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Theoretical predictions for the nucleus ^{296}118

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Theoretical predictions for the α-decay chain of the nucleus ^{296}118 are performed. The synthesis of this nucleus is being attempted in experiments running in Dubna. The α-decay energies Q_α, and the α-decay and spontaneous-fission half-lives, T_α and T_{sf}, are studied. The analysis of the α decay is based on a phenomenological model using only three parameters. The calculations are performed in nine variants using masses obtained within nine nuclear-mass models describing masses of the heaviest nuclei. The experimental Q_α energies, known from earlier experiments for the potential daughter, ^{292}Lv, and grand-daughter, ^{288}Fl, nuclei are reproduced with an average of the absolute values of the discrepancies: from 0.13 to 1.52 MeV within the considered variants. Measured half-lives T_α are reconstructed within average ratios: from 1.7 to 1054. Within all variants considered, the half-life T_α of the nucleus ^{296}118 is obtained larger than needed (around 1 μs) for its observation.

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Introduction. At the present time attempts are being made to synthesize the nucleus ^{296}118 [1]. If successful, this would be the heaviest nuclide observed, with the largest number (178) of neutrons, situated at the border of the known nuclear chart, both in terms of proton and neutron numbers. Simultaneously, it would be closest to the strongest closed shell at $N = 184$, predicted in Refs. [2–4]. This strong shell may have an influence on the stability of this nucleus. The synthesis of this nucleus is expected to be via the reaction ^{251}Cf(^{48}Ca,$3n$)^{296}118. The specifics of the experiment of this synthesis consist of the use of a specific target. In contrast to the usual cases, when one tries to use as isotopically pure a target as possible, the target in the discussed experiment is a mixture of the three isotopes: ^{249}Cf (50%), ^{250}Cf (15%), and ^{251}Cf (35%) [5].

Simultaneously, this peculiarity of the experiment puts a special requirement on predictions of the result, to be helpful in the interpretation of these results. They should be as realistic and precise as possible. Aiming at this, I first tested the model to be used in the predictions by the description of already known results for a nucleus very close to the predicted one. This was performed for the nucleus ^{294}118 [6] differing by only two neutrons from the nucleus being predicted. Among the three models used for the description of the α-decay energy Q_α, the best result was obtained with the model WS3+ [7]. The experimental decay energies Q_α, measured for three nuclei appearing in the decay chain, were reproduced with an average of the absolute values of the discrepancies between calculated and measured values equal to 180 keV. With these Q_α, measured half-lives were reproduced within an average factor of 2.9, i.e., with very good accuracy. The simple phenomenological approach of Ref. [8] was used to describe the half-lives. The length of the chain was also reproduced correctly.

Although, as stated above, the initial nucleus ^{296}118 of the studied chain was never observed, its potential daughter, ^{292}116, and grand-daughter, ^{288}114, were studied experimentally in other reactions in a number of works [9–16]. These results are reviewed in Refs. [17,18]. They will be a test for the present calculations.

An analysis of the properties of super-heavy nuclei (SHN) with the use of methods other those used in the present paper is given, e.g., in [19–40]. An extensive discussion of the interaction between theory (predictions) and experiment (discovery) in the region of SHN has been recently undertaken in Ref. [41].

Description of the calculations. A very strong dependence of the α-decay half-life T_α on the α-decay energy Q_α requires a very careful choice of mass model to calculate a realistic Q_α. Due to the strong dependence of the accuracy of a given model on the region of the nuclear chart to which it is applied, illustrated recently in [42,43], one should take the model which is best in the close neighborhood of the region of interest.

The problem is illustrated in Table I, slightly extended with respect to that given in [6]. The accuracy of six mass models is shown for three regions: global ($Z,N \geqslant 8$), heavy ($Z \geqslant 82$, $N \geqslant 126$), and very heavy ($Z \geqslant 100$). The accuracy is characterized by the rms of the discrepancies between the calculated and measured masses. For the latter, the masses evaluated recently in Ref. [44] are taken.

