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Half-Lives of Superheavy Nuclei in $Z = 113$ Alpha Decay Chain *

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The generalized liquid drop model (GLDM), including the proximity effects and centrifugal potential, and the cluster model with Cosh potential are used to study the half-lives of some $Z = 113$ isotopes and their α-decay products. The experimental half-lives of $^{284}113$, $^{283}113$, $^{282}113$ and their α-decay products are well reproduced by the two models when zero angular momenta transfer is assumed. For $^{278}113$ and its α-decay products, both the GLDM and the cluster model could provide satisfactory results if we assume the α particle carry five units of angular momenta, which indicates that possible nonzero angular momenta transfer and need further experimental measurements with high precision. Finally, we show that half-lives of α-decay are quite sensitive to the angular momentum transfers, and a formula could be used to describe the correlation between α-decay half-life and angular momentum transfer successfully.

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Much attention has been paid to the synthesis and properties of superheavy nuclei (SHN), since the prediction of the existence of the superheavy island in the 1960s.[1,2] Recently, isotopes of the elements 118, 116, 115, 114, 113 have been produced. The new nuclide $^{282}113$ has been synthesized in 2007 through the ^{237}Np+^{48}Ca fusion reaction and its α-decay chain has been observed.[3] The study of α-decay properties plays a significant role for the dominant decay mode of SHN is the α emission. Experimental α-decay of SHN is one of the efficient approach to identify new nucleus via the observation of α-decay chain from unknown parent nucleus to a known nuclide. However, the extreme difficulties to synthesize SHN restrict experimental studies on it, so that the theoretical studies are very important. Now various approaches have been used to study α-decay half-life such as the VSS formulae,[4] the cluster model,[5−11] the GLDM and the density-dependent M3Y(DDM3Y) effective interaction.[12,13]

Some α-decay chains from element 113 have been investigated by the GLDM without considering the α particle angular momentum and by the DDM3Y effective interaction.[14−16] In this work, the cluster model and the GLDM are used to calculate the half-lives of $Z = 113$ isotopes and their α-decay products at the same time. The contribution of α particle angular momentum is included for the first time in GLDM. It is well known that the GLDM is one of the most successful macroscopic models for describing the process of fusion, fission, light nucleus and α emission,[14,15,17−25] which includes the volume-, surface-, Coulomb-energies and the proximity effects, the mass asymmetry. The proximity energy decreases the barrier height by several MeV and moves the position of the barrier top forwards, corresponding to two separated fragments in unstable equilibrium by the balance between the attractive nuclear proximity force and the repulsive Coulomb force. In this Letter, the centrifugal potential energy will be introduced in the GLDM, and can be taken as

$$V_{\rm cen}(r) = \frac{\hbar^2}{2\mu_\alpha}\frac{(L+\frac{1}{2})^2}{r^2}, \qquad (1)$$

where r and μ_α are the distance and reduced mass of the α-daughter system, respectively. A modified centrifugal potential barrier is used with $L(L+1)$ replaced by $(L+1/2)^2$. In GLDM, the α-decay constant is simply defined as $\lambda = \nu_0 P$, where the assault frequency ν_0 has been taken as $\nu_0 = 10^{19}\,{\rm s}^{-1}$, with P being the barrier penetrability without introducing the preformation factor. The half-life could be obtained by $T_{1/2} = \ln 2/\lambda$. The detail formalism can be found in reference [14,21] and we do not discuss it here. The cluster model is one of the most successful microscopic models to describe α-decay properties. Buck and co-workers proposed the cluster model with Cosh potential of α-decay and they successfully reproduced the experimental data.[9−11] This model needs to determine the α-decay width Γ and the α-decay half-life is given by $T_{1/2} = \hbar \ln 2/\Gamma$, which has no concept of assault frequency but introduces the preformation factor: $P_\alpha = 1.0$ for even–even nuclei, $P_\alpha = 0.6$ for odd-A nuclei and $P_\alpha = 0.35$ for odd–odd nuclei.

