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The excellent possibilities which can be provided by accelerated ^{48}Ca ions to induce reactions leading to the synthesis of superheavy elements and to verify the hypothesis about their existence have been discussed since long ago [1–3].

As is known, the stability and very existence of superheavy nuclei in the vicinity of $Z = 114$ and $N = 184$ (refs. [4–6]) are fully determined by the shell effects which are rather sensitive to the nuclear composition and excitation energy. Therefore the only possible way of synthesizing superheavy nuclei with the help of heavy-ion induced reactions involves two sorts of difficulties.

As a rule, the excitation energy of a compound nucleus amounts to tens of *MeV*, which can strongly suppress the stabilizing shell effect [7]. This is expected to lead to a sharp enhancement of the fission probability and to a corresponding decrease in cross sections for (HI, xn) reactions because of the absence of the liquid-drop fission barrier in superheavy nuclei.

The other difficulty is associated with the ground state properties of superheavy nuclei. Heavy-ion induced reactions usually lead to the formation of neutron-deficient nuclei. At the same time, calculations [8] suggest that with a removal from the closed shells with $N = 184$ and $Z = 114$ nuclear stability decreases sharply, and this can influence drastically both the lifetimes of the nuclei being synthesized and the cross sections for fusion reactions.

If one puts aside the problem of the existence of superheavy elements as they are, these particular features of fusion reactions are very likely to have been the reason why attempts to synthesize superheavy nuclei by these reactions have so far been unsuccessful [9–11].

The extreme neutron excess of the ^{48}Ca nucleus makes it possible to reduce to a minimum the neutron deficit of the nuclei being synthesized as compared with reactions using other ions, and to approach the closed neutron shell with N = 184 in the synthesis of superheavy nuclei (Z = 114).

On the other hand, a simple calculation shows that the excitation energy of the compound nucleus $^{292}114$ formed as a result of the $^{244}Pu + ^{48}Ca$ reaction is as low as 18 *MeV* at $E_{ion} = V_{c_{48}}$ (the Coulomb barrier height). The most probable ($^{48}Ca, 2n$) reaction will lead to the formation of the isotope $^{290}114$ which is only by 8 neutrons removed from the double magic nucleus $^{298}114$.

Despite these quite obvious advantages, the ^{48}Ca ions have so far been accelerated nowhere. The reason for this is that the content of ^{48}Ca in the natural mixture of Ca isotopes is very small (0.18%) while its separation is a complicated and expensive matter. The world reserve of the enriched isotope ^{48}Ca seems to amount to only several tens of grams. In addition, the chemical element of calcium has no appropriate gaseous compounds, and this rules out the possibility of using it in common ion sources operated with a gas as a working material.

Below we shall describe experiments on the acceleration of ^{48}Ca ions and model experiments using these ions, aimed at the synthesis of the $^{252}102$ isotope.

For the purpose of accelerating ^{48}Ca ions, a new type of multiply-charged ion source was developed with a solid as a working material /12/. In contrast to an ion source supplied with a gas, the discharge chamber of the new ion source has an additional electrode with the working material contained therein. This electrode is fastened on a movable insulated water-cooled holder in the vicinity of the chamber emission slit (*fig. 1*). The position of the electrode and the potential applied to it are continuously regulated for the optimal operating condition to be established.

To manufacture the electrode a specially developed technology was used providing its mechanical and thermal stability for the case of using metals, oxydes, salts and

