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PREDICTIONS FOR A SUPERHEAVY ELEMENT 120

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Predictions are made for the decay chains of the nuclei $^{298}120$ and $^{299}120$, *i.e.* for two isotopes of the not-yet-observed superheavy element 120. These nuclei are planned to be synthesized in the nuclear reaction $^{54}\mathrm{Cr} + {}^{248}\mathrm{Cm}$, in an experiment to be performed in Darmstadt (Germany). We predict that at least four α decays in both the $^{298}120$ and $^{299}120$ chains should be observed. This means that at least six new superheavy nuclides and one new superheavy element (120) should be seen, if the cross section for the reaction is sufficiently large. The predicted half-lives: 11 μs and 15 μs for the nuclei $^{298}120$ and $^{299}120$, respectively, indicate that we are not far from the lower limit of the half-life (about 1 μs) for a nucleus to be observable. Due to this, the planned experiment will be an important step towards answering the essential question: where is the limit of the periodic table of the elements?

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1. Introduction

One witnesses swift progress in the synthesis of and studies of the physical properties of heaviest nuclei (*e.g.*, [1, 2, 3, 4, 5]) and of the chemical properties of heaviest elements (*e.g.*, [6, 7, 8, 9]). In particular, more than 90 superheavy (transactinide) isotopes of 15 superheavy elements have already been observed. These exotic objects, synthesized in the laboratory and not observed in nature, exist due to their shell structure (similar to that of an atom) and are an important source of our knowledge of this structure and its consequences. The heaviest of these nuclei is $^{294}118$, synthesized in Dubna (Russia) [5, 3], *i.e.* the nucleus with atomic number $Z = 118$ and mass number $A = 294$.

As a continuation of this research, the synthesis of a new element 120 (*i.e.* with $Z = 120$) is planned to be performed in Darmstadt (Germany) in the fusion reaction $^{54}\mathrm{Cr} + {}^{248}\mathrm{Cm}$ [10]. Two channels of the reaction, corresponding to emission of 4 and 3 neutrons from the compound nucleus $^{302}120$ are expected, leading to the production of $^{298}120$ and $^{299}120$, respectively. Both these nuclei, as well as all products of the α decay of $^{299}120$ would be new, while the α-decay products of $^{298}120$ would be just the nuclei already observed in Dubna [5] and would supply us with an independent confirmation of that observation.

The objective of this paper is to get an idea of the properties of the new nuclei, in particular their α-transition energies Q_α^{t} and half-lives T_α, which will be measured. First of all it would be of great interest to know whether the half-lives of the nuclei $^{298}120$ and $^{299}120$ are expected to be large enough (larger than about 1 μs) to allow for their observation. If so, we would also like to know how long their decay chains would be, especially that of $^{299}120$ which will be completely new. Also the relation between the properties of the nuclei of the chains of $^{298}120$ and $^{299}120$ is of great interest, as the latter are nearer to the closed neutron shell at $N = 184$. This strong closed shell was predicted a long time ago by various models [11, 12, 13] and should be manifested by an especially large stability of such nuclei. It is very interesting then to see how this shift towards $N = 184$ will be reflected in the properties of the nuclei.

Our theoretical analysis is based on a traditional, well tested, macroscopic–microscopic model (see *e.g.*, [14]). One should mention, however, that studies of superheavy nuclei are also being performed within more recent, purely microscopic approaches (*e.g.*, [15, 16, 17, 14]).

2. Method of the analysis

The main quantities calculated by us for a nucleus are: the α-decay energy Q_α and α-decay half-life T_α. The energy Q_α is directly obtained from the masses of the nuclei, which are calculated within a macroscopic–microscopic approach, as already mentioned in the Introduction. The Yukawa-plus-exponential model [18] which is an improvement of the liquid-drop model used in earlier work, is taken for the macroscopic part of the mass and the Strutinski shell correction [19], based on the Woods–Saxon single-particle potential [20], is used for its microscopic part. The short-range pairing interaction between nucleons is treated within the Bardeen–Cooper–Schrieffer approximation. The model is specially adapted to the description of heavy nuclei and is denoted by HN (Heavy Nuclei). Details of the approach may be found in [21].

