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Production of superheavy elements

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Abstract

We propose a discovery experiment for production and identification of isotopes of unobserved elements up to element 119. We predict decay properties of nuclear systems which might be obtained in this experiment and discuss posibilities of identification of new elements on the basis of the calculated properties.

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Over the last few years, much progress has been made in the production and investigation of decay properties of the heaviest atomic nuclei. At GSI-Darmstadt, α-decaying isotopes of the elements 110, 111 and 112 [1–3] have been synthesized in reactions based on the ^{208}Pb$_{126}$ or ^{209}Bi$_{126}$ target nuclei. Very recently, the Dubna-Livermore collaboration has made an attempt at production of a new element 114. The ^{244}Pu$_{150}$ target nucleus was bombarded by the ^{48}Ca$_{28}$ projectile ions at Dubna at the end of 1998. According to the authors of Ref. [4], the results of this experiment may be interpreted as decays of a superheavy nucleus $^{289}114_{175}$ and its descendants.

The aim of this Rapid Communication is to propose a discovery experiment for elements 113−119 and, simultaneously, for unobserved isotopes of known transactinide elements which might be identified by chemistry. In Ref. [5], we made predictions for the formation cross sections of many superheavy nuclei and came to the conclusion that the most promising reaction based on the ^{208}Pb$_{126}$ target nucleus and stable projectile is ^{208}Pb$_{126}$(^{86}Kr$_{50}$,1n)$^{293}118_{175}$. We obtained a value of 670 pb for the formation cross section of $^{293}118_{175}$ at the optimal bombarding energy in the LAB system $E_{\rm LAB}$ = 449.1 MeV which corresponds to the excitation energy of the compound nucleus E^* = 13.3 MeV. If this prediction is correct then the production of a large number of superheavy nuclei is possible in contrast to recent experiments in which only very few superheavy nuclear systems were synthesized with the measured formation cross sections of the order of $0.1 - 1$ pb, e.g. [6,3].

The use of ^{209}Bi$_{126}$ as a target instead of ^{208}Pb$_{126}$ may lead to the production of $^{294}119_{175}$ and its descendants. From experimental systematics of the formation cross sections of transactinide nuclei, we can expect that the cross section of ^{209}Bi$_{126}$(^{86}Kr$_{50}$,1n)$^{294}119_{175}$ should be smaller than the one of ^{208}Pb$_{126}$(^{86}Kr$_{50}$,1n)$^{293}118_{175}$ by a factor of $4 - 9$ [7] for the typical excitation energy in the 1n-emission chanel equal to $E^* = 12 - 14$ MeV ($E_{\rm LAB} = 452.6 - 455.4$ MeV). The use of the doubly magic ^{208}Pb$_{126}$ and the magic ^{87}Rb$_{50}$ as reaction partners might be even more profitable for the production of element 119 ($E_{\rm LAB} = 461.6 - 464.4$ MeV).

In the present paper, we calculate decay properties of even-odd and odd-odd nuclei which might be produced in bombardments of $^{208}\mathrm{Pb}_{126}$ and $^{209}\mathrm{Bi}_{126}$ by $^{86}\mathrm{Kr}_{50}$ and discuss the posibilities of identification of these nuclei on the basis of the obtained theoretical properties. We use the model which have had some success in reproducing and predicting the ground-state decay properties of even-even transactinide nuclei [8,9].

We predict that $^{293}118_{175}$ initiates an α-decay chain of so far unobserved nuclei. Mass excess M, ground state to ground state α-decay energy Q_α and half-life T_α, calculated for these nuclei, are given in the left side of Table I. Mass and, consequently, Q_α is obtained by means of the macroscopic-microscopic model [8,9] with the Yukawa-plus-exponential potential [10] taken as the macroscopic energy and the Strutinsky shell correction [11] based on the Woods-Saxon single-particle potential [12] used as the microscopic energy. The calculation is performed in the four-dimensional deformation space describing axially symmetric nuclear shapes. T_α is obtained by using the Viola and Seaborg formula with the parameters fitted to even-even nuclei with $Z > 82$ and $N > 126$ [8]. The effect of an odd particle is taken into account in the macroscopic potential. Next, we make use of the spontaneous-fission half-lives calculated in Refs. [8,9] for even-even nuclei which are lighter neighbours of nuclei in the decay chain in question. We assume that an unpaired nucleon increases the fission barrier by about half MeV and, consequently, increases the spontaneous-fission half-life by a factor of 1000 in comparison with the respective quantities for the lighter neighbouring even-even nucleus [13]. With the spontaneous-fission half-lives obtained in such a way, we come to the conclusion that α-decay is considerably faster than spontaneous fission until a fissioning nucleus $^{265}\mathrm{Rf}_{161}$ is reached, which terminates the decay chain.

A large half-life equal to 8 min is calculated for $^{269}\mathrm{Sg}_{163}$ because of the influence of the predicted deformed shell closures at $N = 162$, e.g. [14–16], and $Z = 108$, e.g. [14,15]. This large half-life, calculated for an unobserved isotope $^{269}\mathrm{Sg}_{163}$ of the element Sg ($Z = 106$) with known chemical properties [17,18], permits identification of this nucleus by chemistry and, consequently, permits identification of the entire decay chain.

