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# Production of even-even superheavy nuclei in cold fusion reactions

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## Abstract

We investigate the possibilities of the formation of even-even superheavy nuclei in the cold fusion reactions $^{207}\mathrm{Pb}_{125}(\mathrm{HI},1n)$. We reproduce the measured cross sections of the reactions $^{207}\mathrm{Pb}_{125}(^{50}\mathrm{Ti}_{28},1n)^{256}\mathrm{Rf}_{152}$, $^{207}\mathrm{Pb}_{125}(^{54}\mathrm{Cr}_{30},1n)^{260}\mathrm{Sg}_{154}$ and $^{207}\mathrm{Pb}_{125}(^{58}\mathrm{Fe}_{32},1n)^{264}\mathrm{Hs}_{156}$ within a factor of 2.9 on average. We predict the optimal bombarding energies and the formation cross sections of even-even superheavy nuclei with $Z = 110 - 120$.

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Only three even-even transactinide nuclei, $^{256}$Rf$_{152}$ [1], $^{260}$Sg$_{154}$ [2] and $^{264}$Hs$_{156}$ [3,4], were synthesized in bombardments of $^{207}$Pb$_{125}$ with heavy ions. The isotope $^{264}$Hs$_{156}$, produced in the reaction $^{207}$Pb$_{125}$($^{58}$Fe$_{32}$,1$n$)$^{264}$Hs$_{156}$ [3], is the heaviest experimentally known even-even nucleus. Even-even superheavy nuclei provide a perfect opportunity for testing theoretical models [5–15] which predict the ground-state properties of nuclei with very large proton numbers. Nevertheless, the synthesis and investigations of even-even transactinide nuclei were performed very rarely over the last years.

In the present paper, we want to draw the attention to even-even superheavy nuclei. We discusse posibilities of the synthesis of these nuclei in reactions of the $^{207}$Pb$_{125}$ target nucleus with stable and radioactive neutron-rich projectiles. We consider the reactions with the emission of only one neutron. (The "cold" fusion reactions [16,17].) We calculate the optimal bombarding energies and the formation cross sections by means of our model developed in Ref. [18] and extended for the description of the excitation functions in Ref. [19]. This model is based on the concepts of the quantal penetration of the Coulomb barrier and the statistical description of the deexcitation of the compound nucleus. Within our model, we have reproduced in Ref. [18] the cross sections of the reactions $^{208}$Pb$_{126}$(HI,1$n$) leading to odd-$N$ transactinide nuclei [20,21,2,17] and predicted the increased probability of the production of element 118 in the reaction $^{208}$Pb$_{126}$($^{86}$Kr$_{50}$,1$n$)$^{293}$118$_{175}$. This result, followed by our study of the properties of the predicted $\alpha$-decay chain initiated by $^{293}$118$_{175}$ [22], has prompted an experiment on the production of elements 118 and 116, which was performed at Berkeley this year [23].

In the present calculation, we take into account the so called odd-even effect caused by the larger density of the low energy levels for the odd-$N$ compound nucleus in comparison with the level density of the even-even compound nucleus, as well as the larger density of the low lying levels for the odd-$N$ 1$n$-evaporation residue in comparison with the level density of the even-even 1$n$-evaporation residue. We describe this effect replacing the excitation dependent functions $a_n$ and $a_f$ given by Eq.(13) in Ref. [18] with

$$a_n \to a_n(1 - \frac{\Delta}{E^* - E_{rot}(eq) - S_n}), \qquad a_f \to a_f(1 + \frac{\Delta}{E^* - E_{rot}(sd) - B_f^{stat}}). \qquad (1)$$

Here, $\Delta = 12/\sqrt{A_{CN}}$, $A_{CN}$ is the mass number of the compound nucleus, $E^*$ is the excitation energy, $E_{rot}(eq)$ ($E_{rot}(sd)$) is the rotational energy at the deformation corresponding to the equilibrium (saddle) configuration, $S_n$ is the neuton separation energy and $B_f^{stat}$ is the static fission barrier for the compound nucleus. The expressions in the denominators are the intrinsic excitation energies in the transition states for neutron emission and fission. It is worth noting that, for large excitation energies ($E^* >> S_n$ and $E^* >> B_f^{stat}$) and zero angular momentum, the neuton-to-fission width ratio given by Eq.(12) in Ref. [18] transforms into the well known formulas $\Gamma_n/\Gamma_f = \exp((B_f^{stat} - S_n)/\sqrt{E^*/\tilde{a}})$ for the even-even compound nucleus and $\Gamma_n/\Gamma_f = \exp((B_f^{stat} - S_n - 2\Delta)/\sqrt{E^*/\tilde{a}})$ for the odd-$N$ compound nucleus. These formulas are accurate to within a pre-exponential factor and $\tilde{a}$ is the asymptotic level density parameter. In the present calculation, the neutron-to-fission width ratio is calculated with a pre-factor $1/(2I+1)$ [24], where $I$ is the ground-state spin of the odd $^{207}Pb_{125}$ target nucleus ($I = 1/2$ [25]). Like in the previous papers [18,19], we calculate $Q$-values, neutron separation energies, static fission barriers and microscopic energies by means of the macroscopic-microscopic model [14,5] and use the measured masses of the target nucleus and the projectiles [26].