The α-decay half-lives are calculated with the use of a recently proposed [22] simple phenomenological formula

$$\log_{10} T_\alpha^{\mathrm{ph}}(Z,N) = aZ\left[Q_\alpha(Z,N) - \bar{E}_i\right]^{-1/2} + bZ + c\,, \qquad (1)$$

where the parameters a, b, c are

$$a = 1.5372\,, \qquad b = -0.1607\,, \qquad c = -36.573 \tag{2}$$

and the parameter $\bar{E}_i$ (average excitation energy of the daughter nucleus) is

$$\bar{E}_i = 0 \quad \text{for e–e}\,, \qquad \bar{E}_i = \bar{E}_p = 0.113\,\text{MeV} \quad \text{for o–e}\,,$$
$$\bar{E}_i = \bar{E}_n = 0.171\,\text{MeV} \quad \text{for e–o}\,,\ \text{and}\ \bar{E}_i = \bar{E}_p + \bar{E}_n \quad \text{for o–o nuclei}\,. \tag{3}$$

Here, *e.g.* o–e, means (odd-Z, even-N) nuclei, where Z is the proton and N is the neutron number.

The above values of the 5 parameters $a, b, c, \bar{E}_p$ and $\bar{E}_n$ have been obtained by fitting calculated $T_\alpha^{\rm ph}$ of Eq. (1), with the use of experimental Q_α [23], to experimental T_α [24]. Details of the fit are described in [22].

The formula (1) is of the Viola–Seaborg type [25]. The main difference between the original formula and the new one is that the latter gives a specific interpretation of the hindrance of the α-transition in the presence of odd nucleons, namely it is assumed that the whole effect of these nucleons is to reduce the transition energy,

$$Q_\alpha^{\rm t} = Q_\alpha - \bar{E}_i\,, \tag{4}$$

with respect to the α-decay energy Q_α (the ground-state (g.s.) to the ground-state transition) by the average excitation energy $\bar{E}_i$ of the daughter nucleus. Such an assumption is rather natural as the half-life is determined by the most probable transition and this occurs between states with the same structure (the same quantum numbers). As, in general, the structure of the ground states of parent and daughter nuclei is different, transition to an excited state occurs, reducing the transition energy. With such a reduction, there is no other hindrance, and the transition occurs with the same probability as in an even-even nucleus, described by the three parameters: a, b, c. One should remember, however, that in specific cases (existence of isomeric states in the parent nucleus), the excitation of the parent nucleus may also contribute to the transition energy $Q_\alpha^{\rm t}$. An additional difference between the two formulae is that the new one has one adjustable parameter less.

To illustrate the odd-neutron effect on T_α, let us say that according to Eq. (1), the effect prolongs T_α of the nucleus $^{299}120$ by a factor of more than 2. For this short-lived nucleus, such a prolongation is significant in answering the question: may we expect to observe this nucleus or not?

3. Results and discussion

Table I gives the results for the decay chain of the nucleus $^{298}120$ calculated with our α-transition energies $Q_\alpha^{\rm t}$ (given in MeV). Here (even–even nuclei), the transition energies $Q_\alpha^{\rm t}$ are equal to the decay energies Q_α (g.s. to g.s. transitions). The α-transition half-lives T_α are calculated according to Eq. (1), with the excitation energy of the daughter nuclei, E_i, equal to zero. The spontaneous-fission half-lives, $T_{\rm sf}$, are taken from Refs. [26, 27], where they were calculated (by the dynamical programming method) in a 4-dimensional deformation space with the metric specified by the parameters describing the inertia of a nucleus to the respective deformation modes. The half-lives appeared to be rather realistic, properly predicting or reproducing measured values of $T_{\rm sf}$ (cf. *e.g.* Refs. [2, 3, 14]). The calculated values of $T_{\rm sf}/T_\alpha$, shown in the table, indicate that at least four α particles should be observed in the chain. It is not excluded, however, that even a very long chain of eight consecutive α decays might be seen. But the latter would need a larger statistics in the synthesis of the nucleus $^{298}120$, which is hard to expect at present.

TABLE I

Values of the characteristic quantities for the decay chain of $^{298}120$ (HN).

Nucleus	$^{298}120$	$^{294}118$	$^{290}116$	$^{286}114$	^{282}Cn	^{278}Ds	^{274}Hs	^{270}Sg	^{266}Rf
$Q_\alpha^{\rm t}$	13.14	12.09	11.08	10.86	10.46	10.76	9.55	8.74	7.05
T_α	11 μs	0.43 ms	23 ms	19 ms	46 ms	2.0 ms	0.62 s	32 s	0.27 y
$T_{\rm sf}$	28 ms	22 m	12 m	1.5 s	71 ms	56 ms	5.8 s	55 s	23 s
$T_{\rm sf}/T_\alpha$	2.6×10^3	3.2×10^6	3.3×10^4	78	1.6	28	9.3	1.7	2.7×10^{-6}

Table II shows the results for the decay chain of the even–odd nucleus $^{299}120$. Here, again, at least four α particles may be expected to be seen in the chain. The calculated T_α of the initial nucleus of the chain, $^{299}120$, is slightly larger than that of $^{298}120$, locating it at a larger distance from the lower limit of about 1 μs, needed for a nucleus to reach the detector (*i.e.* to be observed).