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Table 1 displays the results with the cluster model and the GLDM, not including the contribution of angular momenta transfers, and the calculations of DDM3Y and the data from experiment are listed for comparison. The calculated values by the cluster model and the GLDM are in good agreement with most of the experimental data. The good agreement between the calculated half-lives and experimental ones for nuclei in $^{282}113$ α-decay chain shows that experimental half-lives of these nuclei are compatible with experimental decay energies. This suggests that the experimental data are reasonable and the claim of new nuclide $^{282}113$ is reliable.

The potential barriers of GLDM and cluster model for α emission have been presented in Fig. 1 for comparison. In the region of $r = 8-14$ fm, the GLDM potential barrier is lower than that of the cluster model for the proximity energy reduces the potential barrier, so that the penetration probability in the GLDM is larger than that in the cluster model.

The synthesis of nuclide $^{278}113$ and its α-decay chain, has been reported recently.[27] Before this experiment, $^{278}113$ and its α-decay products have been observed by cold-fusion reaction at RIKEN in Japan.[28] Theoretical investigation has been performed in Ref.[29], but they took the α particle kinetic energy as decay energy Q_α by mistake, so they obtained the wrong theoretical half-lives and drew an unreliable conclusion. The theoretical half-lives calculated by the GLDM and the cluster model with experimental Q_α values have been presented in Table 2, the DDM3Y's results and experimental data are also shown for comparison. The half-life of $^{270}109$ has not been presented since its experimental Q_α escaped. None of the models can provide good explanation for the measured half-lives if the contributions of angular momentum transfers are not included. This may imply that the emitted α particles carry nonzero angular momentum L to satisfy spin-parity conservation. Interestingly, we find that like DDM3Y, the calculated values by the GLDM and cluster model with the angular momentum transfers $L = 5$ are in agreement with the experimental data.

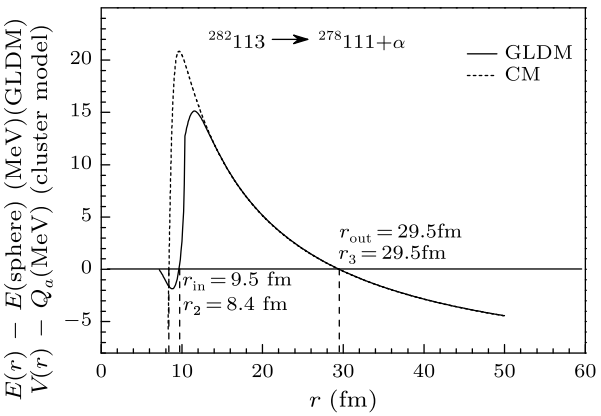

Fig. 1. Potential barriers by the GLDM (solid line) and the cluster model (dashed line) against emission of α particle from the $^{282}113$ mother nucleus. Here r is the centre-of-mass distance. The potential barrier penetration from r_{in} to r_{out} in GLDM and from r_2 to r_3 in cluster model.

Table 1. Comparison between experimental and calculated α-decay half-lives of SHN for zero angular momentum transfers by the DDM3Y effective interaction,[16] the GLDM and the cluster model (CM) using experimental Q_α values.

