α decay properties of ^{296}Og within the two-potential approach *

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Abstract: The present work is a continuation of our previous paper [J.-G. Deng, et al., Chin. Phys. C, **41**: 124109 (2017)]. In the present work, the α decay half-life of the unknown nucleus ^{296}Og is predicted within the two-potential approach and the hindrance factors of all 20 even-even nuclei in the same region as ^{296}Og, i.e. proton number $82<Z<126$ and neutron number $152<N<184$, from ^{250}Cm to ^{294}Og, are extracted. The prediction is 1.09 ms within a factor of 5.12. In addition, based on the latest experimental data, a new set of parameters of α decay hindrance factors for the even-even nuclei in this region, considering the shell effect and proton-neutron interaction, are obtained.

Keywords: α decay, ^{296}Og, hindrance factor, two-potential approach

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1 Introduction

The synthesis and identification of superheavy nuclei has been a hot topic in nuclear physics since the prediction of the existence of a superheavy island in the 1960s [1–5]. During more than ten years, the superheavy nuclei, from $Z=113$ to $Z=118$, have been synthesized by hot-fusion reactions between ^{48}Ca beams and radioactive actinide targets [6–11]. Presently, the synthesis of ^{296}Og is excepted to be via the reaction ^{251}Cf(^{48}Ca, 3n)^{296}Og at the Flerov Laboratory of Nuclear Reactions (FLNR) in Dubna, Russia [12, 13]. If the experiment succeeds, ^{296}Og will be the nucleus with the largest number of protons and neutrons of any observed nucleus, and be closest to the predicted N=184 shell closure [3, 4]. Spontaneous fission and α decay are the two main decay modes of superheavy nuclei. For superheavy nuclei around Rf, α decay is a weaker candidate than spontaneous fission [5]. For the most of the recently synthesized proton-rich nuclei, α decay is the dominant decay mode [5]. Recently, Bao et al. [14] also predicted that α decay is the main decay mode for ^{296}Og.

An accurate prediction of α decay half-life will be used as a reference for experiments synthesizing ^{296}Og. Recently, Sobiczewski [13] predicted the α decay half-life $T_{1/2}$ of ^{296}Og by adopting a 3-parameter phenomenological formula for $T_{1/2}$ [15], while the α decay energy Q_α was obtained from nine different mass models as follows: Möller et al. (FRDM) [16], Duflo and Zuker (DZ) [17], Nayak and Satpathy (INM) [18], Wang and Liu (WS3+) [19], Wang et al. (WS4+) [20, 21], Muntian et al. (HN) [22, 23], Kuzmina et al. (TCSM) [24], Goriely et al. (HFB31) [25], and Liran et al. (SE) [26]. To obtain a more accurate $T_{1/2}$ of ^{296}Og, the method of selecting a more precise Q_α is at the heart of the matter. Sobiczewski [13] found that the deviation between measured α decay half-life and calculation, adopting Q_α from WS3+ [19], was minimal, by analyzing calculations of nine different mass models. However, the parameters of the phenomenological formula [15] adopted by Sobiczewski were extracted from NUBASE2003 [27] and AME2003 [28, 29] for nuclei with Z=84–110, and N=128–160. Very recently, Mohr [30] adopted the sys-

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tematic behavior of strength parameter for the double-folding potential of α-core to predict the Q_α and $T_{1/2}$ of ^{296}Og. The predicted results are Q_α=11.655 ± 0.095 MeV and $T_{1/2}$ = 0.825 ms with an uncertainty factor of 4.

In our previous works [31–34], we used the two-potential approach (TPA) [35, 36] to systematically study the α decay hindrance factors and/or preformation probabilities for even-even, odd-A and doubly-odd nuclei, and we found that the behaviors of the α decay hindrance factors and/or preformation probabilities of the same kinds of nuclei (even-even nuclei, odd-A nuclei and doubly-odd nuclei) in the same region are similar, while the regions are divided by the magic numbers of proton and neutron. In the present work, in order to reduce the uncertainty factor of the prediction of ^{296}Og, we systematically study all 20 even-even nuclei of $82 < Z < 126$ and $152 < N < 184$ in the same region as ^{296}Og, from ^{250}Cm to ^{294}Og. The α decay energies and half-lives are taken from the latest evaluated nuclear properties table NUBASE2016 [37] and evaluated atomic mass table AME2016 [38, 39], except for the Q_α of ^{296}Og, which is from WS3+ [19].