TABLE II

Values of the characteristic quantities for the decay chain of $^{299}120$ (HN).

Nucleus	$^{299}120$	$^{295}118$	$^{291}116$	$^{287}114$	^{283}Cn	^{279}Ds	^{275}Hs	^{271}Sg	^{267}Rf
$Q_\alpha^{\rm t}$	13.06	12.05	10.74	10.39	9.99	10.07	9.24	8.54	7.24
T_α	15 μs	0.52 ms	0.16 s	0.30 s	0.80 s	0.11 s	4.9 s	2.4 m	16 d
$T_{\rm sf}$	42 ms	2.0 h	20 h	18 m	2.0 s	34 ms	2.9 s	28 s	12 s
$T_{\rm sf}/T_\alpha$	2.7×10^3	1.4×10^7	4.6×10^5	3.5×10^3	2.6	0.31	0.59	0.20	0.88×10^{-5}

3.1. Sensitivity to changes of the model

To get an idea of the reliability of the results, it is instructive to see their sensitivity to changes of the model used to obtain them. Here, the model used in the calculation of the α-decay energy Q_α is important. The model which is used to calculate the half-life T_α is rather reliable. It reproduces very well the experimental T_α for many nuclei when the experimental Q_α are taken (see [22]).

To test the sensitivity of the results to changes of the model supplying us with Q_α, we take the semi-empirical (SE) model [28]. This approach gives the best description of the measured masses of heaviest nuclei (see Ref. [14]). The test was performed for the chain of $^{298}120$ which is more critical for the question, whether the chain will be observed or not, than the chain of $^{299}120$.

The results are presented in Table III. One can see that the values of $Q^{\rm t}_\alpha$ and T_α are very different from those of Table I, especially for the first nuclei in the chain, *i.e.* the heaviest ones. In particular, the α-transition energy $Q^{\rm t}_\alpha$ obtained in the semi-empirical model for $^{298}120$ is 1.67 MeV smaller than that of the HN model, which results in a T_α more than three orders of magnitude larger than the HN value. This would mean that the nucleus $^{298}120$ would undergo fission, rather than emit α particle, and no chain would be observed. In that case, even the identification of the nucleus decaying by fission would not be possible.

TABLE III

Values of the characteristic quantities for the decay chain of $^{298}120$ (SE).

Nucleus	$^{298}120$	$^{294}118$	$^{290}116$	$^{286}114$	^{282}Cn	^{278}Ds	^{274}Hs	^{270}Sg	^{266}Rf
$Q^{\rm t}_\alpha$	11.47	11.55	11.42	11.10	10.64	10.08	9.47	8.82	8.16
T_α	41 ms	6.9 ms	3.6 ms	5.1 ms	16 ms	0.10 s	1.0 s	18 s	8.0 m
$T_{\rm sf}$	28 ms	22 m	12 m	1.5 s	71 ms	56 ms	5.8 s	55 s	23 s
$T_{\rm sf}/T_\alpha$	0.68	2.0×10^5	2.1×10^5	3.0×10^2	4.4	0.55	5.5	3.0	4.8×10^{-2}

Due to this large difference in predictions by the two models, one should test their predictive power, to choose the more reliable one.

3.2. Predictive power of the two models

It is fortunate that three nuclei of the investigated chain have been observed earlier [5] (see also Ref. [3]) and the measured values of Q_α and T_α may be used for a test of the discussed models. These values are specified in Table IV.

Figure 1 shows in a graphical form the α-decay energies Q_α calculated within the two models considered (as given in Tables I and III). The available experimental values (Table IV) are also shown, for comparison. One can see

TABLE IV

Experimental data for Q_α (in MeV) and T_α for the indicated three nuclei.

Nucleus	$^{294}118$	$^{290}116$	$^{286}114$
Q_α	11.81	11.00	10.33
T_α	0.89 ms	7.1 ms	0.26 s

that the energies of the two models really differ quite a lot, especially for the initial nucleus in the chain, $^{298}120$. Concerning the description of the experimental values, the macroscopic–microscopic (HN) results are closer to them. For the three nuclei for which measured values are available, the average of the absolute values of the discrepancy between calculation and experiment is 0.30 MeV and 0.48 MeV for the HN and SE models, respectively. Thus, the predictive power of the HN model is better.

