# Synthesis of neutron-deficient isotopes of fermium, kurchatovium, and element 106

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Experiments on the synthesis of elements with atomic numbers Z = 102, 103, 104, and 105 have been performed in various countries from 1955 through 1970. In these experiments the targets $_{94}$Pu, $_{96}$Cm and $_{98}$Cf, having the highest atomic numbers, were bombarded with C, O, and Ne ions.[1]

Artificial synthesis of heavier elements with $Z \geq 106$ has been considered recently in various laboratories. This is a very important problem not only in the sense of discovering a new element and investigating its physical and chemical properties. In our opinion, it would be of fundamental importance to establish a direct connection between the half-lives of the spontaneous fission of the new elements and the existence of a new stability region for superheavy elements.

At the same time, the synthesis of 106 and of heavier elements by the traditional method entails great difficulties, in view of the following circumstances: The nuclei of new elements, produced in a fusion reaction, have a high excitation energy $E^*$, and only a fraction ($10^{-9}$–$10^{-10}$) of these nuclei can go to the ground state by successive emission of neutrons and $\gamma$ quanta. The formation of a new element is therefore a rare process with a cross section $10^{-34}$ cm$^2$ or less.

However, this difficult situation can change significantly if instead of following the traditional path in synthesis we use as the targets not the heavy isotopes of Pu, Cm, and Cf but the stable nuclei Pb or Bi, and bombard them with ions of mass $A_1 \geq 40$ (suggestion by one of the authors—Yu. Ts. O.).

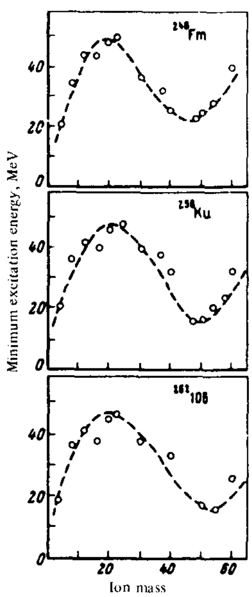


FIG. 1. Minimum excitation energies of the compound nuclei $^{248}$Fm, $^{258}$Ku, and $^{262}$106 as functions of the ion mass. The points show the calculated values for different target and particle combinations.

Since the isotopes of Pb are "magic" and the synthesized nucleus is deformed, there is a large gain in the $Q$ of the reaction, and the compound nucleus may turn out to be weakly excited. Figure 1 shows by way of example the calculated values of the minimum excitation energy $E^*_{min}$ of the compound nuclei $^{248}$Fm, $^{258}$Ku, and $^{262}$106, as functions of the mass $A_1$ of the bombarding ion. We see that with increasing ion mass the excitation energy increases to a value ~40–50 MeV at $A_1$ ~20–30, and then decreases, reaching a minimum value in the region $A_1$ ~40–50. The lowering of the excitation energy of the compound nucleus should lead to a decrease in the number of the emitted neutrons, and one can consequently expect an increase in the cross section for the production of the nuclei in the ground state.

To verify this assumption, we have set up experiments aimed at measuring the cross sections for the production of the known light isotopes $^{244}$Fm and $^{246}$Fm in the reactions $^{200,207,208}$Pb + $^{40}$Ar. The experimental values of the cross sections of the reaction ($^{40}$Ar, $xn$) with $x = 1$, 2, 3, and 4, which are listed in the first part

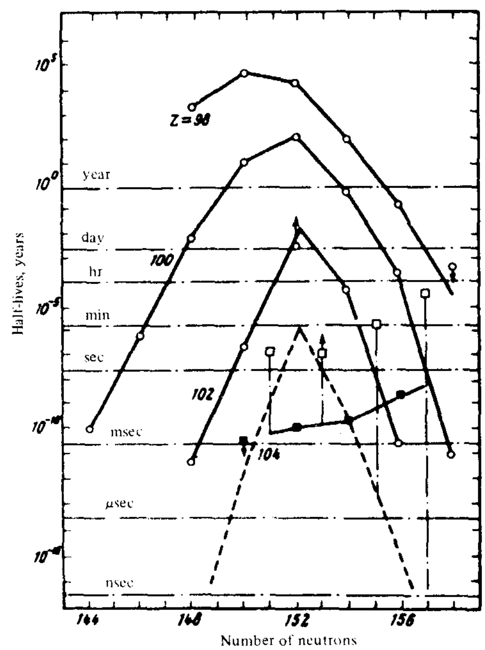


FIG. 2. Systematics of the spontaneous fission half-lives for different isotopes of elements with atomic numbers 98, 100, 102, and 104. The systematics include new data on the half-lives of the spontaneous fission of the isotopes $^{250}$102, $^{254}$104, $^{255}$104, and $^{256}$104. The black squares correspond to even-even isotopes of Ku, and the open squares to odd ones. The dashed curve shows the half-lives of the spontaneous fission in accordance with the Ghiorso systematics.[2]

TABLE Experimental results.