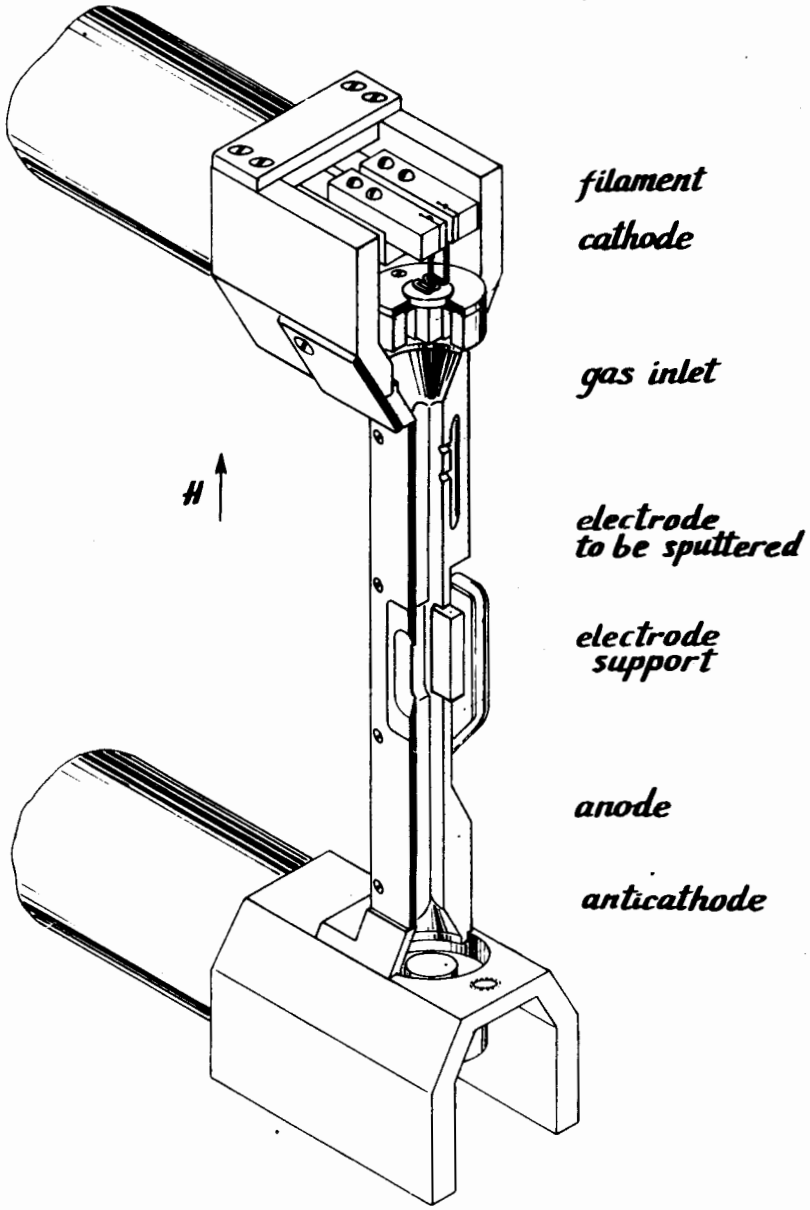

Fig. 1. Schematic view of the source of multiply charged calcium ions.

other working materials. In experiments with calcium, both natural and enriched ^{48}Ca in the form of metal and CaF_2 were used.

At the U-300 cyclotron, the ion energy at the terminal radius is given by the relation: $E = 250 Z^2/A$ *MeV*, where Z and A are the ion charge and mass number, respectively. It is estimated that in order to reach the energy necessary to induce reactions on uranium and plutonium targets one should produce in the ion source and then accelerate ^{48}Ca ions with a charge not lower than 7^+. This problem is complicated by the fact that ions with a charge as high as this one should be produced with a minimum amount of working material consumed. This was achieved by some modifications and the choice of appropriate operating modes of the ion source and the U-300 cyclotron as well as by a special technology for electrode manufacture and the recovery of about 60% of the original substance deposited on the walls of the ion source discharge chamber. As a result of different developments and modifications, at the terminal radius of the cyclotron a $^{48}Ca^{7+}$ ion beam was produced with an energy of 255 *MeV* and intensity of 1.7×10^{12} particles per second with a 4 *mg* consumption of the isotope per hour (about 1.3×10^{16} neutral *atoms/sec).*

The purpose of the first experiments using the ^{48}Ca ion beam was to verify experimentally the above-mentioned excellent advantages of these ions in terms of nuclear fusion. To do so, we chose the $Pb(^{48}Ca, xn)^{252}102$ reactions for a model experiment. The isotope $^{252}102$ formed by this reaction has a half-life of 2.3 *sec* and undergoes spontaneous fission with a 30% probability. The targets used were the separated high-purity Pb isotopes, ^{208}, ^{207}, ^{206}, ^{204} Pb. The minimum excitation energies of the compound nuclei formed were 17-18 *MeV* at $E_{ion} = V_c$ (see the table), and estimates suggest that reactions with a small number of neutrons evaporated are expected to have comparatively large cross sections.