Parent Nuclei	Q_{expt} (MeV)	Expt $T_{1/2}$	DDM3Y $T_{1/2}(Q_{expt})$	GLDM $T_{1/2}(Q_{expt})$	CM $T_{1/2}(Q_{expt})$	References expt
$^{284}113$	10.15(6)	$0.48^{+0.58}_{-0.17}$ s	$1.55^{+0.72}_{-0.48}$ s	$0.44^{+0.21}_{-0.14}$ s	$2.15^{+0.96}_{-0.67}$ s	[26]
$^{283}113$	10.26(9)	100^{+490}_{-45} ms	$201.6^{+164.9}_{-84.7}$ ms	226^{+175}_{-97} ms	634^{+466}_{-267} ms	[26]
$^{282}113$	10.83(8)[a]	73^{+134}_{-29} ms	-	$7.8^{+4.6}_{-2.8}$ ms	$38.9^{+22.1}_{-13.9}$ ms	[3]
$^{280}111$	9.87(6)	$3.6^{+4.3}_{-1.3}$ s	$1.9^{+0.9}_{-0.6}$ s	$0.70^{+0.35}_{-0.23}$ s	$2.7^{+1.3}_{-0.9}$ s	[26]
$^{279}111$	10.52(16)	170^{+810}_{-80} ms	$9.6^{+14.8}_{-5.7}$ ms	$12.6^{+20.3}_{-7.7}$ ms	$30.9^{+47.5}_{-18.4}$ ms	[26]
$^{278}111$	10.89(8)[a]	$4.2^{+7.5}_{-1.7}$ ms	-	$1.5^{+0.9}_{-0.5}$ ms	$6.7^{+3.7}_{-2.3}$ ms	[3]
$^{276}109$	9.85(6)	$0.72^{+0.87}_{-0.25}$ s	$0.45^{+0.23}_{-0.14}$ s	$0.19^{+0.10}_{-0.06}$ s	$0.66^{+0.30}_{-0.21}$ s	[26]
$^{275}109$	10.48(9)	$9.7^{+46}_{-4.4}$ ms	$2.75^{+1.85}_{-1.09}$ ms	$4.1^{+2.8}_{-1.7}$ ms	$9.0^{+6.0}_{-3.6}$ ms	[26]
$^{274}109$	9.95(10)[a]	440^{+810}_{-170} ms	-	108^{+96}_{-51} ms	353^{+303}_{-162} ms	[3]
$^{272}107$	9.15(6)	$9.8^{+11.7}_{-3.5}$ s	$10.1^{+5.4}_{-3.4}$ s	$5.5^{+3.0}_{-1.9}$ s	$13.6^{+7.0}_{-4.6}$ s	[26]
$^{270}107$	9.11(8)[a]	61^{+292}_{-28} s	-	$7.7^{+6.1}_{-3.3}$ s	$17.8^{+13.3}_{-7.6}$ s	[3]

[a] Q_α values calculated using the measured α kinetic energies.

Table 2. Comparison between the new experimental and calculated α decay half-lives of SHN for zero and five units of angular momenta transfers by the DDM3Y effective interaction,[16] the GLDM and the cluster model(CM) using experimental Q_α values.

Parent Nuclei	Q_{expt} (MeV)	Expt $T_{1/2}$	DDM3Y,$L=0$ $T_{1/2}(Q_{expt})$	GLDM,$L=0$ $T_{1/2}(Q_{expt})$	CM,$L=0$ $T_{1/2}(Q_{expt})$	DDM3Y,$L=5$ $T_{1/2}(Q_{expt})$	GLDM,$L=5$ $T_{1/2}(Q_{expt})$	CM,$L=5$ $T_{1/2}(Q_{expt})$
$^{278}113$	11.737(40)	$1.8^{+3.3}_{-1.3}$ ms	$0.23^{+0.05}_{-0.04}$ ms	$0.075^{+0.016}_{-0.014}$ ms	$0.34^{+0.07}_{-0.06}$ ms	$3.71^{+0.68}_{-0.84}$ ms	$0.64^{+0.15}_{-0.12}$ ms	$4.44^{+0.98}_{-0.78}$ ms
$^{274}111$	11.525(71)	$15.2^{+27.7}_{-11.1}$ ms	$0.17^{+0.07}_{-0.05}$ ms	$0.061^{+0.024}_{-0.018}$ ms	$0.25^{+0.11}_{-0.09}$ ms	$2.75^{+1.20}_{-0.84}$ ms	$0.56^{+0.25}_{-0.17}$ ms	$3.35^{+1.44}_{-0.99}$ ms
$^{266}107$	9.964(41)	$1.32^{+2.36}_{-0.97}$ s	$0.058^{+0.017}_{-0.013}$ s	$0.029^{+0.008}_{-0.007}$ s	$0.070^{+0.020}_{-0.015}$ s	$1.06^{+0.30}_{-0.24}$ s	$0.31^{+0.08}_{-0.07}$ s	$1.04^{+0.29}_{-0.23}$ s