This article is organized as follows. In the next section, the theoretical framework for calculating α decay half-life is briefly described. The detailed calculations and discussion are presented in Section 3. Finally, a summary is given in Section 4.

2 Theoretical framework

The TPA [35, 36] was put initially forward to investigate quasi-stationary problems. Recently, it has been widely used to deal with α decay [40–45]. In the framework of the TPA, the α decay half-life $T_{1/2}$ is calculated by

$$T_{1/2}=\frac{\hbar\ln2}{\Gamma}=\frac{\ln2}{\lambda}, \tag{1}$$

where $\hbar$, Γ and λ denote the Planck constant, decay width and decay constant, respectively. λ depends on the α particle preformation factor P_0, the penetration probability P, and the normalized factor F. It can be expressed by

$$\lambda=\frac{\hbar P_0 F P}{4\mu h}, \tag{2}$$

where $\mu=\frac{m_\mathrm{d}m_\alpha}{m_\mathrm{d}+m_\alpha}$ is the reduced mass between daughter nucleus and preformed α particle, with the mass of the daughter nucleus m_d and α particle m_α. P_0 is the α preformation factor. On account of the complicated structure of quantum many-body systems, there are a few works [46–50] studying P_0 from the viewpoint of microscopic theory. In accordance with the calculations by adopting the density-dependent cluster model (DDCM) [51], P_0 is 0.43 for even-even nuclei.

h is the hindrance factor, denoting the deviation between calculation and experimental data of the α decay half-life, and can be expressed as

$$h=\frac{T^{\mathrm{exp}}_{1/2}}{T^{\mathrm{cal}}_{1/2}}, \tag{3}$$

where $T^{\mathrm{exp}}_{1/2}$ and $T^{\mathrm{cal}}_{1/2}$ are the α decay half-lives for experimental data and calculated value with P_0=0.43 [51]. Recently, a simple formula, considering the nuclear shell effect and proton-neutron interaction to estimate the variation in the α decay hindrance factors, was put forward [31, 52, 53] and written as

$$\begin{aligned}\log_{10}h \;=\; & a+b(Z-Z_1)(Z_2-Z)+c(N-N_1)(N_2-N)\\ & +dA+e(Z-Z_1)(N-N_1),\end{aligned} \tag{4}$$

where Z and N are the proton and neutron number of the parent nucleus. Z_1 (N_1) and Z_2 (N_2) denote the proton (neutron) magic numbers with $Z_1 < Z < Z_2$ and $N_1 < N < N_2$. a, b, c, d and e are adjustable parameters.

The barrier penetration probability P is obtained by the semi-classical Wentzel-Kramers-Brillouin (WKB) approximation and written as

$$P=\exp\left(-2\int_{r_2}^{r_3}k(r)\mathrm{d}r\right), \tag{5}$$

where $k(r)=\sqrt{\frac{2\mu}{\hbar^2}|Q_\alpha-V(r)|}$ represents the wave number of the α particle. r is the mass center distance between the α particle and the daughter nucleus. $V(r)$ denotes the entire α-core potential.

The normalized factor F, indicating the assault frequency of the α particle, can be approximatively obtained by

$$F\int_{r_1}^{r_2}\frac{1}{2k(r)}\mathrm{d}r=1, \tag{6}$$

where r_1, r_2 and r_3 (Eq. 5) are the classical turning points, which satisfy the conditions $V(r_1)=V(r_2)=V(r_3)=Q_\alpha$.