The six selected models are the following: the widely used (for over 20 years) models of Möller *et al.* (FRDM) [45] and of Duflo and Zuker (DZ) [46] and four more recent models: Nayak and Satpathy (INM, infinite nuclear matter) [47], Wang and Liu (WS3+) [7], Wang *et al.* (WS4+) [48], and Muntian *et al.* (HN) [49] (see also Ref. [50]). Five of them are of a global character giving masses for nuclei with $Z,N \geqslant 8$. One model (HN) is of a local nature, being specially adapted to the description of heavy nuclei: $Z \geqslant 82$, $N \geqslant 126$. Four of the models (FRDM, WS3+, WS4+, and HN) are of the macroscopic-microscopic type. The WS3+ model (often also denoted as WS3+RBF) and the WS4+ one (often denoted as WS4+RBF) are Weizsäcker-Skyrme models applying the radial basis function (RBF) approach, which is a general

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TABLE I. Rms (in keV) of the discrepancies between measured and calculated masses. The latter are obtained with the use of the indicated models for the regions of global ($Z,N \geqslant 8$), heavy ($Z \geqslant 82$, $N \geqslant 126$) and very heavy ($Z \geqslant 100$) nuclei. The year of publication of each model, as well as the number of nuclei with measured masses in each region, N_{nucl}, are also specified.

Model Year	FRDM 1995	DZ 1995	INM 2012	WS3+ 2010	WS4+ 2014	HN 2001	N_{nucl}
$Z,N \geqslant 8$	654	394	362	248	170		2353
$Z \geqslant 82$, $N \geqslant 126$	484	398	258	136	115	355	312
$Z \geqslant 100$	676	828	471	126	130	118	36

mathematical method of extrapolation of known data of some quantity to predict unknown values for it.

One can see in Table I that the rms for the FRDM, DZ, and INM models are significantly larger than for the WS3+ and WS4+ approaches in all the considered regions. Especially interesting are the results for the heaviest nuclei ($Z \geqslant 100$) as all SHN are contained in it. It is clear from Table I that the three models WS3+, WS4+, and HN should be used in predictions for the nucleus $^{296}118$. Simultaneously, the sensitivity of the results to the differences between them will be instructive.

One could ask the question, does a good description of masses by a given model result in a good description of the decay energy Q_α? It seems the answer is yes, at least for even-even nuclei, for which Q_α is directly the difference between the masses of nuclei differing in Z and N by 2. Let us test this in the case of SHN.

Table II shows the discrepancies between calculated and measured masses, δM, and the respective discrepancies, δQ_α, for the four heaviest nuclei, for which both these quantities are known experimentally. The discrepancies are calculated for all six models considered in Table I.

It is seen in Table II that a small δM (WS3+ and WS4+) has as a consequence small δQ_α. Accidentally, a relatively large δM may be accompanied by small δQ_α (e.g., the case of FRDM for ^{264}Hs and ^{262}Sg).

One should mention that the result showing the good accuracy of the description of Q_α for SHN by the model WS4+ agrees with the results of Ref. [37], which gives a very wide and detailed review of the accuracy of the description of SHN by various approaches. Similar analyses are also performed in Refs. [30,38].

The calculations of the α-decay half-lives are based on the phenomenological model of α decay worked out in Ref. [8]. For even-even nuclei, as considered in this Rapid Communication, the formula for the logarithm of the α half-life T_α^{th} has the form

$$\log_{10} T_\alpha^{\text{th}}(Z,N) = aZ[Q_\alpha(Z,N)]^{-1/2} + bZ + c, \qquad (1)$$

where Q_α is the α-decay energy (the ground-state to ground-state transition). The parameters a,b,c, adjusted to experimental data for even-even nuclei [51–53], have the values

$$a = 1.5372, \quad b = -0.1607, \quad c = -36.573. \qquad (2)$$

Results. The results are collected in Table III. These are mainly the α-decay energies Q_α and the half-lives T_α. Both experimental and theoretical values are given. The latter are calculated in three variants using three nuclear-mass models: two recent global models WS3+ [7] and WS4+ [48] and one older, the Warsaw local model HN [49] (see also Ref. [50]). As already mentioned earlier, the experimental values are based on measurements described in Refs. [9–16] and reviewed in Refs. [17,18]. The nucleus ^{288}Fl decays by both α emission and spontaneous fission, while the next nuclide, ^{284}Cn, decays only by spontaneous fission, ending the chain. The respective experimental half-lives of spontaneous fission $T_{\text{sf}}^{\text{expt}}$ are 0.30 s and 38 ms, as compared with the theoretical ones, $T_{\text{sf}}^{\text{th}}$, 2.1×10^3 and 4.0 s, taken from Refs. [54,55].