In Table I, the calculated formation cross section $\sigma$ of $^{256}Rf_{152}$, $^{260}Sg_{154}$ and $^{264}Hs_{156}$ is compared with the measured formation cross section $\sigma_{exp}$ of these nuclei [1–4]. The values of $\sigma_{exp}$ are accurate to within a factor of two because of systematic uncertainties. In Table I only statistical errors of $\sigma_{exp}$ are given. The calculation reproduce the measured values of the cross section within a factor of 2.9 on average.

The calculated optimal bombarding energy in the lab system $E_{lab}$, the corresponding excitation energy $E^*$ and the cross section $\sigma$ of the reactions $^{207}Pb_{125}$(HI,1$n$) with the stable neutron-rich projectiles are given in the upper part of Table II while these quantities obtained for the reactions with the neutron-rich radioactive heavy ions are listed in the lower part of the table. Table II contains also the calculated $Q$ value, fusion barrier height $B_{fu}$, transmission probability through the fusion barrier $T_0$ for the optimal bombarding energy and zero angular momentum, neutron separation energy $S_n$, the height of the static fission barrier $B_f^{stat}$, neutron-to-fission width ratio reduced to zero angular momentum $(\Gamma_n/\Gamma_f)_0$, and maximal angular momentum $l_{max}$ defined as $l$ for which the contribution to the cross section becomes less than 1%. The optimal excitation energies are predicted by means of the simple rule introduced in Ref. [18]. In case of the odd-$N$ compound nuclei in question existing before the formation of the even-even superheavy nuclei, this rule states that the optimal excitation energy is equal to the sum of the neutron separation energy for the compound nucleus and the static fission barrier for the $1n$-evaporation residue. (The optimal excitation energy obtained as the maximum of the calculated excitation function is usually larger by $0.3-0.4$ MeV and the formation cross section changes not more than by several percent.)

The optimal excitation energies calculated in the present paper for $^{256}\mathrm{Rf}_{152}$ and $^{260}\mathrm{Sg}_{154}$ are lower by 6.7 MeV and 5.3 MeV, respectively, in comparison with the energies used in the experiments [1,2]. These energy differences increase the calculated formation cross sections by a factor of 7.1 and 5.4, respectively.

The predicted optimal excitation energies are usually lower by about 2 MeV in comparison with the ones calculated for the reactions $^{208}\mathrm{Pb}_{126}(\mathrm{HI},1n)$ leading to the odd-$N$ transactinide nuclei discussed in Ref. [18]. The lower optimal excitation energies and the odd-even effect lead usually to the smaller formation cross sections for the even-even nuclei in question in comparison with their heavier odd-$N$ neighbors. The only exceptions are the nuclei $^{256}\mathrm{Rf}_{152}$ and $^{298}118_{180}$ for which we obtained the cross sections 1.8 and 1.2 times larger than for $^{257}\mathrm{Rf}_{153}$ and $^{299}118_{181}$, respectively.

For $^{292}118_{174}$, we predict the formation cross section of 97 pb. This value is 6.9 times smaller than the one predicted in Ref. [18] for the neighboring odd-$N$ isotope $^{293}118_{175}$. The direct production of the latter nucleus is the most likely interpretation of the experiment performed by the Berkeley group [23]. The measured formation cross section of $^{293}118_{175}$ [23] is smaller than our predicted value [18]. The reason for this might be experimental uncertainties, as well as theoretical uncertainties arising, for example, from the used mass formula and the predicted shape of the excitation function, which were discussed in Ref. [19]. Another explanation of this discrepancy have been proposed recently by the authors of Ref. [27]. They suggested that the structurally forbidden ground state to ground state $\alpha$ decays for so heavy odd-$N$ nuclei might be responsible for a smaller number of decays and, consequently, for measuring via $\alpha$ decay only a part of the formation cross section of $^{293}118_{175}$. If their hypothesis is true then the entire formation cross section of an even-even isotope $^{292}118_{174}$ of element 118 should be measurable via $\alpha$ decay because allowed ground state to ground state $\alpha$ decays are expected for even-even nuclei.

