α-decay properties of $^{296}_{118}$ from double-folding potentials

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α-decay properties of the yet unknown nucleus $^{296}_{118}$ are predicted using the systematic behavior of parameters of α-nucleus double-folding potentials. The results are $Q_\alpha = 11.655 \pm 0.095$ MeV and $T_{1/2} = 0.825$ ms with an uncertainty of about a factor of 4.

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Very recently, Sobiczewski [1] has analyzed the decay properties of the yet unknown nucleus $^{296}_{118}$ using a combination of $Q_\alpha$ values from mass models and a phenomenological formula for the α-decay half-lives. This study was motivated by ongoing experiments which attempt to synthesize this heaviest nucleus to date. The present work uses a completely different approach which is based on the smooth and systematic behavior of parameters of α-decay using double-folding potentials [2].

Sobiczewski finds $Q_\alpha$ values between 10.93 MeV and 13.33 MeV from 9 different mass models. Using the phenomenological formula for α-decay half-lives of [3], the resulting half-lives for $^{296}_{118}$ vary by more than 5 orders of magnitude between 1.4 µs and 0.21 s. To reduce this uncertainty, three mass models are identified in [1] which describe the masses of nearby nuclei with the smallest deviations: Wang and Liu (WS3+, [3]), Wang et al. (WS4+, [3, 4]), and Muntian et al. (HN, [3, 5]). In detail, two α-decay chains are studied for this purpose: the known chain $^{294}_{118} \rightarrow ^{290}_{114} \text{Lv} \rightarrow ^{286}_{110} \text{Fl} \rightarrow ^{282}_{106} \text{Cn}$ (hereafter: “chain-1”), and the chain $^{296}_{118} \rightarrow ^{292}_{114} \text{Lv} \rightarrow ^{288}_{110} \text{Fl} \rightarrow ^{284}_{106} \text{Cn} (“chain-2”) where only the two latter α-decays are known from experiment. The selection of the mass formulae leads to a restricted range of $Q_\alpha$ for $^{296}_{118}$ from 11.62 MeV (WS3+), 11.73 MeV (WS4+), and 12.06 MeV (HN), and the corresponding α-decay half-lives are 4.8 ms (WS3+), 2.7 ms (WS4+), and 0.50 ms (HN). This range of predictions of almost one order of magnitude for the α-decay half-life of $^{296}_{118}$ does not yet include an additional uncertainty of the phenomenological formula of [3] which is on average a factor of 1.34 for even-even nuclei and does not exceed a factor of 1.78 in most cases [3].

In a further study Budaca et al. [9] have applied empirical fitting formulae for the prediction of the decay properties of $^{296}_{118}$. They obtain a slightly lower $Q_\alpha = 11.45$ MeV and half-lives of about 3 ms. A very low value of $Q_\alpha = 10.185$ MeV is derived from mass formulae in [10, 11], leading to predicted half-lives up to minutes for $^{296}_{118}$. Half-lives of the order of 1 ms have been found in [12, 13, 14] using the WS4+ $Q_\alpha$ and various empirical formulae for the half-life, and similar half-lives slightly below 1 ms were found very recently in [13, 14].

\[ V(r) = \lambda V_{DF}(r) + V_C(r) \]  \hspace{1cm} (1)

with the strength parameter $\lambda \approx 1.1 - 1.3$ for heavy nuclei [28, 30]. The Coulomb potential is calculated from the model of a homogeneously charged sphere where the Coulomb radius $R_C$ is taken from the root-mean-square (rms) radius of the double-folding potential.

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The strength parameter $\lambda$ is adjusted to reproduce the experimental $Q_\alpha$; i.e., the potential $V(r)$ has an eigenstate at the correct energy with a chosen number of nodes in the corresponding wave function ($N = 11$ in the present case of $0^+$ ground states of even-even superheavy nuclei; see [2]). The resulting $\lambda$ values and volume integrals $J_R$ of the nuclear potential are given in Table 1 for chain-1 and chain-2. In addition, Fig. 1 shows $J_R$ as a function of the proton number $Z_D$, neutron number $N_D$, and mass number $A_D$ of the daughter nucleus. Fig. 1 is a copy of Fig. 3 of my previous study [2] where recent experimental data for chain-1 (blue triangles) and chain-2 (red diamonds) have been added. Otherwise, this figure is identical to Fig. 3 of my previous study [2]; the lines are quadratic fits to the experimental data available in 2006.