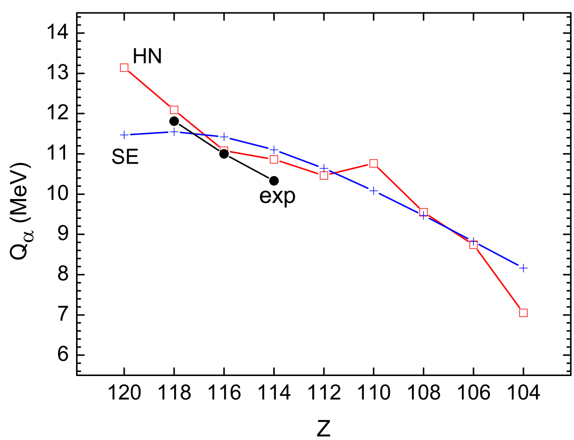

Fig. 1. α-decay energies Q_α calculated within HN and SE models for the decay chain of the nucleus $^{298}120$, compared with the experimental values.

The ability of the HN model to realistically foresee the decay properties of heaviest nuclei has also been tested recently on the decay chains of $^{293}117$ and $^{294}117$. The predictions for these chains [29] have been confirmed by experiment [30]. The predicted values of Q_α and T_α were quoted in the paper announcing the observation of these chains, for comparison with the observed results.

Figure 2 illustrates the logarithm of T_α of the nuclei in the chain, calculated within the two models. The measured values are also shown, for comparison.

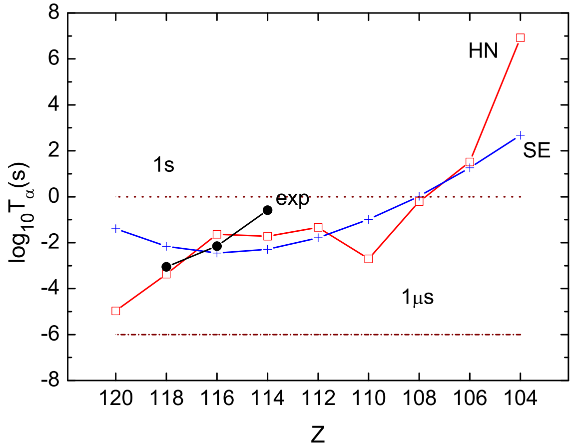

Fig. 2. The same as in Fig. 1, but for the logarithm of the α-decay half-lives T_α (given in seconds). Two lines indicating approximate lower limits of the half-life of a nucleus which could be observed (1 μs) and of an atom which could be studied chemically (1 s), are shown.

To get an idea how long the chain could be, one should take into account the competing decay mode, *i.e.* fission. One can see in Table I that the fission half-life $T_{\rm sf}$ is expected to be significantly larger than T_α for the first four nuclei. For the fifth one, ^{282}Cn, the two half-lives are already comparable, which means that this nucleus may also undergo fission, ending the chain. Two lines corresponding to 1 μs and 1 s are shown in the figure. The 1 μs line indicates an approximate lower limit of the half-life of a nucleus which could be observed, and the 1 s line shows an approximate half-life of a nucleus, the atom of which could be studied chemically. It is seen in the figure that nuclei in the expected chain (from ^{298}120 to ^{282}Cn) are predicted, by the HN model, to have sufficiently long half-lives to be observed, but not sufficient for the chemical study of their atoms.

4. Conclusions

The following conclusions may be drawn from this study:

(1) Half-lives of nuclei appearing in long decay chains of the not-yet-observed nuclei, ^{298}120 and ^{299}120, are calculated. Two main decay modes, α decay and spontaneous fission, are considered. For the α decay, two different models for calculation of the decay energy Q_α are used. The models have been tested in a prediction for the synthesis of isotopes of the new element 117.

(2) It is found that the half-lives: 11 μs and 15 μs predicted for the nuclei $^{298}120$ and $^{299}120$, respectively, are already not far from the lower limit (around 1 μs) needed for a detection of the synthesized nucleus. Still, they are sufficiently distant from this limit to reasonably expect their observation. Due to this, a non-observation of these nuclei in the experiment to be performed in Darmstadt should be rather interpreted as a too small cross section for their synthesis (under the conditions of the experiment) than as not-sufficiently-long their half-lives.

(3) At least four α decays in both chains are expected to be observed.

(4) If so, the observation would be a discovery of one (the heaviest) new superheavy element (120) and six new superheavy nuclei.

(5) The results indicate that the planned experiment will be an important step towards answering the essential and fascinating question: where is the limit of the periodic table of chemical elements?

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