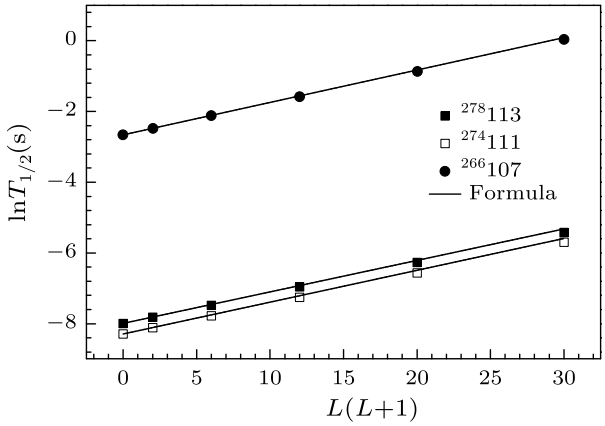

Fig. 2. Influence of angular momentum transfers on α-decay half-lives in cluster model.

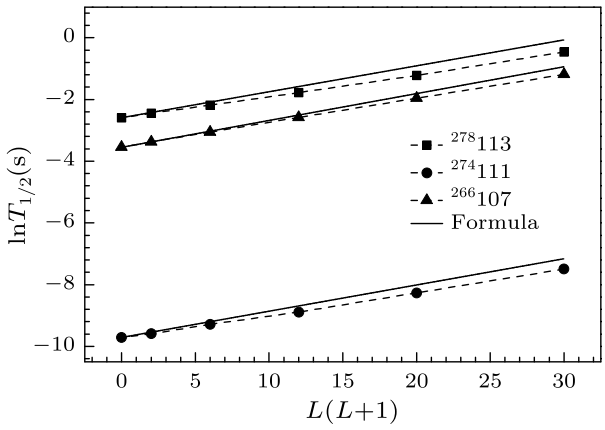

Fig. 3. Influence of angular momentum transfers on α-decay half-lives in GLDM.

Since centrifugal potential barrier is much lower than Coulomb potential barrier, the ratio of the $T_{1/2}$ with nonzero L to $T_{1/2}$ with $L = 0$ could be written as[30]

$$\frac{T_L(Q_\alpha)}{T_0(Q_\alpha)} = \exp\left[\frac{2L(L+1)}{KR}\right], K = \left(\frac{2\mu_\alpha}{\hbar^2}\frac{2Ze^2}{4\pi\varepsilon_0 R}\right)^{\frac{1}{2}}. \quad (2)$$

and R is the entrance point of potential barrier. This equation can be written in the form

$$\ln T_L(Q_\alpha) = \ln T_0(Q_\alpha) + \frac{2}{KR}L(L+1). \quad (3)$$

The relationships between $\ln T_L(Q_\alpha)$ and $L(L+1)$ are presented in Fig. 2 from the cluster model and in Fig. 3 from the GLDM respectively, compared with the results from the formula (3). As can be seen, the results by the cluster model are quite coincide with the formula (3), but the GLDM results are slightly poor agreement with this formula, which could be traced back to the proximity effect lowing the potential barrier by several MeV and the formula (3) only based on the Coulomb and centrifugal potential penetration. However, both the models suggest that $T_L(Q_\alpha) = T_0(Q_\alpha)\exp[cL(L+1)]$ can be taken as a successful formula to describe the influence of α particle angular momentum transfers on half-lives, where c is constant for a given nucleus but slightly different for these two models (for example, $c = 0.071$ in GLDM and $c = 0.086$ in cluster model for $^{278}113$). It is obvious that centrifugal potential barrier plays a significant role if α particle carries away angular momenta L.

In summary, the half-lives of SHN for some $Z = 113$ isotopes including newly synthesized nuclei via α emission have been investigated in the framework of the GLDM and the cluster model. The experimental half-lives of $^{284}113$, $^{283}113$, $^{282}113$ and their α-decay products could be well reproduced by the two models as well as DDM3Y calculations if $L = 0$ is used. For $^{282}113$ and its decay products, the experimental $T_{1/2}$ are consistent with the experimental Q_α from the two models, implying that the synthesis of new nuclide $^{282}113$ and its half-life measurement are reliable. When the nonzero angular momenta transfers is supposed, both GLDM and cluster model can provide the reasonable half-lives for $^{278}113$ and its decay products. Finally, the function between the centrifugal potential barriers and half-lives of α-decay has been studied and it is found that centrifugal potential barrier plays a significant role in the study of SHN.

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