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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_α 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 α-decay parameters using double-folding potentials [2].

Sobiczewski finds Q_α values between 10.93 MeV and 13.33 MeV from nine 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+ [4]), Wang *et al.* (WS4+ [5,6]), and Muntian *et al.* (HN [7,8]). In detail, two α-decay chains are studied for this purpose: the known chain $^{294}118 \rightarrow {}^{290}\mathrm{Lv} \rightarrow {}^{286}\mathrm{Fl} \rightarrow {}^{282}\mathrm{Cn}$ (hereafter: "chain-1"), and the chain $^{296}118 \rightarrow {}^{292}\mathrm{Lv} \rightarrow {}^{288}\mathrm{Fl} \rightarrow {}^{284}\mathrm{Cn}$ ("chain-2"), where only the two latter α decays are known from experiment. The selection of the mass formulas leads to a restricted range of Q_α 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 formulas 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 formulas in [10,11], leading to predicted half-lives up to minutes for ^{296}118. Half-lives of the order of 1 ms have been obtained in [12] using the WS4+ Q_α and various empirical formulas for the half-life, and similar half-lives slightly below 1 ms were found very recently in [13,14] which are also based on Q_α from WS4+.

Also very recently somewhat shorter half-lives of ^{296}118 of 14 – 285 μs [15] and ≈ 25 μs [16] were reported which are based on $Q_\alpha = 12.4$ MeV [15] and 12.3 MeV [16] from earlier mass formulas.

For completeness it has to be mentioned that α decay is the dominant decay mode of ^{296}118. Partial half-lives of ^{296}118 for spontaneous fission have been estimated in [1,17]; they exceed the α-decay half-life by several orders of magnitude.

Contrary to the study of Sobiczewski and the other recent calculations for ^{296}118 [9–16], the present approach does not use mass models for the prediction of the unknown Q_α of ^{296}118 which is the most important quantity for the prediction of its half-life. Instead, the smooth behavior of parameters is used which is obtained in calculations with systematic double-folding potentials [2]. This method is particularly well suited for the present case where the available experimental results for chain-1 and chain-2 have to be extrapolated only to a very close neighbor. For completeness it should be noted that there is another method for an independent determination of Q_α from the systematics of Q_α differences of neighboring nuclei; unfortunately, the published values end at ^{295}118 and do not include ^{296}118 [18].

The application of double-folding potentials for α decay in a simple α+nucleus two-body model has been described in detail already in [2], and it has been applied and further developed in a series of α-decay studies in the last years (e.g., [19–29]). Here I briefly repeat the essential points. First, the interaction between the daughter nucleus and the α particle is calculated by a double-folding procedure using an effective nucleon-nucleon interaction; for details, see [30]. As in [2], the unknown density of the daughter nucleus is calculated from a two-parameter Fermi distribution with the radius parameter $R = R_0 A_D^{1/3}$ which scales with the mass number A_D of the daughter, and R_0 and the diffuseness a are taken from the average values of ^{232}Th and ^{238}U [31]. The density of the α particle is also derived from from the charge density in [31]. This results in the double-folding potential $V_{\mathrm{DF}}(r)$. The total potential is given by

$$V(r) = \lambda\, V_{\mathrm{DF}}(r) + V_{\mathrm{C}}(r) \tag{1}$$

with the strength parameter $\lambda \approx 1.1$–1.3 for heavy nuclei [30,32]. 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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TABLE I. Parameters of the α decays in chain-1 and chain-2. Experimental values are taken from [34].