In a next step the $\alpha$-decay half-lives $T_{1/2,\alpha}^{\text{calc}}$ are calculated from the transmission through the barrier of the potential in Eq. (1) using the semi-classical formalism of [31]. And finally the preformation factor $P$ is calculated from the ratio

$$ P = \frac{T_{1/2,\alpha}^{\text{calc}}}{T_{1/2,\alpha}^\text{exp}}. $$

The resulting preformation factors are shown in Fig. 2 which is a repetition of Fig. 1 of [2] with the additional results for chain-1 and chain-2. An average value of about 8% for $P$ was found in [2], and the new data for chain-1 and chain-2 fit nicely into this systematics. Because $\alpha$-decay is the dominating decay mode of the nuclei in chain-1 and chain-2 (except $^{296}$Pb), in the following the subscript $\alpha$ is omitted in $T_{1/2}$.

The very smooth and systematic behavior of the volume integrals $J_R$ in Fig. 1 can be used for the prediction of unknown $Q_\alpha$ values. Instead of adjusting the strength parameter $\lambda$ to experimentally known $Q_\alpha$, the strength parameter $\lambda$ is now fixed from neighboring nuclei, and from the resulting potential $V(r)$ the eigenstate energy is calculated. This is illustrated in Fig. 3 where recent experimental data for $^{296}$Pb (28% for $P$ was found in [2]) are used as a reference. The very smooth and systematic behavior of the volume integrals $J_R$ in Fig. 1 can be used for the prediction of unknown $Q_\alpha$ values. Instead of adjusting the strength parameter $\lambda$ to experimentally known $Q_\alpha$, the strength parameter $\lambda$ is now fixed from neighboring nuclei, and from the resulting potential $V(r)$ the eigenstate energy is calculated. This is illustrated in Fig. 3 where recent experimental data for $^{296}$Pb (28% for $P$ was found in [2]) are used as a reference.
TABLE I. Parameters of the $\alpha$-decays in chain-1 and chain-2. Experimental values are taken from [32].

| decay          | $Q_\alpha$ (MeV) | $\lambda$ | $J_R$ (MeV fm$^2$) | $T_{1/2}^{\text{calc}}$ (s) | $T_{1/2}^{\text{exp}}$ (s) | $P$  |
|----------------|------------------|-----------|--------------------|-----------------------------|-----------------------------|-----|
| chain-1 $^{286}\text{Fl} \rightarrow ^{284}\text{Cn}$ | 10.35 | 1.1633 | 302.86 | $4.8 \times 10^{-3}$ | $2.0 \times 10^{-1}$ | 0.0424 |
| chain-1 $^{290}\text{Lv} \rightarrow ^{288}\text{Fl}$ | 11.00 | 1.1568 | 300.96 | $7.36 \times 10^{-4}$ | $8.3 \times 10^{-3}$ | 0.0887 |
| chain-1 $^{294}\text{II} \rightarrow ^{292}\text{Lv}$ | 11.82 | 1.1486 | 298.63 | $3.27 \times 10^{-5}$ | $6.9 \times 10^{-4}$ | 0.0473 |
| chain-2 $^{288}\text{Fl} \rightarrow ^{286}\text{Cn}$ | 10.07 | 1.1615 | 302.29 | $4.70 \times 10^{-2}$ | $6.6 \times 10^{-1}$ | 0.0713 |
| chain-2 $^{292}\text{Lv} \rightarrow ^{288}\text{Fl}$ | 10.78 | 1.1545 | 300.26 | $2.51 \times 10^{-1}$ | $1.3 \times 10^{-2}$ | 0.1930 |
| chain-2 $^{296}\text{II} \rightarrow ^{294}\text{Lv}$ | 11.655 | $0.095^a$ | $1.15^b$ | 297.80 | $7.30 \times 10^{-5}$ | $8.25 \times 10^{-4}$ | 0.0885$^d$ |