In Table III, we collected the values of the nuclear mass $M$, the ground state to ground state $\alpha$-decay energy $Q_\alpha$ and $\alpha$-decay half-life $T_\alpha$ for nuclei constituting the predicted $\alpha$-decay chains. These chains might be initiated by three even-even nuclei for which we predict the formation cross section larger than 1 pb and which might be synthesized by using stable projectiles. Two of these nuclei, $^{270}110_{160}$ and $^{292}118_{174}$, are planned to be synthesized at LBNL-Berkeley in a near future [28]. Measured spontaneous-fission half-life $T_{sf}^{exp}$ for $^{258}Rf_{154}$ [29] and $^{260}Rf_{156}$ [29] and predicted spontaneous-fission half-life $T_{sf}$ for the other nuclei are also given in Table III. All theoretical results for $M$, $Q_\alpha$, $T_\alpha$ and $T_{sf}$ were taken from Refs. [14,30,5]. For the nuclei in question, $\beta$-decay half-lives calculated recently in Ref. [12] are considerably larger than the $\alpha$-decay half-lives listed in Table III. For most of these nuclei, $\beta$-decay half-lives calculated in Ref. [12] are also larger than the spontaneous-fission half-lives given in Table III. According to the present calculation of the formation cross sections, the best stable projectiles for the production of even-even superheavy nuclei in bombardments of $^{207}Pb_{125}$ target nucleus are $^{64}Ni_{36}$, $^{70}Zn_{40}$ and $^{86}Kr_{50}$. The use of these projectiles might lead to the production of $^{270}110_{160}$, $^{276}112_{164}$ and $^{292}118_{174}$, respectively, and their descendants listed in Table III.

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TABLE I. The excitation energy $E^*$, the calculated, $\sigma$, and measured, $\sigma_{exp}$, cross section of reactions listed in the first column. Experimental values are taken from Refs. [1–4]. Measured cross sections are accurate to within a factor of about 2 because of systematic uncertainties.

| Reaction | $E^*$ (MeV) | $\sigma$ | $\sigma_{exp}$ | Ref. |
|---|---|---|---|---|
| $^{207}Pb_{125}(^{50}Ti_{28},1n)^{256}Rf_{152}$ | 20.1 | 2.4 nb | $0.6^{+0.2}_{-0.2}$ nb | [1] |
| $^{207}Pb_{125}(^{54}Cr_{30},1n)^{260}Sg_{154}$ | 18.2 | 65 pb | $22^{+50}_{-18}$ pb | [2] |
| $^{207}Pb_{125}(^{58}Fe_{32},1n)^{264}Hs_{156}$ | 12.9 | 7.5 pb | $8.8^{+16.0}_{-3.5}$ pb | [4] |
| | 18.3 | 830 fb | $2.8^{+5.1}_{-1.8}$ pb | [3] |

TABLE II. Calculated ground-state $Q$ value, the height of the fusion barrier $B_{fu}$, transmission probability through the fusion barrier $T_0$ for the optimal bombarding energy and zero angular momentum, neutron separation energy $S_n$, the height of the static fission barrier $B_f^{stat}$, neutron-to-fission width ratio reduced to zero angular momentum $(\Gamma_n/\Gamma_f)_0$, maximal angular momentum $l_{max}$ defined as $l$ for which the conribution to the cross section becomes less than 1%, optimal bombarding energy in the lab system $E_{lab}$ and the corresponding optimal excitation energy $E^*$, and formation cross section $\sigma$ of reactions $^{207}$Pb(HI,1$n$)ER with the projectiles HI and the 1$n$-evaporation residues ER listed in the first two columns.