Decay properties of nuclei constituting the α-decay chain initiated by the nucleus $^{294}119_{175}$ are given in the right side of Table I. This chain contains isotopes of unknown elements 119, 117, 115 and 113, and unobserved isotopes of known elements 111, Mt, Bh and Db. The last nucleus in the decay chain is the experimentally known isotope $^{262}Lr_{159}$ which decays by electron capture with the measured half-life of $T_{EC}^{\rm exp} = 3.6$ h [19]. The calculated large α-decay half-life of 3.6 h for $^{266}Db_{161}$ permits chemical identification of this decay chain. Moreover, the calculated α-decay half-life of 15 s for $^{270}Bh_{163}$ allows investigation of chemical properties of element Bh ($Z = 107$).

Recent calculations give only the lower limit for the β-decay half-life equal to 100 s [20] for almost all nuclei considered in the present work. This would mean that β decay might compete with emission of the α-particle from $^{269}Sg_{163}$ and $^{266}Db_{161}$ or with spontaneous fission of $^{265}Rf_{161}$. It is very likely for $^{266}Db_{161}$. Electron capture energy, calculated for this nucleus in the present paper, is equal to 3.14 MeV. Even if we assume very pesimistically that $^{269}Sg_{163}$ and $^{266}Db_{161}$ would decay by emission of the positron or by electron capture with the half-life equal to 100 s then these nuclei still could be identified by chemistry.

The increase (decrease) of Q_α by 0.1 MeV decreases (increases) T_α by $0.2-0.4$ orders of magnitude for the nuclei in question. Moreover, a nucleus with an unpaired nucleon decays often to the excited state of the daughter nucleus with low excitation energy of the order of a few hundreds of keV. This usually leads to the increase of the half-life by a factor of $1-10$. It may happen, however, that the hindrance of the half-life may be even larger [3].

The α-decay half-lives calculated in the present paper are smaller by even more than 4 orders of magnitude in comparison with the recent calculations described in Ref. [20] and also in comparison with the older ones presented in Ref. [21].

The proposed experiment, if successful, would extend considerably the Mendeleyev table and the chart of the nuclei. Theoretical investigations of other possibilities of production and identification of superheavy nuclei are in progress.

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Table I. Mass excess M, ground state to ground state α-decay energy Q_α and half-life T_α predicted for α-decay chains beginning with the nuclei $^{293}118_{175}$ (left side) and $^{294}119_{175}$ (right side), which might be obtained in the reactions $^{208}\mathrm{Pb}_{126}(^{86}\mathrm{Kr}_{50},1n)$ and $^{209}\mathrm{Bi}_{126}(^{86}\mathrm{Kr}_{50},1n)$ ($^{208}\mathrm{Pb}_{126}(^{87}\mathrm{Rb}_{50},1n)$), respectively. The last nucleus in the α-decay chain of even-Z nuclei is a fissioning isotope $^{265}\mathrm{Rf}_{161}$ with the predicted spontaneous-fission half-life $T_{\mathrm{sf}} = 41$ min. The predicted α-decay chain of odd-Z nuclei is terminated by the known nucleus $^{262}\mathrm{Lr}_{159}$, which decays by electron capture with the measured half-life $T_{EC}^{\mathrm{exp}} = 3.6$ h [19]. β decay might compete with α decay for $^{266}\mathrm{Db}_{161}$. The calculated electron capture energy for this nucleus is equal to 3.14 MeV. The decay product of $^{266}\mathrm{Db}_{161}$ would be in such a case the fissioning isotope $^{266}\mathrm{Rf}_{162}$ with the predicted half-life of 23 s [9].

^AZ_N	M (MeV)	Q_α (MeV)	T_α	^AZ_N	M (MeV)	Q_α (MeV)	T_α
				$^{294}119_{175}$	207.05	12.81	3 μs
$^{293}118_{175}$	199.21	12.23	31 μs	$^{290}117_{173}$	191.82	11.87	110 μs
$^{289}116_{173}$	184.56	11.37	960 μs	$^{286}115_{171}$	177.53	11.56	180 μs
$^{285}114_{171}$	170.77	11.18	800 μs	$^{282}113_{169}$	163.55	11.41	120 μs
$^{281}112_{169}$	157.17	11.00	610 μs	$^{278}111_{167}$	149.72	11.18	120 μs
$^{277}110_{167}$	143.75	10.77	620 μs	$^{274}\mathrm{Mt}_{165}$	136.12	10.44	2.2 ms
$^{273}\mathrm{Hs}_{165}$	130.56	9.69	120 ms	$^{270}\mathrm{Bh}_{163}$	123.26	8.90	15 s
$^{269}\mathrm{Sg}_{163}$	118.45	8.35	8 min	$^{266}\mathrm{Db}_{161}$	111.94	7.86	3.6 h
$^{265}\mathrm{Rf}_{161}$	107.68		$T_{\mathrm{sf}} = 41$ min	$^{262}\mathrm{Lr}_{159}$	101.66		$T_{EC}^{\mathrm{exp}} = 3.6$ h

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