	decay	Q_α (MeV)	λ	J_R (MeV fm^3)	$T_{1/2}^{\mathrm{calc}}$ (s)	$T_{1/2}^{\mathrm{exp}}$ (s)	P
chain-1	^{286}Fl $\rightarrow$ ^{282}Cn	10.35	1.1633	302.86	8.48×10^{-3}	2.0×10^{-1}	0.0424
chain-1	^{290}Lv $\rightarrow$ ^{286}Fl	11.00	1.1568	300.96	7.36×10^{-4}	8.3×10^{-3}	0.0887
chain-1	^{294}118 $\rightarrow$ ^{290}Lv	11.82	1.1486	298.63	3.27×10^{-5}	6.9×10^{-4}	0.0473
chain-2	^{288}Fl $\rightarrow$ ^{284}Cn	10.07	1.1615	302.29	4.70×10^{-2}	6.6×10^{-1}	0.0713
chain-2	^{292}Lv $\rightarrow$ ^{288}Fl	10.78	1.1545	300.26	2.51×10^{-3}	1.3×10^{-2}	0.1930
chain-2	^{296}118 $\rightarrow$ ^{292}Lv	11.655 ± 0.095[a]	1.1458[b]	297.80	7.30×10^{-5}	8.25×10^{-4}[c]	0.0885[d]

[a]Calculated using $\lambda = 1.1458 \pm 0.0010$.
[b]Extrapolated from neighboring nuclei; see Fig. 3.
[c]$T_{1/2}^{\mathrm{predict}}$.
[d]average of neighboring nuclei; see Fig. 4.

The strength parameter λ is adjusted to reproduce the experimental Q_α, 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 λ values and volume integrals J_R of the nuclear potential are given in Table I 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. Figure 1 is a copy of Fig. 3 of my previous study [2] where recent experimental data for chain-1 and chain-2 have been added. It is obvious from Fig. 1 that the volume integrals J_R show a regular and smooth dependence of Z_D, N_D, and A_D, which can be used to obtain reliable estimates for unknown nuclei. Discontinuities of J_R appear only at shell closures, e.g., at the doubly magic daughter nucleus ^{208}Pb (see Fig. 1 and [2]).

In a next step the α-decay half-lives $T_{1/2,\alpha}^{\mathrm{calc}}$ are calculated from the transmission through the barrier of the potential in Eq. (1) using the semiclassical formalism of [33]. And finally the preformation factor P is calculated from the ratio

$$P = \frac{T_{1/2,\alpha}^{\mathrm{calc}}}{T_{1/2,\alpha}^{\mathrm{exp}}}. \qquad (2)$$