| HI | ER | $Q$ | $B_{fu}$ | $T_0$ | $S_n$ | $B_f^{stat}$ | $(\Gamma_n/\Gamma_f)_0$ | $l_{max}$ | $E_{lab}$ | $E^*$ | $\sigma$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | MeV | MeV | | MeV | MeV | | $\hbar$ | MeV | MeV | |
| $^{50}$Ti | $^{256}$Rf | 170.10 | 199.53 | $2.5 \cdot 10^{-4}$ | 6.39 | 7.52 | $3.1 \cdot 10^{-3}$ | 28 | 227.8 | 13.41 | 17 nb |
| $^{54}$Cr | $^{260}$Sg | 187.80 | 219.25 | $6.7 \cdot 10^{-5}$ | 6.58 | 6.86 | $3.2 \cdot 10^{-4}$ | 26 | 253.1 | 12.94 | 350 pb |
| $^{58}$Fe | $^{264}$Hs | 205.88 | 238.62 | $2.9 \cdot 10^{-5}$ | 6.84 | 6.02 | $2.1 \cdot 10^{-5}$ | 25 | 279.4 | 12.36 | 7.8 pb |
| $^{62}$Ni | $^{268}$110 | 224.39 | 257.66 | $1.6 \cdot 10^{-5}$ | 7.11 | 4.77 | $4.6 \cdot 10^{-7}$ | 23 | 306.4 | 11.38 | 72 fb |
| $^{64}$Ni | $^{270}$110 | 225.47 | 257.01 | $6.9 \cdot 10^{-5}$ | 6.86 | 5.38 | $2.7 \cdot 10^{-6}$ | 25 | 310.5 | 11.74 | 2.0 pb |
| $^{68}$Zn | $^{274}$112 | 242.69 | 275.76 | $2.3 \cdot 10^{-5}$ | 6.63 | 4.98 | $8.5 \cdot 10^{-7}$ | 24 | 337.2 | 11.11 | 180 fb |
| $^{70}$Zn | $^{276}$112 | 244.03 | 275.10 | $6.4 \cdot 10^{-5}$ | 6.27 | 4.92 | $1.9 \cdot 10^{-6}$ | 25 | 340.9 | 10.69 | 1.1 pb |
| $^{76}$Ge | $^{282}$114 | 264.33 | 292.92 | $2.3 \cdot 10^{-4}$ | 6.34 | 3.74 | $7.8 \cdot 10^{-8}$ | 22 | 374.5 | 9.58 | 120 fb |
| $^{80}$Se | $^{286}$116 | 283.26 | 311.14 | $6.3 \cdot 10^{-4}$ | 6.73 | 3.63 | $1.1 \cdot 10^{-9}$ | 22 | 406.4 | 9.86 | 4 fb |
| $^{82}$Se | $^{288}$116 | 284.63 | 310.49 | $2.5 \cdot 10^{-3}$ | 6.45 | 4.25 | $1.4 \cdot 10^{-8}$ | 25 | 411.6 | 10.20 | 250 fb |
| $^{84}$Kr | $^{290}$118 | 302.71 | 329.14 | $3.6 \cdot 10^{-3}$ | 6.84 | 4.57 | $1.9 \cdot 10^{-8}$ | 26 | 440.9 | 10.91 | 520 fb |
| $^{86}$Kr | $^{292}$118 | 304.96 | 328.48 | $2.0 \cdot 10^{-2}$ | 6.49 | 5.41 | $4.9 \cdot 10^{-7}$ | 29 | 447.8 | 11.40 | 97 pb |
| $^{78}$Ge | $^{284}$114 | 265.11 | 292.26 | $4.7 \cdot 10^{-4}$ | 6.25 | 3.62 | $5.2 \cdot 10^{-10}$ | 22 | 377.9 | 9.37 | 2 fb |
| $^{80}$Ge | $^{286}$114 | 265.06 | 291.61 | $6.6 \cdot 10^{-4}$ | 6.11 | 3.82 | $5.7 \cdot 10^{-9}$ | 23 | 380.6 | 9.43 | 28 fb |
| $^{82}$Ge | $^{288}$114 | 264.04 | 290.96 | $6.3 \cdot 10^{-4}$ | 5.80 | 4.58 | $2.2 \cdot 10^{-7}$ | 26 | 382.4 | 9.88 | 1.3 pb |
| $^{84}$Se | $^{290}$116 | 285.10 | 309.83 | $5.7 \cdot 10^{-3}$ | 6.16 | 5.01 | $3.0 \cdot 10^{-7}$ | 27 | 415.8 | 10.67 | 16 pb |
| $^{86}$Se | $^{292}$116 | 282.28 | 309.18 | $2.2 \cdot 10^{-3}$ | 5.97 | 5.82 | $5.3 \cdot 10^{-6}$ | 30 | 415.5 | 11.29 | 130 pb |
| $^{88}$Se | $^{294}$116 | 278.68 | 308.53 | $3.8 \cdot 10^{-4}$ | 5.71 | 6.44 | $4.8 \cdot 10^{-5}$ | 32 | 413.8 | 11.65 | 230 pb |
| $^{88}$Kr | $^{294}$118 | 303.39 | 327.83 | $1.4 \cdot 10^{-2}$ | 6.23 | 5.95 | $3.7 \cdot 10^{-6}$ | 31 | 449.0 | 11.68 | 590 pb |
| $^{90}$Kr | $^{296}$118 | 301.14 | 327.17 | $6.1 \cdot 10^{-3}$ | 6.03 | 6.29 | $1.2 \cdot 10^{-5}$ | 32 | 449.0 | 11.82 | 900 pb |
| $^{92}$Kr | $^{298}$118 | 297.98 | 326.52 | $1.3 \cdot 10^{-3}$ | 5.71 | 6.58 | $4.2 \cdot 10^{-5}$ | 33 | 447.4 | 11.79 | 700 pb |
| $^{94}$Sr | $^{300}$120 | 320.52 | 344.95 | $1.5 \cdot 10^{-2}$ | 6.04 | 6.12 | $4.7 \cdot 10^{-6}$ | 32 | 483.0 | 11.66 | 780 pb |
| $^{96}$Sr | $^{302}$120 | 317.65 | 344.30 | $3.6 \cdot 10^{-3}$ | 5.69 | 6.01 | $9.1 \cdot 10^{-6}$ | 32 | 481.4 | 11.20 | 360 pb |
| $^{98}$Sr | $^{304}$120 | 315.09 | 343.65 | $6.2 \cdot 10^{-4}$ | 5.16 | 5.61 | $1.4 \cdot 10^{-5}$ | 32 | 479.4 | 10.27 | 97 pb |

