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PREDICTIONS FOR NUCLEI OF A NEW ELEMENT 117

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Predictions for the decay chains of the nuclei $^{293}117$ and $^{294}117$ are done within a macroscopic–microscopic model. The nuclei are planned to be synthesized in the reaction ^{249}Bk + ^{48}Ca ($4n$ and $3n$ channels), to be performed in Dubna. It is obtained in our study that at least three α decays in both $^{293}117$ and $^{294}117$ chains should be observed. Thus, at least six new superheavy nuclides and one new superheavy element should be seen, if cross-sections for the reactions are sufficiently large. Additionally, it is expected that the decay chain of $^{294}117$ would be the first one in which the isotope of the element 113, $^{286}113$, has a chance to be studied chemically.

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1. Introduction

Studies of superheavy nuclei (SHN) constitute presently a fast developing branch of nuclear physics (*e.g.* [1–3]). More than 80 nuclei of 14 superheavy elements (SHE) have been already observed. As a continuation of this research, the synthesis of a new element 117 is planned to be performed in Dubna in the reaction ^{249}Bk + ^{48}Ca. Channels $4n$ and $3n$ of the reaction are expected, leading to the production of the odd-A nucleus $^{293}117$ and the odd–odd one $^{294}117$, respectively. These nuclei and their decay products would constitute completely new decay chains composed of not only the isotopes of a new element, but also of new isotopes of lighter elements. This is because the nuclei $^{287}115$ and $^{288}115$ and their decay products, observed previously [4, 5], have by two neutrons less than these expected presently.

The objective of this paper is to get an orientation in the properties of the expected nuclei, in particular in such ones as the transition energies Q^{t}_{α} and the half-lives T_{α}. We would also like to know how long the chains may be expected. Also the relation between the properties of the nuclei of the new chains and of the previous ones is of a great interest, as the new ones are by two units, in the neutron number N, closer to the strong magic number

$N = 184$, predicted already long time ago by various models [6–8]. It is interesting, if this shift towards $N = 184$ will be reflected in the properties of the nuclei.

The theoretical analysis is performed within a macroscopic–microscopic model (*e.g.* [9]), as described in the next section.

2. Method of the analysis

The ground-state mass of a nucleus is calculated within a macroscopic–microscopic approach. The Yukawa-plus-exponential model [10] is taken for the macroscopic part of the energy and the Strutinski shell correction, based on the Woods–Saxon single-particle potential [11], is used for its microscopic part. Pairing interaction, with the isotopic-dependent strength of the monopole type, is treated within the BCS approximation. Details of the approach are specified in [12].

No blocking is used when solving the pairing equations for odd-A or odd–odd nuclei. It has been shown that the description of masses [13] and also α-decay energies [14] of odd-A and also odd–odd heavy nuclei, done this way, is similarly good as of even–even ones.

Alpha-decay half-lives are calculated with the use of a recently proposed [15] simple phenomenological formula. The formula is

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

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

$$\begin{aligned}
\bar{E}_i &= 0 && \text{for e–e}\,,\\
\bar{E}_i &= \bar{E}_p = 0.113 \text{ MeV} && \text{for o–e}\,,\\
\bar{E}_i &= \bar{E}_{\rm n} = 0.171 \text{ MeV} && \text{for e–o}\,,\\
\bar{E}_i &= \bar{E}_p + \bar{E}_{\rm n} && \text{for o–o nuclei}\,.
\end{aligned} \tag{3}$$

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 adjustment of them to experimental values of T_α [16] with the use of experimental values of Q_α [17]. Details of the fit are described in [15].

The basic assumption of the formula (1) is that the whole effect of odd 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, the transition to an excited state occurs, reducing the transition energy. With such a reduction, there is no other hindrance, and the transition is done with the same probability as in an even–even nucleus, described by three parameters: a, b, c.

For odd–odd nuclei, the reduction of the transition energy is: $\bar{E}_p + \bar{E}_n = 0.283\,\mathrm{MeV}$. Such reduction elongates the half-life of *e.g.* the nucleus $^{294}117$ by a factor of 5, which is not a small effect.

