# Reports of the Academy of Sciences of the USSR

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1965

SovietRxiv

**Abstract**

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**Reports of the Academy of Sciences of the USSR**

1965. Volume 164, No. 3

**PHYSICS**

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# ON THE POSSIBILITY OF OBTAINING UNEXCITED COMPOUND NUCLEI OF HEAVY TRANSURANIUM ELEMENTS

*(Presented by Academician A. P. Vinogradov on 25 II 1965)*

The main difficulty in obtaining elements with $Z = 104, 105$ and higher by irradiation with multiply charged ions consists in the very small formation cross section of these elements, which moreover decreases with increasing $Z$. According to theoretical concepts ([1–3]), when the projectile nucleus—the incident multiply charged ion—collides with the target nucleus at an energy equal to or exceeding their Coulomb barrier, a compound nucleus is formed with a cross section of the order of the geometrical one. At an incident-ion energy equal to $E_{\text{b}}$ in the center-of-mass system ($E_{\text{b}}$ is the energy of the Coulomb barrier), the excitation energy of the compound nucleus is

$$E_{\text{b}}^{*} = E_{\text{b}} - Q, \tag{1}$$

where $Q$ is the fusion energy of the target and projectile, calculated from their masses. The compound nucleus, heated to the temperature $E_{\text{b}}^{*}$, cools by evaporation of particles, mainly neutrons. In heavy compound nuclei, neutron evaporation competes with fission. If other de-excitation processes are neglected, then the mean probability of evaporation of one neutron $\bar{\sigma}(1n) = \Gamma_n/(\Gamma_n + \Gamma_f)$ reaches, for nuclei with $A \cong 250$, a value of the order of 0.1—0.01 ([4]). Evaporation of each neutron from the compound nucleus removes approximately 8-10 MeV of excitation energy ([4,5]) and at the same time is accompanied by fission of the compound nucleus with a probability approximately 10–100 times larger.

It is known that the formula for calculating the formation cross section of compound nuclei in the reaction (ion, $xn$)

$$\sigma_{xn}(E) = \sigma_c(E) \sum_{i=1}^{x} \left( \frac{{}^i\Gamma_n}{{}^i\Gamma_n + {}^i\Gamma_f} \right) P(xn, E) = \sigma_c(E)\, \bar{\sigma}^{(x)}(1n)\, P(xn, E) \quad (2)$$

contains the factor $\bar{\sigma}(1n) \approx 0.1$—$0.01$ to the $x$-th power. In formula (2), $\sigma_c$ is the formation cross section of the compound nucleus, of order $\sim 10^{-25}$ cm$^2$ at $E \geq E_\text{b}$; $P(xn, E)$ is the probability of de-excitation by evaporation of $x$ neutrons ($P(xn, E)$ for $x = E$ MeV/10 MeV lies between 0.1 and 1).

From formula (2) it is seen that the only radical way to increase the yields of the reaction (ion, $xn$) may be to reduce the number of evaporated neutrons, i.e., to reduce the excitation energy $E^*_\text{b}$. Here each reduction of the excitation energy by 10 MeV may lead to an increase in $\sigma_{xn}(E)$ by 1-2 orders of magnitude, in accordance with a decrease in the probability of neutron evaporation by 1 neutron.

The formation cross section of isotopes of elements 98-104, hitherto obtained by reactions (ion, $xn$) with projectiles C, N, O, and Ne, lies in the range $10^{-28}$—$10^{-34}$ cm$^2$, since evaporation of 3-5 neutrons is necessary for de-excitation of the compound nuclei. From this point of view it seems important to consider possible ways of obtaining compound nuclei with the minimum possible excitation.

To estimate $E^*_\text{b}$ of the compound nucleus, a calculation was carried out for elements of three different regions of the Mendeleev periodic system: for ${}^{90}_{40}$Zr, co-

which lies at the minimum of the mass-defect curve ($M - A = -60.177$ MeV), for $\text{Hf}^{178}_{72}$, which lies approximately at the zero level of the mass-defect curve ($M - A = 0.125$ MeV), and for $104^{264}$, which lies high on the rising branch of the approximately parabolic mass-defect curve ($M - A = 183.729$ MeV).

The calculation of $E^*_b$ was carried out for a series of isotopes of target and projectile nuclei according to formula (1), with their $Z$ and $A$ varied according to the reaction

$$(Z_1, A_1) + (Z_2, A_2) = (Z_c, A_c), \quad (3)$$

where index 1 denotes the projectile, index 2 the target, and index $c$ the compound nucleus. The calculation was performed for $\text{H}^1_1$ and for even $Z_1$ and $A_1$: $\text{He}^4_2$, $\text{Be}^9_4$, $\text{C}^{12}_6$, $\text{O}^{18}_8$, $\text{Ne}^{22}_{10}$,

**Fig. 1.** $E^*_b$ of compound nuclei $\text{Zr}^{90}_{40}$, $\text{Hf}^{178}_{72}$, and $104^{264}$; black points—other isotopes of element (104) (target elements underlined)