The identification of $^{252}102$ and its yield measurements were carried out by detecting the fragments of spontaneous fission of reaction products and by an exact determination of its half-life. The experimental set-up

used was similar to that described previously [13]. The ^{48}Ca ion beam was incident grazingly onto the lateral face of a rotating hollow cylinder. This surface was covered by a thin, about 2 mg/cm^2, layer of the target material deposited by vacuum vaporization. In this geometry the target is considered to be "infinitely" thick for the ion beam and recoil nuclei and, at the same time, sufficiently thin for an efficient detection of the fragments of spontaneously fissioning reaction products. Thus the cylinder surface served both as a target and a recoil catcher. The cylinder rotation transported the nuclei to mica fission track detectors placed along the cylinder surface, and set a time scale for measuring spontaneous fission half-lives. The detectors were protected reliably from the background due to scattered ions. The detection efficiency was about 50%.

During the experiments, the ion beam intensity was controlled by a special device placed outside the target. The integral ion beam was determined using an activation analysis method, namely from the build-up of a long-lived activity in an Al sample occupying a small fraction of the working surface of the rotating cylinder.

In all of the bombardments the incident ^{48}Ca ion energy was equal to 235 *MeV*. The table to follow presents the minimum values of compound nucleus excitation energies at $E_{ion} = V_c$, and the measured results. The numbers of tracks correspond to the total number of fission events recorded during bombardments of the order of one hour long.

Table

Reaction	E_{ion}, *MeV*	$E^{min}_{exc.}$, *MeV*	Number of tracks
$^{208}Pb(^{48}Ca, 4n)^{252}102$	235	17	30
$^{207}Pb(^{48}Ca, 3n)^{252}102$	235	18	59
$^{206}Pb(^{48}Ca, 2n)^{252}102$	235	18	438
$^{204}Pb(^{48}Ca, \gamma)^{252}102$	235	18	3

Figure 2 shows the time distribution of the fragments formed as a result of fission of $^{252}102$. The measured half-life value (2.3 *sec*) is exactly the same as the known one [14].

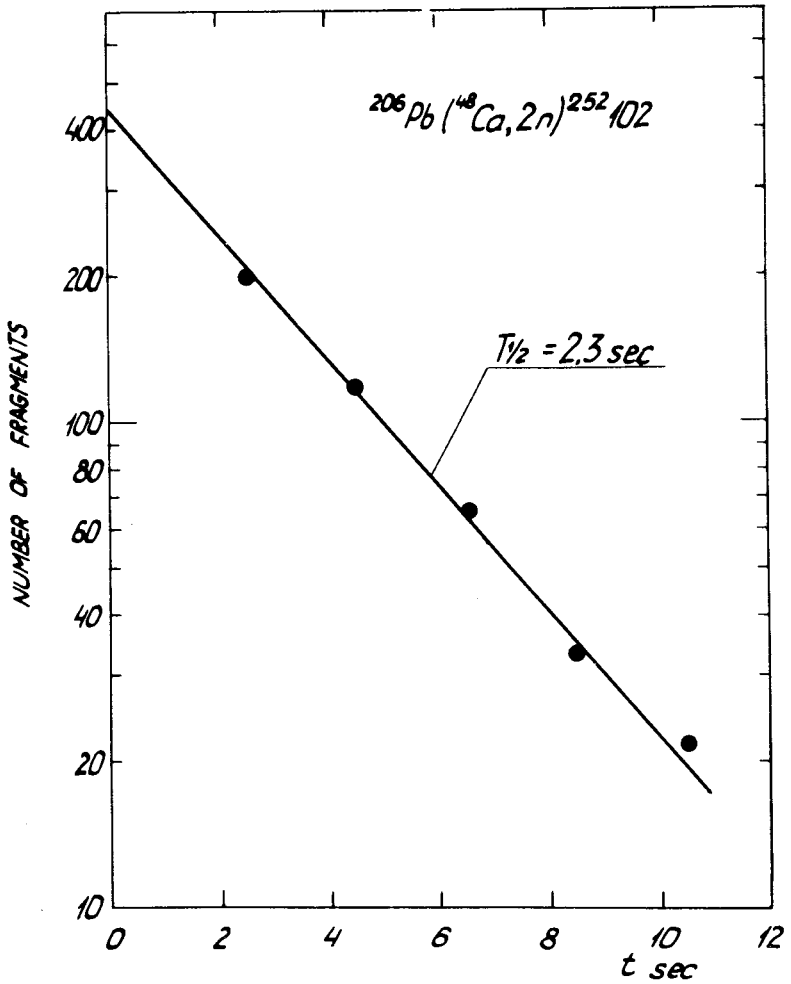

Fig. 2. Time distribution of fission fragments of the isotope $^{252}102$.