One can see in Table III that the description of Q_α(expt) by the three variants of the calculations are of similar quality and are quite good. The absolute values of the discrepancies, $|\,\delta Q_\alpha\,|$, between theory and experiment are smaller than 0.45 MeV for the two α decays in all three variants of the calculations. The average (Avg.) of these values in the chain are given in the last column of the table.

The quality of the description of the experimental T_α, noted as T_α(expt), by theory is characterized in the table by the factor *f*, which is the ratio of the larger value of T_α^{th} and T_α^{expt} to the smaller one. The average values of *f* for the chain are given in the last column. It is seen that they are related with the average values of the discrepancies $|\,\delta Q_\alpha\,|$. Thus, the experimental half-lives T_α are reproduced on the average by the theory within a factor smaller than 33 in all three variants of the calculations, i.e., with a reasonable accuracy. The best description is obtained by the HN model: with the average of $|\,\delta Q_\alpha\,|$ equal to 260 keV and the half-lives T_α reproduced within an average factor equal to 1.7, i.e., with a very good accuracy.

Figures 1 and 2 illustrate the results in graphical form. It is seen that the α-decay energies Q_α obtained within the recent nuclear mass models WS3+ and WS4+ are close to each other

TABLE II. Discrepancies between calculated and measured masses, δM, and decay energies, δQ_α, both in MeV, obtained for four heaviest nuclei, for which experimental values of both these quantities exist. Theoretical values are calculated for all six models considered in Table I.

Model Nucleus	FRDM δM	FRDM δQ_α	DZ δM	DZ δQ_α	NS δM	NS δQ_α	WS3+ δM	WS3+ δQ_α	WS4+ δM	WS4+ δQ_α	HN δM	HN δQ_α
^{270}Ds	−2.00	−0.80	−3.06	−1.37	0.62	−0.27	0.06	−0.03	−0.06	0.08	−0.09	0.25
^{266}Hs	−1.20	−0.66	−1.69	−1.39	0.89	−0.04	0.09	0	−0.14	−0.01	−0.34	−0.30
^{264}Hs	−0.83	−0.01	−0.79	−1.41	1.18	0.36	0.08	0.05	−0.02	0.07	0.13	0
^{262}Sg	−0.54	0.01	−0.30	−0.49	0.33	0.76	0.09	0.07	−0.13	0.05	−0.04	−0.10

TABLE III. Calculated and measured values of the α-decay energies Q_α (in MeV), α-decay and spontaneous-fission half-lives, T_α and T_{sf}, for the decay chain of the nucleus $^{296}118$. Some quantities derived from them are also given (see text).

Nucleus	$^{296}118$	^{292}Lv	^{288}Fl	Avg.
Q_α(WS3+)	11.62	11.05	9.73	
Q_α(WS4+)	11.73	11.10	9.62	
Q_α(HN)	12.06	11.06	10.32	
Q_α(expt)		10.78	10.07	
δQ_α(WS3+)		0.27	−0.34	0.30
δQ_α(WS4+)		0.32	−0.45	0.38
δQ_α(HN)		0.28	0.25	0.26
T_α(WS3+)	4.8 ms	27 ms	19 s	
T_α(WS4+)	2.7 ms	20 ms	41 s	
T_α(HN)	0.50 ms	25 ms	0.45 s	16
f(WS3+)		2.1	29	32
f(WS4+)		1.5	62	1.7
f(HN)		1.9	1.5	
T_α^{expt}		13 ms	0.66 s	
$T_{\mathrm{sf}}^{\mathrm{th}}$	1.3×10^4 s	1.4×10^5 s	2.1×10^3 s	
$T_{\mathrm{sf}}^{\mathrm{expt}}$			0.30 s	

even for an artificially elongated α-decay chain (seven decays), which reflects the fact that the models are rather similar to each other.

