	0.1451
107	261	10.5620	10.1740	0.1180×10^{-1}	0.2050×10^{-2}	0.1976×10^{-1}	0.7601	−0.2239

Table 3. α decay half-lives for nuclei in α decay chains of $^{289}114$, $^{288}115$ and $^{287}115$. $T_\alpha^{(1)}$ and $T_\alpha^{(2)}$) represent the results with the recoiling effect (not) considered.

α decay	E_k^{exp}/MeV	Q_α^{exp}/MeV	T_α^{exp}/s	$T_\alpha^{(1)}$/s	$T_\alpha^{(2)}$/s	$T_\alpha^{(2)}/T_\alpha^{(1)}$
$^{289}114 \rightarrow ^{285}112$	9.71		3.04×10^{1}	5.71×10^{1}	1.45×10^{2}	2.53
$^{285}112 \rightarrow ^{281}110$	8.67		9.24×10^{2}	2.48×10^{4}	6.60×10^{4}	2.66
$^{281}110 \rightarrow ^{277}108$	8.83		9.60×10^{1}	1.37×10^{3}	3.60×10^{3}	2.62
$^{288}115 \rightarrow ^{284}113$	10.46	10.61	8.70×10^{-2}	9.97×10^{-1}	2.51×10^{0}	2.51
$^{284}113 \rightarrow ^{280}111$	10.00	10.15	4.80×10^{-1}	4.13×10^{0}	1.09×10^{1}	2.63
$^{280}111 \rightarrow ^{276}109$	9.75	9.87	3.60×10^{0}	5.70×10^{0}	1.26×10^{1}	2.21
$^{276}109 \rightarrow ^{272}107$	9.71	9.85	7.20×10^{-1}	1.44×10^{0}	3.57×10^{0}	2.48
$^{272}107 \rightarrow ^{268}105$	9.02	9.15	9.80×10^{0}	3.38×10^{1}	8.53×10^{1}	2.52
$^{287}115 \rightarrow ^{283}113$	10.59	10.74	3.20×10^{-2}	2.07×10^{-1}	5.13×10^{-1}	2.47
$^{283}113 \rightarrow ^{279}111$	10.12	10.26	1.00×10^{-1}	9.37×10^{-1}	2.28×10^{0}	2.43
$^{279}111 \rightarrow ^{275}109$	10.37	10.52	1.70×10^{-1}	4.53×10^{-2}	1.11×10^{-1}	2.46
$^{275}109 \rightarrow ^{271}107$	10.33	10.48	9.70×10^{-3}	1.37×10^{-2}	3.33×10^{-2}	2.43

For this purpose, we choose the three nuclei in the α decay chain of $^{289}114$ which were measured in Dubna[22] (only E_k's are given in this reference) and the nuclei in two α decay chains of the superheavy nuclei with $Z=115$[23] (both E_k and Q_α given). The results are listed in Table. 3. We may see that if we ignore the recoiling energies of daughter nuclei, α decay half-lives become about 2.5 times longer.

4 Summary

We calculated α decay energies of 323 nuclei with $Z \geqslant 82$ by using a macroscopic-microscopic model in which the macroscopic part is treated by the continuous medium model and the microscopic part consists of shell and pairing corrections based on the Nilsson potential. The decay half-lives are obtained by using the Viola-Seaborg formula. Our results agree with the experimental data reasonably well both for the decay energies and half lives. An investigation of the recoiling effect of the daughter nucleus on the α decay half lives reveals that the recoiling in the α decay of superheavy nuclei has an influence of the factor of three on the α decay half-lives.

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