3. Results

3.1. Decay chain of the nucleus $^{293}117$

Table I gives the α-transition energies Q_α^{t} (in MeV), the α-transition half-lives T_α and the spontaneous-fission half-lives T_{sf}, calculated for a long α-decay chain of the odd-A nucleus $^{293}117$. The chain is artificially taken so long, to see the dependence of the values of T_α and T_{sf}, and also of the relation between them, on the length of it. The transition energy Q_α^{t} in Table I is: $Q_\alpha^{\mathrm{t}} = Q_\alpha - \bar{E}_i$, (see Eq. (4)), where $\bar{E}_i = 0.113\,\mathrm{MeV}$ (see Eq. (3) for the case of o–e nuclei). The calculated α-decay energies Q_α (the g.s. to g.s. transitions) are taken from Refs. [13, 18]. The α-transition half-lives are calculated according to the formula (1), with Q_α^{t} given in the table.

TABLE I

Values of the quantities characteristic for the decay chain of $^{293}117$ calculated with the use of our Q_α [13, 18].

Nucleus	$^{293}117$	$^{289}115$	$^{285}113$	^{281}Rg	^{277}Mt	^{273}Bh	^{269}Db	^{265}Lr
Q_α^{t}	11.42	10.63	10.10	10.37	9.73	8.78	8.06	6.51
T_α	7.0 ms	0.15 s	0.84 s	38 ms	0.42 s	55 s	42 m	27 y
$T_{\mathrm{sf}}^{\mathrm{av}}$	20 h	24 m	2.8 s	42 ms	51 ms	3.0 s	28 s	23 s
$T_{\mathrm{sf}}^{\mathrm{av}}/T_\alpha$	1.0×10^{7}	9.7×10^{3}	3.3	1.1	0.12	5.4×10^{-2}	1.1×10^{-2}	2.7×10^{-8}

Concerning the spontaneous-fission half-lives $T_{\mathrm{sf}}^{\mathrm{av}}$, they are obtained, for each nucleus, as the average of the values calculated [19, 20] for two neighboring e–e nuclei (only for the nucleus ^{265}Lr, the value for the near nucleus ^{266}Rf is taken). Thus, this average value is about the lower limit of T_{sf}, as it disregards the effect of the odd proton. We try to estimate the latter effect in Subsec. 3.3.

One can see in Table I that $T_\alpha < T_{\rm sf}^{\rm av}$ for the first four decays. Thus, we may expect to see at least four α particles, but the appearance of an additional one or even two of them is quite possible. One should not expect, however, to see seven and especially eight alphas.

3.2. Decay chain of the nucleus $^{294}117$

Table II shows the same quantities as Table I, but calculated for the odd–odd nuclei in the decay chain of $^{294}117$. Here, because of odd–odd nuclei in the chain, the spontaneous-fission half-life $T_{\rm sf}^{\rm av}$ of each nucleus is obtained as the average of the values calculated [19, 20] for four neighboring e–e nuclei (only for the nucleus ^{266}Lr, the average of the values for the nearest two e–e Rf nuclei is taken). One can see that $T_\alpha < T_{\rm sf}^{\rm av}$ for the first three transitions. Thus, one may expect to see at least three α particles in the chain. The appearance of the fourth α is quite possible, but that of the fifth one is much less probable. It looks then that the decay chain of $^{294}117$ may be shorter (three or four alphas) than that of $^{288}115$ (five alphas) [4]. This would be just opposite to what one could think, as in the case of $^{294}117$ one starts from the nucleus with two protons more and one could expect one α more in the chain.

TABLE II

Values of the quantities characteristic for the decay chain of $^{294}117$ calculated with the use of our Q_α [13, 18].