Figures 3 and 4, plotted in [6] for the decay properties of the nucleus $^{294}118$, are shown for comparison. One can see that the corresponding pictures for $^{296}118$ and $^{294}118$ are similar. This is not specially strange, as the nuclei are close to each other. An impressive result in Fig. 4 is the closeness of the predictions by all three models to the experimental result for T_α of $^{294}118$. This is a good prognostic for using the same models to predict T_α of still heavier nuclei.

Discussion. To extend the illustration of the sensitivity of Q_α and T_α to a change of the mass model, let us take six

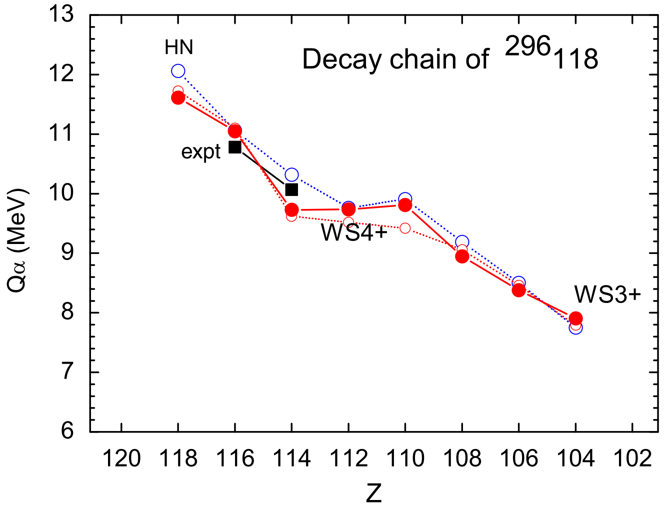

FIG. 1. α-decay energy Q_α calculated within the models WS3+, WS4+, and HN, as compared with the experimental values available for the nuclei ^{292}Lv and ^{288}Fl.

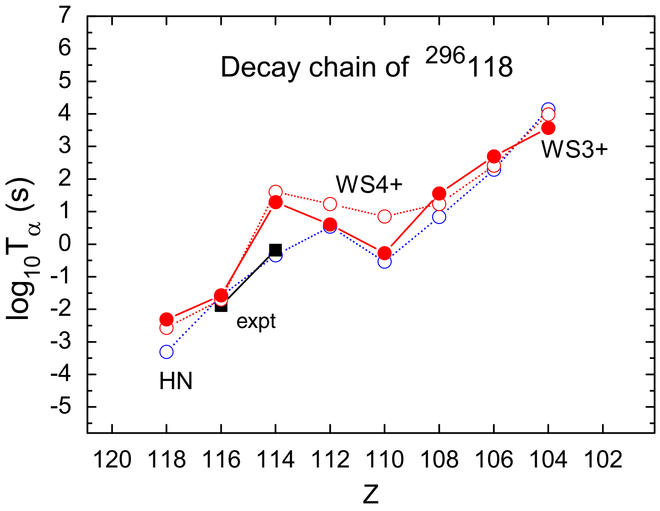

FIG. 2. Logarithm of the α-decay half-lives T_α (given in seconds) calculated with the use of WS3+, WS4+, and HN masses, as compared with the experimental values available for the nuclei ^{292}Lv and ^{288}Fl.