$\text{Mg}^{26}_{12}$, $\text{Si}^{30}_{14}$, $\text{S}^{36}_{16}$, $\text{Ar}^{40}_{18}$, $\text{Ca}^{48}_{20}$, $\text{Ti}^{50}_{22}$, $\text{Cr}^{54}_{24}$, $\text{Fe}^{58}_{26}$, $\text{Ni}^{64}_{28}$, $\text{Zn}^{70}_{30}$, $\text{Ge}^{76}_{32}$, $\text{Se}^{82}_{34}$, $\text{Kr}^{86}_{36}$, $\text{Sr}^{88}_{38}$, $\text{Zr}^{90}_{40}$, $\text{Mo}^{100}_{42}$, $\text{Ru}^{104}_{44}$, $\text{Pd}^{110}_{46}$, $\text{Cd}^{116}_{48}$, $\text{Sn}^{124}_{50}$, $\text{Te}^{130}_{52}$, $\text{Xe}^{136}_{54}$.

Fig. 1. $E_b^*$ of compound nuclei $Zr_{40}^{90}$, $Hf_{72}^{178}$, and $104^{264}$; black points–other isotopes of element (104) (target elements underlined)

Figure 1: Fig. 1. $E_b^*$ of compound nuclei $Zr_{40}^{90}$, $Hf_{72}^{178}$, and $104^{264}$; black points –other isotopes of element (104) (target elements underlined)

Figure 2

Figure 2: Figure 2

$Q$ for the reaction according to scheme (3) was calculated using Seeger' s tables for $M-A$ [6], by the formula

$$Q = (M-A)_{(Z_c,A_c)} - (M-A)_{(Z_1,A_1)} - (M-A)_{(Z_2,A_2)}. \tag{4}$$

For calculating $E_b$, as a first approximation, the simple classical formula was used

$$E_b(Z_1,Z_c) = Z_1(Z_c-Z_1)e^2/\left[A_1^{1/3}+(A_c-A_1)^{1/3}\right]r_0, \tag{5}$$

where $r_0 = 1.5\cdot 10^{-13}$ cm, in accordance with the data of Thomas [8] and Bazikov [9]. They showed, for such an $r_0$, good agreement of the quantities $\sigma_c$ and $E_b$, calculated by quantum and classical methods, for the fusion of nuclei of the type N, O, Ne with U and Bi nuclei.

It is evident from Fig. 1 that $E_b^*$ in the case of $Zr_{40}^{90}$, as $Z_1$ increases, at first rises rapidly and then slowly. Such a behavior of $E_b^*$ is characteristic for producing, according to scheme (3), all $(Z_c, A_c)$ for which $M-A$ for $A_c$ lies at the minimum of an approximately parabolic function $M-A$ of $A$ [7]. The $E_b^*$ curve for $Hf_{72}^{178}$ also first rises rapidly and then, as a consequence of oscillations of $Q$, oscillates between 40 and 50 MeV (up to $(Z_1,A_1) = Kr_{36}^{86}$). The $E_b^*$ curve for $104^{264}$ has a substantially different course: after a rapid rise at the beginning, a maximum is observed in the region of $Mg_{12}^{26}$, $Si_{14}^{30}$, and thereafter $E_b^*$ decreases. For $Z_1 \approx 30$ it approaches zero, and for $Z_1 \gtrsim 50$ it takes negative values. Such a behavior of the $E_b^*$ curve is characteristic for the synthesis of all heavy elements with $Z_c \geq 100$. It is associated with the strong increase of $Q$ for heavy nuclei according to formula (4), while $E_b$ grows more slowly if $(Z_1, A_1)$ approaches $(Z_c, A_c/2)$.

From these considerations it is clear that a substantial lowering of $E_b^*$ of the compound nucleus and, consequently, an increase in the yields of heavy elements can be achieved in two ways: to a lesser extent by using $H_1^1$, $He_2^4$ as projectiles, and to a greater extent by using very heavy projectiles, for which $(Z_1, A_1)$ approaches $(Z_c, A_c/2)$. In addition, the use of very light projectiles is limited by the availability of very heavy targets; for example

**Fig. 2.** $E_b^*$ of compound nuclei for the targets $Cf^{252}$, $U^{238}$, and $Hg^{204}$ (compound nuclei are shown in parentheses; target elements are underlined)

$Cf_{98}^{252}$ with $He_2^4$ gives only $Fm_{100}^{256}$ with an excitation of 15–20 MeV, while obtaining $104^{264}$ from $Cf^{252}$ requires $C^{12}$, which entails a large excitation ($\sim$ 35 MeV) and leads to the evaporation of 3–4 neutrons and the formation of $104^{261}$ or $104^{260}$; similarly, irradiation of $Cm^{244}$ with oxygen $O^{18}$, or $Pu^{242}$ with neon $Ne^{22}$, gives only $104^{264}$.