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

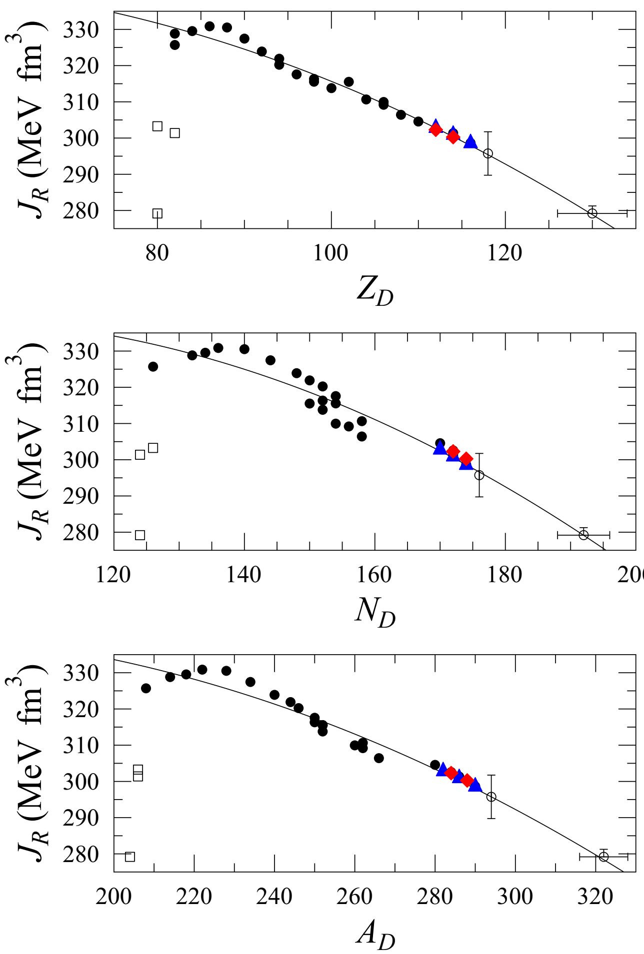

FIG. 1. Volume integrals J_R for superheavy nuclei as a function of Z_D (upper), N_D (middle), and A_D (lower). Data for chain-1 (blue triangles) and chain-2 (red diamonds) have been added. Otherwise, this figure is identical to Fig. 3 of my previous study [2]; the lines are quadratic fits to the experimental data available in 2006.

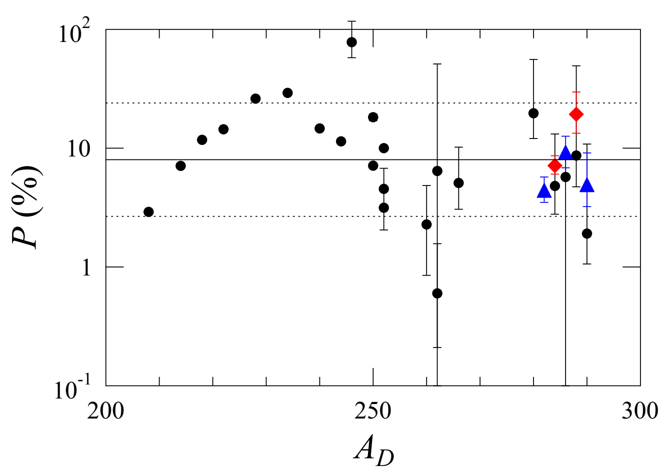

FIG. 2. Preformation factors P as a function of the mass number A_D of the daughter nucleus, taken from [2] and extended by data for chain-1 (blue triangles) and chain-2 (red diamonds). The horizontal lines indicate an average value of $P \approx 8\%$ (full line) and typical uncertainties of a factor of three (dotted lines); taken from [2].

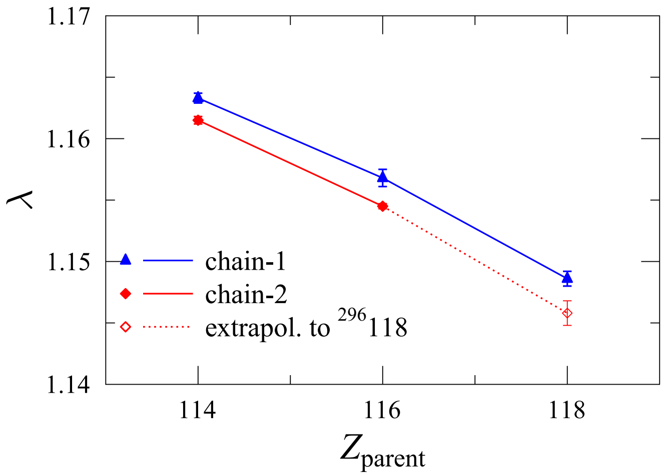

FIG. 3. Potential strength parameter λ for chain-1 (blue triangles) and for chain-2 (red diamonds). The full symbols are derived from experimental data [34]; the open diamond is the extrapolation for the unknown nucleus $^{296}118$. Further discussion see text.

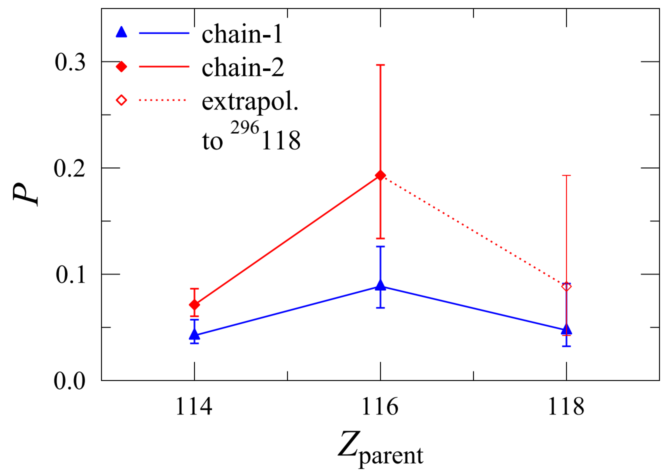

FIG. 4. Extrapolation of the preformation factor P to $^{296}118$.