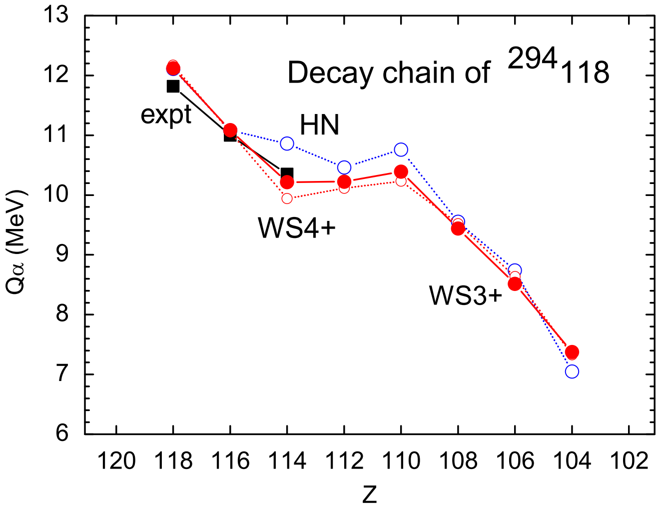

FIG. 3. Same as in Fig. 1, but for the nucleus $^{294}118$ [6].

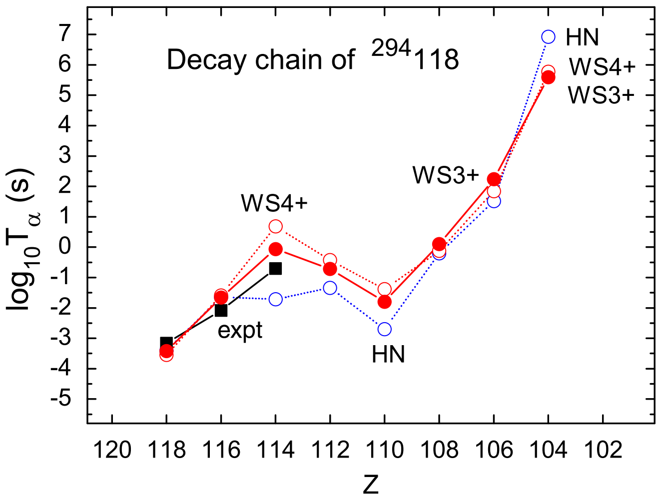

FIG. 4. Same as in Fig. 2, but for the nucleus $^{294}118$ [6].

TABLE IV. Same as in Table III, but with the use of the FRDM, DZ, INM, TCSM, HFB31, and SE nuclear-mass models.

Nucleus	$^{296}118$	^{292}Lv	^{288}Fl	Avg.
Q_α(FRDM)	12.29	10.83	9.17	
Q_α(DZ)	11.83	11.35	11.10	
Q_α(INM)	13.33	12.28	11.60	
Q_α(TCSM)	11.01	10.77	10.32	
Q_α(HFB31)	10.93	10.60	10.80	
Q_α(SE)	10.94	10.91	10.68	
Q_α(expt)		10.78	10.07	
δQ_α(FRDM)		0.05	−0.90	0.48
δQ_α(DZ)		0.57	1.03	0.80
δQ_α(INM)		1.50	1.53	1.52
δQ_α(TCSM)		−0.01	0.25	0.13
δQ_α(HFB31)		−0.18	0.73	0.46
δQ_α(SE)		0.13	0.61	0.37
T_α(FRDM)	0.16 ms	93.4 ms	948 s	
T_α(DZ)	1.6 ms	5.2 ms	5.1 ms	
T_α(INM)	1.4 μs	46.9 μs	0.36 ms	
T_α(TCSM)	0.14 s	0.13 s	0.45 s	
T_α(HFB31)	0.21 s	0.36 s	27 ms	
T_α(SE)	0.20 s	59 ms	54 ms	
f(FRDM)		7.2	1440	724
f(DZ)		2.5	129	66
f(INM)		277	1830	1054
f(TCSM)		10	1.5	5.8
f(HFB31)		28	24	26
f(SE)		4.5	12	8.2
$T_\alpha^{\rm expt}$		13 ms	0.66 s	

models other than those analyzed in Table III. Two of them, FRDM and DZ, are very popular and widely used for over 20 years, and one, INM, is much more recent. An additional three models are the following: a modified two-center shell model (TCSM) [56], a recent version of a long series of the Hartree-Fock-Bogoliubov models (HFB31) [57], and a semiempirical model (SE) [58]. Each of these three models is of a different nature. The TCSM is of a macroscopic-microscopic (macro-micro) kind, the HFB31 is of a pure microscopic, self-consistent nature, and the SE model is semiempirical. The results are presented in Table IV in a full analogy to those given in Table III for the WS3+, WS4+, and HN models.