The entire α-core potential $V(r)$, which is composed of the nuclear potential $V_\mathrm{N}(r)$, the Coulomb potential $V_\mathrm{C}(r)$, and the centrifugal potential $V_\mathrm{l}(r)$, is expressed as

$$V(r)=V_\mathrm{N}(r)+V_\mathrm{C}(r)+V_\mathrm{l}(r). \tag{7}$$

In this work, we choose a type of cosh parametrized form for $V_\mathrm{N}(r)$, obtained by analyzing experimental data of α decay [54], which is written as

$$V_\mathrm{N}(r)=-V_0\frac{1+\cosh(R/a_0)}{\cosh(r/a_0)+\cosh(R/a_0)}, \tag{8}$$

where V_0 and a_0 denote the depth and diffuseness of the nuclear potential. In our past work [31], we have obtained a set of parameters considering the isospin effect, which is $a_0=0.5958$ fm and $V_0=192.42+31.059\frac{N_\mathrm{d}-Z_\mathrm{d}}{A_\mathrm{d}}$ MeV. Here N_d, Z_d and A_d denote the neutron, proton and mass number of the daughter nucleus, respectively. The nuclear potential sharp radius R is calculated by the nuclear droplet model and proximity energy [55] with the mass number of parent nucleus A, and written as

$$R=1.28A^{1/3}-0.76+0.8A^{-1/3}. \quad (9)$$

The Coulomb potential $V_{\rm C}(r)$ is taken as the potential of a uniformly charged sphere with sharp radius R, which is expressed as follows

$$V_{\rm C}(r)=\begin{cases}\dfrac{Z_{\rm d}Z_\alpha e^2}{2R}\left[3-\left(\dfrac{r}{R}\right)^2\right], & r<R,\\ \dfrac{Z_{\rm d}Z_\alpha e^2}{r}, & r>R,\end{cases} \quad (10)$$

where $Z_\alpha=2$ denotes the proton number of the α particle.

For the centrifugal barrier $V_{\rm l}(r)$, we adopt the Langer modified form, because $l(l+1)\rightarrow(l+1/2)^2$ is a necessary correction for one-dimensional problems [56]. It can be expressed as

$$V_{\rm l}(r)=\frac{\hbar^2(l+1/2)^2}{2\mu r^2}, \quad (11)$$

where l denotes the orbital angular momentum taken away by the α particle. $l=0$ for the favored α decays, while $l\neq0$ for the unfavored decays. In the case of even-even nuclei α decay, $l=0$.

3 Results and discussion

Recently, Yao et al. [57] used fourteen different versions of proximity potentials to calculate α decay half-life. Their research shows that the results of the generalized proximity potential 1977 (gp77) [58] are strongly in agreement with the experimental data and that gp77 is the most suitable for calculating the α decay half-life. To obtain a precise prediction of α decay half-life for ^{296}Og, we systematically study all 20 even-even nuclei in the same region as ^{296}Og, from ^{250}Cm to ^{294}Og, by adopting the TPA. In addition, for comparison, we also calculate the α decay half-lives of these nuclei by adopting gp77 [57, 58]. The calculations include two α decay chains: the known chain ^{294}Og $\rightarrow$ ^{290}Lv $\rightarrow$ ^{286}Fl $\rightarrow$ ^{282}Cn, and the chain ^{296}Og $\rightarrow$ ^{292}Lv $\rightarrow$ ^{288}Fl $\rightarrow$ ^{284}Cn, where decay modes of the latter three nuclei are known. ^{282}Cn and ^{284}Cn decay only by spontaneous fission and end chains.

Firstly, we calculate α decay half-lives taking $P_0=0.43$ [51] within the TPA for all 20 even-even nuclei in the same region as ^{296}Og, and obtain the corresponding hindrance factors h by Eq. (3). Further, based on the obtained h and Eq. (4), we fit and extract the corresponding parameters a, b, c, d and e, and list them in Table 1, where in this region, $82<Z\leq126$ and $152<N\leq184$, $Z_1=82$, $Z_2=126$, $N_1=152$, $N_2=184$. In our previous work [31], we obtained a set of parameters for this region. In this work, based on the latest experimental data of NUBASE2016 [37] and AME2016 [38, 39], we extracted a new set of parameters for this region. The standard deviation $\sigma_{\rm pre}=\sqrt{\sum(\log_{10}T^{\rm pre}_{1/2}-\log_{10}T^{\rm exp}_{1/2})^2/n}$ denotes deviations of α decay half-life between predictions considering the hindrance factor correction and experimental data for these 20 even-even nuclei. The value of $\sigma_{\rm pre}$ drops from 0.32 when the parameters of Ref. [31] are used to 0.26 when the new parameters are used. This indicates that the predictions using the new parameters improve by $\frac{0.32-0.26}{0.32}=18.75\%$, where $T^{\rm pre}_{1/2}=h^{*}*T^{\rm cal}_{1/2}$ with h^* obtained by Eq. (4) and $T^{\rm cal}_{1/2}$ taking $P_0=0.43$ [51].