$^a$ calculated using $\lambda = 1.1458 \pm 0.0010$
$^b$ extrapolated from neighboring nuclei; see Fig. 4
$^c$ $T_{1/2}^{\text{predict}}$
$^d$ average of neighboring nuclei; see Fig. 4

note that already the fits of $J_R$ in Fig. 1 (taken from [2] and based on the available data in 2006) predict $\lambda$ between 1.1413 and 1.1463 for $^{296}$II, corresponding to $Q_\alpha$ between 11.6 MeV and 12.1 MeV which is almost exactly the range of $Q_\alpha$ from the three selected mass models WS3+, WS4+, and HN in [1].

Finally, the half-life of $^{296}$II can be calculated from this potential with $\lambda = 1.1458$. The result is $T_{1/2}^{\text{calc}} = 73.0 \mu$s. According to Eq. [2], for a prediction of the experimental half-life $T_{1/2}^{\text{exp}}$, the calculated half-life has to be divided by the preformation factor $P$. Taking the average preformation factor $P_{av} = 0.0885$ of chain-1 and chain-2, one finally obtains $T_{1/2}^{\text{exp}} = 0.825$ ms.

A careful estimate of the uncertainty of the preformation factor $P$ can be read from Fig. 1. The average value of the 5 known $P$ in chain-1 and chain-2 is $P_{av} = 0.0885$. However, all $P$ have significant uncertainties which result from the uncertainties of the experimental $\alpha$-decay half-lives, and the $P$ vary between 0.0424 for $^{284}$Fl in chain-1 and 0.193 for $^{292}$Lv in chain-2. Thus, I estimate the uncertainty of $P$ for $^{296}$II from the highest and smallest values of $P$ in chain-1 and chain-2, leading to $P = 0.0885^{+0.1045}_{-0.0461}$. Again it is interesting to note that my earlier study in 2006 [2] found very similar values of $P \approx 0.08$ with an uncertainty of a factor of three.

The uncertainty of the predicted half-life $T_{1/2}^{\text{predict}} = 0.825$ ms can be estimated from the uncertainties of $Q_\alpha$ and $P$. The uncertainty of $Q_\alpha$ of about 100 keV translates to a factor of about 1.7 for the uncertainty of the half-life, and the uncertainty of $P$ of slightly above a factor of two enters directly into the uncertainty of $T_{1/2}^{\text{predict}}$. Combining both uncertainties results in a factor of about 4 uncertainty for the predicted half-life; i.e., the half-life of $^{296}$II should lie in between 0.2 ms and 3.3 ms.

In summary, I have used the smooth and regular behavior of the strength parameter $\lambda$ of the $\alpha$-nucleus double-folding potential to estimate the $\alpha$-decay energy $Q_\alpha$ of the unknown nucleus $^{296}$II. The prediction of $Q_\alpha = 11.655 \pm 0.095$ MeV is completely independent of mass formulae, but nevertheless in excellent agreement with the results from the selected mass formulae in [1]. From the barrier transmission and from the preformation $P$ of about 9%, a half-life for $^{296}$II of 0.825 ms is predicted with an uncertainty of a factor of 4. These predictions for the $Q_\alpha$ value and for the $\alpha$-decay half-life of

![FIG. 3. (Color online) Potential strength parameter $\lambda$ for chain-1 (blue triangles) and for chain-2 (red diamonds). The full symbols are derived from experimental data [32]; the open diamond is the extrapolation for the unknown nucleus $^{296}$II. Further discussion see text.](image1)

![FIG. 4. (Color online) Extrapolation of the preformation factor $P$ to $^{296}$II.](image2)
may help to guide experimentalists, and hopefully, these predictions can be confronted with experimental results in the near future.

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