It is seen in Table IV that the discrepancies in the description of Q_α by the six models are very different: from 0.01 MeV (in the absolute value) by the TCSM up to 1.50 MeV by INM for the ^{292}Lv nucleus and from 0.25 MeV by TCSM up to 1.53 MeV by INM for the ^{288}Fl nuclide. A conclusion from this analysis is that the use of the popular models FRDM, DZ, and INM to predict the properties of the not-yet-observed nucleus $^{296}118$ would be a mistake. These models are not the best ones for describing superheavy nuclei.

Finally, let us test the TCSM, HFB31, and SE nuclear-mass models by the data of decay of the nucleus $^{294}118$. Four α-decay chains of this nucleus, composed of three α-decays each, were observed up to now, as discussed recently in Ref. [6].

The results of the test are presented in Table V. It is seen that the best description of both Q_α and T_α is obtained in the case of the macro-micro TCSM, then by the SE, and then by the fully microscopic model HFB31. The average of the absolute values of the discrepancies of Q_α are 0.13, 0.48, and 0.69 MeV, and the average of f factors are 7.0, 17, and 44 for the TCSM, SE, and HFB31 models, respectively. Let us recall, for the comparison, that the respective values are 0.18, 0.27, and 0.29 for Q_α and 2.9, 9.8, and 5.2 for the factor f in the case of the WS3+, WS4+, and HN models, respectively, found in Ref. [6]. Thus, the best description of Q_α is obtained by the TCSM and T_α by the WS3+ model.

TABLE V. Test of the nuclear-mass models: TCSM, HFB31 and SE by experimental data of the decay chains of the nucleus $^{294}118$. The values of Q_α are in MeV.

Nucleus	$^{294}118$	^{290}Lv	^{286}Fl	Avg.
Q_α(TCSM)	11.52	10.90	10.38	
Q_α(HFB-31)	11.25	12.11	10.74	
Q_α(SE)	11.55	11.42	11.10	
Q_α(expt)	11.82	11.00	10.35	
δQ_α(TCSM)	−0.30	−0.10	0.03	0.13
δQ_α(HFB-31)	−0.57	1.11	0.39	0.69
δQ_α(SE)	−0.27	0.42	0.75	0.48
T_α(TCSM)	8.1 ms	62 ms	0.32 s	
T_α(HFB31)	35 ms	0.11 ms	38 ms	
T_α(SE)	6.9 ms	3.6 ms	5.1 ms	
f(TCSM)	12	7.5	1.6	7.0
f(HFB-31)	51	75	5.3	44
f(SE)	10	2.3	39	17
$T_\alpha^{\rm expt}$	0.69 ms	8.3 ms	0.20 s	

Summary. The decay chain of the not-yet-observed nucleus $^{296}118$ has been studied theoretically. The peculiarity of the experiment, in which the synthesis of that heavy nucleus is being attempted, puts a special requirement on the accuracy of theoretical predictions so that they are helpful in the interpretation of the results. The qualities of the predictions are tested by the results obtained in earlier experiments, independent of the presently running experiment, for lighter members of the chain: ^{292}Lv, ^{288}Fl and (partly) ^{284}Cn.

The study was performed with the use of Q_α obtained from nine different nuclear models. This resulted in a rich illustration of the sensitivity of the results to changes of a mass model. The following conclusions may be drawn from the study:

1. The half-life of the nucleus $^{296}118$ predicted with the use of all models is larger than needed (around 1 μs) for its observation. Thus, the nucleus should be observed if the cross section for its synthesis in a given experiment is sufficiently large.
2. The experimental Q_α obtained for the lighter members of the chain, ^{292}Lv and ^{288}Fl, are described with different average accuracy: from 0.13 MeV with the TCSM up to 1.52 MeV with the INM model.
3. The experimental T_α are reproduced within a factor f: from 1.7 with the HN up to 1054 with the INM model.
4. The popular mass models FRDM, DZ, or INM reproduce rather poorly the measured values for the ^{292}Lv and ^{288}Fl nuclei.

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