Table 1. The parameters of α decay hindrance factor for even-even nuclei from $82<Z\leq126$ and $152<N\leq184$.

a	b	c	d	e
−24.4069	0.0017	−0.0010	0.0935	−0.0036

α decay energy is an important input for calculating α decay half-life. Sobiczewski [13] found that the calculation taking α decay energy from WS3+ [19] can best reproduce experimental α decay half-life. In the present work, we select α decay energy from WS3+ [19] to calculate the half-life of ^{296}Og. In order to verify the accuracy of the WS3+ [19] and obtain the errors caused by uncertainty in the α decay energy, we use the α decay energy from WS3+ [19] to calculate the α decay half-life within the TPA for the 20 even-even nuclei in the same region as ^{296}Og. The detailed calculations are given in Table 2. In this table, the first three columns show α decay, experimental data of α decay energy and half-life. The fourth and fifth columns are α decay energy from WS3+ [19], denoted as $Q^{\rm WS3+}_\alpha$, and calculated half-life taking $P_0=0.43$ [51] and $Q^{\rm WS3+}_\alpha$ within the TPA, denoted as $T^{\rm WS3+}_{1/2}$. The sixth and seventh columns are the α decay half-life calculated by adopting the TPA, taking $P_0=0.43$ [51] and experimental decay energy denoted as $T^{\rm cal}_{1/2}$, and extracted hindrance factor by Eq. (3), denoted as h. The eighth column denotes the hindrance factor h^*, considering the shell effect and proton-neutron interaction, calculated with Eq. (4) with the parameters listed in Table 1. The ninth column is the theoretical prediction of experimental half-life by $T^{\rm pre}_{1/2}=h^{*}*T^{\rm cal}_{1/2}$. The last column is the calculation by adopting the gp77 [57, 58], denoted as $T^{\rm gp77}_{1/2}$.

From Table 2, we can clearly see that the $Q^{\rm WS3+}_\alpha$ and $T^{\rm WS3+}_{1/2}$ respectively can reproduce Q_α and $T^{\rm exp}_{1/2}$ well. This confirms our confidence to calculate the α decay energy of ^{296}Og using WS3+ . In addition, we can see that the $T^{\rm pre}_{1/2}$ and $T^{\rm cal}_{1/2}$ are better at reproducing the experimental data $T^{\rm exp}_{1/2}$ than $T^{\rm gp77}_{1/2}$, especially for ^{250}Cm, ^{252}Cf, ^{254}Cf, ^{256}Cf and ^{256}Fm. $T^{\rm pre}_{1/2}$ is the most accurate. Furthermore, we calculate the standard deviations $\sigma_{\rm WS3+}=\sqrt{\sum(\log_{10}T^{\rm WS3+}_{1/2}-\log_{10}T^{\rm exp}_{1/2})^2/n}=0.68$,

Table 2. The calculated results of $T_{1/2}$, Q_α, h and h^* with the Q_α and $T_{1/2}^{\rm exp}$ from NUBASE2016 [37] and AME2016 [38, 39] as well as $Q_\alpha^{\rm WS3+}$ from WS3+ [19], for 20 even-even nuclei in the same region as ^{296}Og. All α decay energies and half-lives are in units of MeV and s, respectively.