Nucl.	$^{294}117$	$^{290}115$	$^{286}113$	^{282}Rg	^{278}Mt	^{274}Bh	^{270}Db	^{266}Lr
$Q_\alpha^{\rm t}$	11.15	10.37	9.70	9.57	9.27	8.55	7.83	6.65
T_α	31 ms	0.70 s	11 s	5.6 s	8.8 s	5.1 m	4.8 h	6.0 y
$T_{\rm sf}^{\rm av}$	0.62 y	1.5 d	17 m	1.4 s	29 ms	1.5 s	14 s	12 s
$T_{\rm sf}^{\rm av}/T_\alpha$	6.3×10^{8}	1.9×10^{5}	0.92×10^{2}	0.25	3.3×10^{-3}	4.9×10^{-3}	0.81×10^{-3}	6.4×10^{-8}

Another interesting thing in the chain is that the isotope of the element 113, $^{286}113$, has a large half-life T_α, sufficient to be studied chemically. This would be for the first time that such an isotope would be reached. A general situation is illustrated in Fig. 1. The figure shows the dependence of logarithm of the α-decay half-lives T_α on the neutron number N for odd–odd nuclei, for which α decay is mostly privileged with respect to spontaneous fission, because of a strong effect of odd nucleons, delaying the latter process (see Subsec. 3.3). The data in Fig. 1 are taken from Refs. [3, 4, 21] and extrapolated to nuclei of the chain $^{294}117$ calculated in the present paper. One can see that, generally, the half-lives T_α increase with increasing N, except only local fluctuation around $N = 162$, due to strong shell effects at this magic number. Due to this, one can really get $T_\alpha > 1$ s ($\log_{10}T_\alpha(s) > 0$), needed for a chemical study, for the element 113 only for $N = 173$, *i.e.*, in the new predicted chain discussed here. This could be also the case for the element Mt ($Z = 109$). However, a chance of the observation of the isotope of this element in the discussed chain is rather small because of a small T_{sf} for this isotope, as already mentioned above.

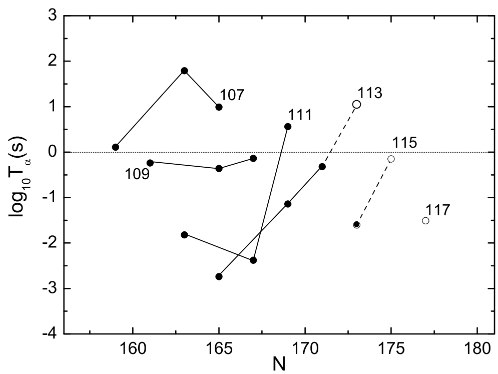

Fig. 1. Dependence of logarithm of the α-decay half-life T_α (given in seconds) on neutron number N for elements with proton number $Z = 107$, 109, 111, 113, 115, and one value for $Z = 117$. Full circles represent experimental values and empty ones correspond to calculated values.

3.3. Effect of odd nucleons on the fission half-lives T_{sf}

To get some orientation on the effect of odd nucleons on the spontaneous-fission half-lives T_{sf}, we choose nuclei for which at least two cases of fission have been observed, and which are not too near to closed shells. Around closed shells, T_{sf} changes very fast and any averaging may be misleading.

3.3.1. An odd-*A* nucleus

For the odd-A nucleus $^{261}\mathrm{Rf}_{157}$, experimental value of T_{sf}, based on three spontaneous-fission cases of all four observed decays [22], is: $T_{\mathrm{sf}}^{\mathrm{exp}} = 7.1\,\mathrm{s}$. The average of the calculated values [19] for two neighboring e–e nuclei, $^{260}\mathrm{Rf}$ and $^{262}\mathrm{Rf}$, is: $T_{\mathrm{sf}}^{\mathrm{av}} = 132$ ms. Thus, the effect of the odd neutron is: $T_{\mathrm{sf}}^{\mathrm{exp}}/T_{\mathrm{sf}}^{\mathrm{av}} = 54$.