nicely into this systematics. Because α decay is the dominating decay mode of the nuclei in chain-1 and chain-2 (except ^{286}Fl [34]), in the following the subscript α 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_α values. Instead of adjusting the strength parameter λ to experimentally known Q_α, the strength parameter λ is now fixed from neighboring nuclei, and from the resulting potential $V(r)$ the eigenstate energy is calculated. This is illustrated in Fig. 3: $\lambda = 1.1458 \pm 0.0010$ is estimated for $^{296}118$. This estimate for λ is well constrained by the similar slope of $\lambda(Z)$ for chain-1 and chain-2 and by the small and almost constant difference between chain-1 and chain-2.

The potential $V(r)$ with the strength parameter $\lambda = 1.1458$ has the eigenstate with $N = 11$ nodes at $Q_\alpha = 11.655$ MeV. The small uncertainty of λ translates to an uncertainty of Q_α of only 95 keV. Thus, the present study predicts $Q_\alpha = 11.655 \pm 0.095$ MeV for the unknown nucleus $^{296}118$. This result is very close to the predictions of the selected mass models WS3+ and WS4+ and slightly lower than the mass model HN [1]. It is interesting to note that already the fits of J_R in Fig. 1 (taken from [2] and based on the available data in 2006) predict λ between 1.1413 and 1.1463 for $^{296}118$, corresponding to Q_α between 11.6 MeV and 12.1 MeV which is almost exactly the range of Q_α from the three selected mass models WS3+, WS4+, and HN in [1].

Finally, the half-life of $^{296}118$ can be calculated from this potential with $\lambda = 1.1458$. The result is $T_{1/2}^{\rm calc} = 73.0$ μs. According to Eq. (2), for a prediction of the experimental half-life $T_{1/2}^{\rm exp}$, the calculated half-life has to be divided by the preformation factor P. Taking the average preformation factor $P_{\rm av} = 0.0885$ of chain-1 and chain-2, one finally obtains $T_{1/2}^{\rm predict} = 0.825$ ms.

A careful estimate of the uncertainty of the preformation factor P can be read from Fig. 4. The average value of the five known P in chain-1 and chain-2 is $P_{\rm av} = 0.0885$. However, all P have significant uncertainties which result from the uncertainties of the experimental α-decay half-lives, and the P vary between 0.0424 for ^{286}Fl in chain-1 and 0.193 for ^{292}Lv in chain-2. Thus, I estimate the uncertainty of P for $^{296}118$ 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 $T_{1/2}^{\rm predict} = 0.825$ ms can be estimated from the uncertainties of Q_α and P. The uncertainty of Q_α 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 $T_{1/2}^{\rm predict}$. Combining both uncertainties results in a factor of about 4 uncertainty for the predicted half-life, i.e., the half-life of $^{296}118$ 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 λ of the α-nucleus double-folding potential to estimate the α-decay energy Q_α of the unknown nucleus $^{296}118$. The prediction of $Q_\alpha = 11.655 \pm 0.095$ MeV is completely independent of mass formulas, but nevertheless in excellent agreement with the results from the selected mass formulas in [1]. From the barrier transmission and from the preformation P of about 9%, a half-life for $^{296}118$ of 0.825 ms is predicted with an uncertainty of a factor of 4. These predictions for the Q_α value and for the α-decay half-life of $^{296}118$ may help to guide experimentalists, and hopefully, these predictions can be confronted with experimental results in the near future.

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