The production of the isotopes $104^{260}$ or $104^{258}$ with small $E_b^*$, or even with negative $E_b^*$, is already practically possible with real targets, as shown by the black points in Fig. 1. In this case $104^{260}$ or $104^{258}$ may be formed, for example, by irradiating a $Te_{52}^{130}$ target with $Te_{54}^{130}$ projectiles, or $Xe_{54}^{136}$ with $Sn_{50}^{124}$ ions; $104^{258}$—by the reactions $Se_{34}^{82}+Yb_{70}^{176}$ or $Ti_{22}^{50}+Pb_{82}^{208}$. In such irradiations, when the projectile energy is chosen so as to give $E^* = 0$ (for negative excitation $E_b^*$, the projectile energy must correspondingly be increased above $E_b$), one may expect a formation cross section for a practically unexcited compound nucleus somewhat below $\sim 10^{-27}$ cm$^2$, if it is assumed that, in irradiation with heavy targets, nuclear fusion into a compound nucleus will occur according to the regularities observed so far. In this case, some of the nuclei produced by sub-barrier fusion (the tunneling effect) may be completely unexcited. The other part of the nuclei, with energy somewhat above the fusion barrier, must overcome the potential barrier against spontaneous fission of the compound nucleus (several MeV), and therefore will be weakly excited. The removal of this excitation will occur (in competition with fission), with appreciable probability, by emission of $\gamma$-rays, since it cannot cause neutron evaporation.

The $E_b^*$ values were also calculated for certain isotopes of elements 98-122 that could be obtained by irradiating $U^{238}$, $Cf^{252}$, and other targets with the projectiles indicated above (see Fig. 2).

It follows from Fig. 2 that: a) near $Z_1 = 10$, for all heavy targets (between $Hg^{204}$ and $Cf^{252}$) there is a maximum of $E_b^*$, which for $(Z_1, A_1) = He_2^4$

decreases to $\sim$ 20 MeV, and at $Z_1 \simeq 30$ falls to zero; b) one and the same compound nucleus is obtained with very small or negative excitation if $(Z_1, A_1)$ approaches $(Z_c, A_c/2)$. This corresponds to the result shown in Fig. 1 for one compound nucleus, $104^{264}$. Therefore, one can probably calculate for each element a curve similar to $104^{264}$ in Fig. 1, if $Z_c \geq 100$.

Uniformly over the entire range of $A_1$, the quantities $E_b^*$ have an error $\Delta Q = 3$–6 MeV, since $Q$ is calculated from formula (4), where each quantity $M - A$ contributes, according to ([6]), its own error of 1-2 MeV. The error in calculating $E_b$ may be estimated from two limiting assumptions: a) **the nuclei, when they approach each other, do not have time to deform under the influence of the Coulomb forces**. Then $\Delta E_b^*$ is small in comparison with $\Delta Q$, and the total error may be estimated as $\Delta E_b^* = \Delta Q + \Delta E_b = \pm 6$ MeV; b) **the nuclei, under the influence of the Coulomb forces, are instantaneously de-**

**formed on contact to shapes with a minimum of potential energy**, i.e., to the flattening of the figures according to the calculations of Geilikman ([10]). Then, according to the calculations ([10]) given for flattened touching equilibrium figures of the nuclei $C^{12}+U^{238}$, it is shown that their Coulomb barrier increases by 2.5 or 4%, if this case is compared with touching nuclei ($Pd^{118}+Pd^{118}$) or with nuclei ($Gd^{150}+Sr^{98}$).

In accordance with this, we shall make a correction to $E_b$ (calculated by (5)) for the case of approximately equal nuclei ($Te^{130}+Te^{130}$). Increasing their $E_b$ by $\sim$ 4% (in the region $A_1 = 50 \div 150$) in comparison with the $E_b$ of light nuclei (of the type $C^{12}+U^{238}$) gives $\Delta E_b \leq 12$ MeV, since $E_b \leq 300$ MeV. At the same time, for $A_1 = 10$–50 one may take $E_b$ from formula (5) (with an accuracy of 1-2%) without a substantial correction, i.e., $\Delta E_b' \leq 2$–4 MeV in the region $A_1 = 10$–50. The total correction $E_b^*$ for case b) will be: in the region $A_1 = 10$–50, $\Delta E_b^* \leq 8$–10; in the region $A_1 = 50$–150, $\Delta E_b^* \leq 18$ MeV.

The calculations presented in this article indicate a new possible direction in methods for obtaining very heavy elements—unexcited compound nuclei by irradiating medium targets with medium-heavy beams (a process inverse to nuclear fission). For the future development of research on heavy elements, the use or construction of accelerators in which very heavy ions, up to $Xe_{54}^{136}$, could be obtained appears promising.

All the calculations presented must be regarded as a first approximation, and they require further refinement. Nevertheless, it seems to us that such refinements will affect only the absolute values of $E_b^*$ and will not change the qualitative behavior of the curves in Figs. 1, 2 and the main conclusion on the possibility of obtaining practically unexcited nuclei of very heavy elements. Experimental verification of the calculations presented, in the region of the calculated zero excitation of the compound nucleus, could be the best way to prove the reality and promise of the proposed line of work.

The author expresses his deep gratitude to V. V. Volkov, G. N. Flerov, and S. M. Polikanov for a number of valuable comments during the preparation of this work.

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Received
22 II 1965

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*Note: Figure translations are in progress. See original paper for figures.*