TABLE III. Mass excess $M$, ground state to ground state $\alpha$-decay energy $Q_\alpha$, $\alpha$-decay half-life $T_\alpha$ and spontaneous-fission half-life $T_{sf}$ [14,30,5] for nuclei constituting $\alpha$-decay chains which might be initiated by the deformed nuclei $^{270}110_{160}$ and $^{276}112_{164}$, and by the almost spherical nuclide $^{292}118_{174}$. The measured values of the spontaneous-fission half-life $T_{sf}^{exp}$ for $^{258}\mathrm{Rf}_{154}$ and $^{260}\mathrm{Rf}_{156}$ are taken from Ref. [29].

| $^AZ_N$ | $M$ (MeV) | $Q_\alpha$ (MeV) | $T_\alpha$ | $T_{sf}$ |
|---|---|---|---|---|
| $^{270}110_{160}$ | 134.68 | 11.24 | 44 $\mu$s | 540 ms |
| $^{266}\mathrm{Hs}_{158}$ | 121.01 | 10.20 | 4.8 ms | 1.6 s |
| $^{262}\mathrm{Sg}_{156}$ | 108.39 | 9.60 | 52 ms | 85 ms |
| $^{258}\mathrm{Rf}_{154}$ | 96.36 | 9.20 | 170 ms | $T_{sf}^{exp} = 13^{+3}_{-3}$ ms [29] |
| $^AZ_N$ | $M$ (MeV) | $Q_\alpha$ (MeV) | $T_\alpha$ | $T_{sf}$ |
| $^{276}112_{164}$ | 150.19 | 12.13 | 1.5 $\mu$s | 1.3 s |
| $^{272}110_{162}$ | 135.64 | 10.80 | 520 $\mu$s | 9.4 m |
| $^{268}\mathrm{Hs}_{160}$ | 122.41 | 9.65 | 160 ms | 1.6 m |
| $^{264}\mathrm{Sg}_{158}$ | 110.34 | 9.06 | 2.1 s | 2.3 s |
| $^{260}\mathrm{Rf}_{156}$ | 98.85 | 8.84 | 2.2 s | $T_{sf}^{exp} = 21^{+1}_{-1}$ ms [29] |
| $^AZ_N$ | $M$ (MeV) | $Q_\alpha$ (MeV) | $T_\alpha$ | $T_{sf}$ |
| $^{292}118_{174}$ | 197.63 | 12.27 | 24 $\mu$s | 37 s |
| $^{288}116_{172}$ | 182.94 | 11.56 | 330 $\mu$s | 2.4 s |
| $^{284}114_{170}$ | 168.95 | 11.51 | 120 $\mu$s | 12 ms |
| $^{280}112_{168}$ | 155.01 | 11.36 | 83 $\mu$s | 34 ms |
| $^{276}110_{166}$ | 141.23 | 11.03 | 140 $\mu$s | 2.1 s |
| $^{272}\mathrm{Hs}_{164}$ | 127.77 | 9.79 | 63 ms | 11 m |
| $^{268}\mathrm{Sg}_{162}$ | 115.55 | 8.05 | 1.7 h | 3.5 h |
| $^{264}\mathrm{Rf}_{160}$ | 105.08 | 7.70 | 6.2 h | 2.5 s |