3.3.2. An odd–odd nucleus

For the odd–odd nucleus $^{262}\mathrm{Db}_{157}$, experimental value of T_{sf}, based on two observed spontaneous-fission cases at the end of the decay chain of the nucleus $^{278}113_{165}$ [3], is: $T_{\mathrm{sf}}^{\mathrm{exp}} = 15\,\mathrm{s}$. The average of the calculated values [19] for the four neighboring e–e nuclei, ^{260}Rf, ^{262}Rf, ^{262}Sg and ^{264}Sg, is: $T_{\rm sf}^{\rm av} = 0.66\,$s. The effect of the odd proton and the odd neutron is then: $T_{\rm sf}^{\rm exp}/T_{\rm sf}^{\rm av} = 23$.

Thus, basing on these two cases, one can say crudely that the effect of one or two nucleons on $T_{\rm sf}$ is the increase of this half-life by roughly one to two orders of magnitude.

3.4. Sensitivity of the results to a model used

Let us look at the results when another model for the calculations of Q_α is taken. As such a model, we take the semi-empirical approach [23]. This approach supplies us with a rather good description of masses and α-decay energies of heaviest nuclei (see *e.g.* [9]). Table III shows the respective results for the decay chain of ^{293}117. One can see that the results are rather similar to the previous ones. The difference in $Q_\alpha^{\rm t}$ between the two models is contained within $\pm 0.3\,$MeV. Only for the nucleus ^{265}Lr, it is larger ($1.07\,$MeV).

TABLE III

Values of the quantities characteristic for the decay chain of ^{293}117 calculated with the use of semi-empirical Q_α [23].

Nucl.	^{293}117	^{289}115	^{285}113	^{281}Rg	^{277}Mt	^{273}Bh	^{269}Db	^{265}Lr
$Q_\alpha^{\rm t}$	11.12	10.94	10.58	10.10	9.53	8.91	8.25	7.58
T_α	36 ms	25 ms	47 ms	0.19 s	1.5 s	22 s	9.3 m	6.7 h
$T_{\rm sf}^{\rm av}$	20 h	24 m	2.8 s	42 ms	51 ms	3.0 s	28 s	23 s
$T_{\rm sf}^{\rm av}/T_\alpha$	2.0×10^{6}	5.7×10^{4}	60	2.2×10^{-1}	3.3×10^{-2}	1.4×10^{-1}	5.0×10^{-2}	0.95×10^{-3}

TABLE IV

Values of the quantities characteristic for the decay chain of ^{294}117 calculated with the use of semi-empirical Q_α [23].

Nucl.	^{294}117	^{290}115	^{286}113	^{282}Rg	^{278}Mt	^{274}Bh	^{270}Db	^{266}Lr
$Q_\alpha^{\rm t}$	10.66	10.52	10.21	9.75	9.20	8.60	7.96	7.28
T_α	0.51 s	0.28 s	0.43 s	1.7 s	14 s	3.5 m	1.6 h	4.2 d
$T_{\rm sf}^{\rm av}$	0.62 y	1.5 d	17 m	1.4 s	29 ms	1.5 s	14 s	12s
$T_{\rm sf}^{\rm av}/T_\alpha$	3.8×10^{7}	4.6×10^{5}	2.4×10^{3}	0.82	2.0×10^{-3}	7.2×10^{-3}	2.4×10^{-3}	3.3×10^{-5}

In the case of the decay chain of $^{294}117$, the results (shown in Table IV) are also rather similar, indicating a chance to observe at least three or four α decays in the chain. Here, however, T_α for the nucleus $^{286}113$ is smaller than in the case of our model (Table II), decreasing a chance for a chemical study of the element 113.

4. Conclusions

The following conclusions may be drawn from this study:

(i) Half-lives of nuclei appearing in long decay chains of not yet observed nuclei, $^{293}117$ and $^{294}117$, 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.

(ii) It is found that half-lives predicted for both nuclei, $^{293}117$ and $^{294}117$, are sufficiently long (in the millisecond region) to observe them, if the cross-sections for their synthesis is enough large.

(iii) At least three α decays in both chains are expected to be observed.

(iv) The decay chain of $^{294}117$ is expected to be the first one in which the isotope of the element 113, $^{286}113$, could be studied chemically.

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