α decay	Q_α	$T_{1/2}^{\rm exp}$	$Q_\alpha^{\rm WS3+}$	$T_{1/2}^{\rm WS3+}$	$T_{1/2}^{\rm cal}$	h	h^*	$T_{1/2}^{\rm pre}$	$T_{1/2}^{\rm gp77}$
^{250}Cm→^{246}Pu	5.17	1.45×10^{12}	5.10	1.30×10^{13}	6.25×10^{12}	0.23	0.33	2.07×10^{12}	5.10×10^{13}
^{252}Cf→^{248}Cm	6.22	8.61×10^{7}	6.17	1.69×10^{8}	1.04×10^{8}	0.83	0.55	5.73×10^{7}	6.77×10^{8}
^{254}Cf→^{250}Cm	5.93	1.68×10^{9}	5.95	2.35×10^{9}	3.25×10^{9}	0.52	0.58	1.88×10^{9}	2.37×10^{10}
^{256}Cf→^{252}Cm	5.56	1.19×10^{11}	5.59	2.50×10^{11}	4.13×10^{11}	0.29	0.62	2.54×10^{11}	3.42×10^{12}
^{254}Fm→^{250}Cf	7.31	1.17×10^{4}	7.32	7.94×10^{3}	8.93×10^{3}	1.31	0.89	7.92×10^{3}	4.75×10^{4}
^{256}Fm→^{252}Cf	7.03	1.16×10^{5}	7.05	9.58×10^{4}	1.20×10^{5}	0.97	0.90	1.08×10^{5}	7.03×10^{5}
^{256}No→^{252}Fm	8.58	2.91×10^{0}	8.61	1.13×10^{0}	1.41×10^{0}	2.07	1.38	1.95×10^{0}	5.88×10^{0}
^{258}No→^{254}Fm	8.15	1.20×10^{2}	8.11	4.87×10^{1}	3.52×10^{1}	3.41	1.36	4.77×10^{1}	1.66×10^{2}
^{258}Rf→^{254}No	9.19	1.05×10^{-1}	9.24	7.20×10^{-2}	1.03×10^{-1}	1.02	2.09	2.15×10^{-1}	3.87×10^{-1}
^{260}Rf→^{256}No	8.90	1.05×10^{0}	8.92	6.23×10^{-1}	6.84×10^{-1}	1.53	1.98	1.36×10^{0}	2.87×10^{0}
^{260}Sg→^{256}Rf	9.90	1.23×10^{-2}	9.94	4.04×10^{-3}	5.12×10^{-3}	2.40	3.06	1.57×10^{-2}	1.78×10^{-2}
^{264}Hs→^{260}Sg	10.59	1.08×10^{-3}	10.63	2.99×10^{-4}	3.67×10^{-4}	2.94	3.86	1.42×10^{-3}	1.19×10^{-3}
^{268}Hs→^{264}Sg	9.63	1.42×10^{0}	9.85	2.60×10^{-2}	1.09×10^{-1}	13.03	3.21	3.49×10^{-1}	4.54×10^{-1}
^{270}Hs→^{266}Sg	9.07	9.00×10^{0}	9.18	2.02×10^{0}	4.73×10^{0}	1.90	3.00	1.42×10^{1}	2.29×10^{1}
^{270}Ds→^{266}Hs	11.12	2.05×10^{-4}	10.88	2.63×10^{-4}	7.39×10^{-5}	2.77	3.99	2.95×10^{-4}	2.32×10^{-4}
			^{294}Og →^{290}Lv →^{286}Fl →^{282}Cn						
^{294}Og→^{290}Lv	11.84	1.15×10^{-3}	11.97	1.09×10^{-4}	2.24×10^{-4}	5.14	1.86	4.16×10^{-4}	8.68×10^{-4}
^{290}Lv→^{286}Fl	11.01	8.00×10^{-3}	10.88	1.15×10^{-2}	5.52×10^{-3}	1.45	2.36	1.30×10^{-2}	2.40×10^{-2}
^{286}Fl→^{282}Cn	10.37	3.50×10^{-1}	9.94	9.13×10^{-1}	6.14×10^{-2}	5.70	2.77	1.70×10^{-1}	2.88×10^{-1}
			^{296}Og →^{292}Lv →^{288}Fl →^{284}Cn						
^{296}Og→^{292}Lv			11.62	6.39×10^{-4}	6.39×10^{-4}		1.71	1.09×10^{-3}	2.64×10^{-3}
^{292}Lv→^{288}Fl	10.78	2.40×10^{-2}	10.92	8.36×10^{-3}	1.93×10^{-2}	1.25	2.21	4.25×10^{-2}	9.04×10^{-2}
^{288}Fl→^{284}Cn	10.07	7.50×10^{-1}	9.47	2.14×10^{1}	3.77×10^{-1}	1.99	2.63	9.90×10^{-1}	1.94×10^{0}