| Reactions | Maximum ion energy, MeV | Coulomb barrier of the reaction, MeV | Integral ion flux (× 10[16] particles) | Number of registered events | Half-life | Reaction cross section (nanobarns) |
|---|---|---|---|---|---|---|
| $^{208}Pb\ (^{40}Ar,\ 4n)\ ^{244}Fm$ | —— | —— | 6 | 214 | 4 msec | 1.5 |
| $^{207}Pb\ (^{40}Ar,\ 3n)\ ^{244}Fm$ | —— | —— | 2 | 111 | 4 msec | 5 |
| $^{208}Pb\ (^{40}Ar,\ 2n)\ ^{246}Fm$ | 220 | 187 ± 1.5 | 10 | 70 | 1 sec | 7 |
| $^{207}Pb\ (^{40}Ar,\ 1n)\ ^{246}Fm$ | —— | —— | 6 | 1 | —— | 0.1 |
| $^{208}Pb + ^{50}Ti$ | —— | —— | 1 | 70 | 5 msec | 6 |
| $^{207}Pb + ^{50}Ti$ | 260 | —— | 2 | 90 | 4 sec | 3 |
| $^{206}Pb + ^{50}Ti$ | —— | —— | 0.4 | 2 | 3 msec | 0.3 |
| $^{208}Pb + ^{54}Cr$ | —— | —— | 2 | 20 | 4 – 10 msec | 1 |
| $^{207}Pb + ^{54}Cr$ | 280 | 254 ± 1.5 | 3 | 31 | 4 – 10 msec | 1 |
| $^{206}Pb + ^{54}Cr$ | —— | —— | 4 | —— | 4 – 10 msec | 0.2 |

of the table, indicate that the compound nucleus emits with maximum probability two or three neutrons, unlike the situation in reactions with ions of smaller mass (Fig. 2).

When lead is used as a target in the given experimental setup, the background due to spontaneous fission of the heavy elements is practically eliminated, as is also the background due to the spontaneously fissioning isomers in the region from U to Cf. The highly sensitive and rapid procedure for the observation of nuclei by their spontaneous fission can therefore be successfully used for the synthesis of new elements by this method.

This circumstance was used for the synthesis of the neutron-deficient isotopes of Ku in the reaction $Pb + ^{50}Ti$.

To accelerate the $^{50}Ti$ ions, a special ion source was developed at the Nuclear Reactions Laboratory of the Joint Institute for Nuclear Research, and was used to obtain, with the 310-cm cyclotron, a beam of these ions with intensity $2 \times 10^{11}$ ions/sec. The experimental procedure has made it possible to observe spontaneously-fissioning emitters if their lifetime exceeds $T_{1/2} \geq 3$ msec.

The results of the experiments are presented in the second part of the table. In the experiments with $^{50}Ti$ we observed two spontaneously fissioning emitters with essentially different half-lives, approximately 5 msec and several seconds. An analysis of the experimental data has established that the emitter with $T_{1/2} \sim 5$ msec is the isotope $^{256}Ku$, which is produced in the reaction $^{208}Pb\ (^{50}Ti,\ 2n)\ ^{256}Ku$.

The long-lived spontaneously fissioning emitter, which is produced with the maximum cross section in the reaction $^{207}Pb + ^{50}Ti$, is in our opinion the odd isotope $^{255}Ku$. The absence of the effect when $^{206}Pb$ is bombarded with $^{50}Ti$ ions may mean that the lifetime of the next isotope $^{254}Ku$ is shorter than 3 msec.

The results alter significantly our ideas concerning the stability of heavy nuclei to spontaneous fission. Whereas for the even isotopes of Cf, Fm, and the element 102 there is an appreciable increase of the stability (by $10^6$–$10^{12}$ times) near $N = 152$, for the even isotopes of Au this effect is practically nonexistent, and the spontaneous fission half-lives increase smoothly (by not more than 100 times) on going from $N = 152$ to $N156$. There is no need to assume here tremendous hinderences for the odd Ku isotopes, as would follow from the older concept, [2] the hindrance for the odd nuclei amounting to $10^3$–$10^4$.

After performing experiments aimed at obtaining neutron-deficient isotopes of Fm and Ku, it was natural to attempt to synthesize the next even element, with atomic number 106, by this method. Calculations based on the experimental data obtained above have shown that the most suitable for this purpose is the combination $Pb + ^{54}Cr$. The results of these experiments are represented in the third part of the table.

In the reactions $^{207}Pb + ^{54}Cr$ and $^{208}Pb + ^{54}Cr$, we observed the formation of spontaneously fissioning nuclei with a half-life of several msec.

We have subsequently performed a large number of control experiments in which various isotopes of Pb and Bi were bombarded with $^{51}V$ and $^{52}Cr$ ions and reactions of the $(p,\ xn)$ and $(\alpha,\ xn)$ type, which could lead to the formation of isotopes with $Z < 106$, were investigated. It was found that in this energy range the contribution of these reactions is negligibly small. We are therefore inclined to assume that the 50 events observed in the experiments are due to spontaneous fission of nuclei with $Z = 106$. From the ratio of the yield of this emitter in experiments with different Pb isotopes, and also on the basis of the new ideas concerning the systematics of the spontaneous fission, it can be assumed that the spontaneous fission is experienced by the odd isotope $^{259}106$, which is produced in reactions with emission of two and three neutrons.


[1]G. N. Flerov and I. Zvara, Soobshchenie OIYaI (JINR Communication) D7-6013, Dubna, 1971.
[2]A. Ghiorso, Proc. P.A. Welch Found. Conf. on Chem. Res., X 111 The Transuranium Elements—The Mendeleev Centennial Nov. 17–19, 1969, Houston, Texas, p. 107.