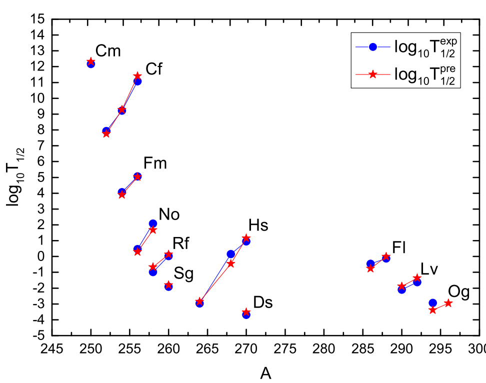

Fig. 1. (color online) Logarithmic half-lives of experimental and predicted data. The blue circles and red stars denote the experimental half-lives $T_{1/2}^{\rm exp}$, and predicted results $T_{1/2}^{\rm pre}$, respectively.

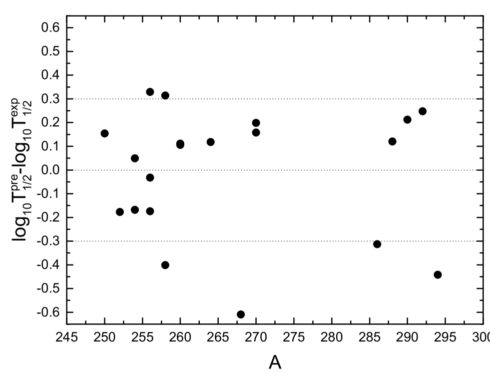

Fig. 2. The logarithmic differences between $T_{1/2}^{\rm pre}$ and $T_{1/2}^{\rm exp}$.

$\sigma_{\rm cal} = \sqrt{\sum(\log_{10}T_{1/2}^{\rm cal} - \log_{10}T_{1/2}^{\rm exp})^2/n} = 0.46$, $\sigma_{\rm gp77} = \sqrt{\sum(\log_{10}T_{1/2}^{\rm gp77} - \log_{10}T_{1/2}^{\rm exp})^2/n} = 0.69$ between $T_{1/2}^{\rm WS3+}$, $T_{1/2}^{\rm cal}$, $T_{1/2}^{\rm gp77}$ and $T_{1/2}^{\rm exp}$, respectively. The values of $\sigma_{\rm cal}$ and $\sigma_{\rm gp77}$ are larger than $\sigma_{\rm pre}$. Therefore $T_{1/2}^{\rm pre}$ improve $\frac{0.46-0.26}{0.46} = 43.48\%$, $\frac{0.69-0.26}{0.69} = 62.32\%$ compared to $T_{1/2}^{\rm cal}$ and $T_{1/2}^{\rm gp77}$, respectively.

The experimental data and predicted results are plotted logarithmically in Fig. 1. In this figure, the blue circles and red stars denote the experimental half-lives $T_{1/2}^{\rm exp}$, and predicted results $T_{1/2}^{\rm pre}$, respectively. From Fig. 1, we can see that the predicted half-lives are almost equal to the corresponding experimental data. In order to intuitively survey their deviations, we plot the logarithmic differences between predictions and experimental data in Fig. 2. From this figure, we can clearly see that the values of $\log_{10}T_{1/2}^{\rm pre} - \log_{10}T_{1/2}^{\rm exp}$ are around 0, indicating our predictions can reproduce the experimental data well. Therefore, extending our study to predict the α decay half-life and hindrance factor of ^{296}Og is believable. The standard deviations caused by $Q_{\alpha}^{\rm WS3+}$ and h^* are $\sigma_{\rm WS3+}=0.68$ and $\sigma_{\rm pre}$=0.26. We assume that the impact of above errors are equal; thus, the predicted half-life of ^{296}Og is 1.09 ms within a factor of $\sqrt{(10^{0.68})^2+(10^{0.26})^2}$=5.12.

4 Summary

In summary, we predict the α decay half-life of ^{296}Og and systematically calculate the α decay half-lives of all 20 even-even nuclei in the same region as ^{296}Og, from ^{250}Cm to ^{294}Og, by adopting the TPA. We also extract the corresponding α decay hindrance factors as well as a new set of parameters of hindrance factors considering the shell effect. Our calculations, i.e. $T_{1/2}^{\rm pre}$ considering the hindrance factor correction, reproduce the experimental data well. The predicted $T_{1/2}$ of ^{296}Og is 1.09 ms within a factor of 5.12. This work will be used as a reference for synthesizing ^{296}Og.

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