The experimental cross section for reactions with the emission of 2, 3 and 4 neutrons are compared with the calculated data in *fig. 3*. The technique used in calculating

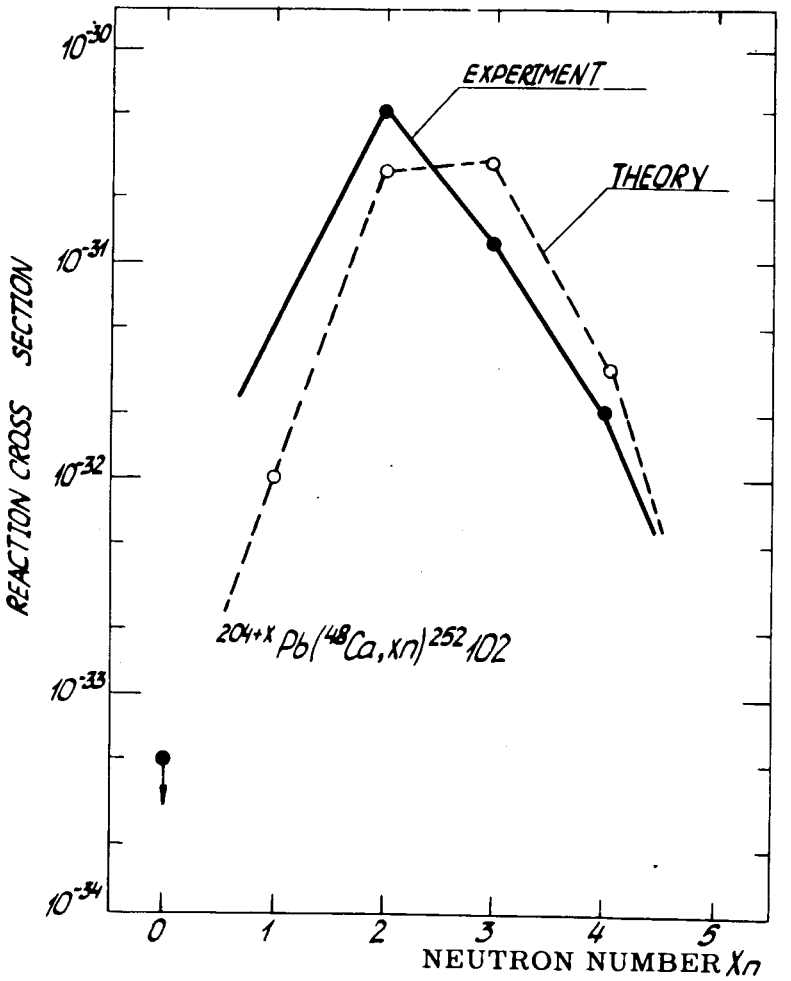

Fig. 3. Production cross sections for the isotope $^{252}102$ *in reactions induced by* ^{48}Ca *ions.*

the cross sections for reactions with a small number of neutrons emitted [15] involves several parameters. In our case the values of the parameters were chosen taking into account the results obtained in experiments with Ar , Ti and Cr ions [16,17].

The most important outcome of these experiments is the establishment of the fact that in the case of ^{48}Ca ions

used, the absolute cross sections for reactions leading to the synthesis of element 102 are comparatively large, the reaction with 2 neutrons emitted having the largest cross section, about $5 \times 10^{-31} cm^2$. This value about a factor of 40 exceeds the cross sections for reactions induced by ^{18}O and ^{22}Ne ions leading to the same product /18/.

In our subsequent experiments we made an attempt to determine the radiative capture probability for ^{48}Ca. We chose the $^{204}Pb(^{48}Ca, \gamma)^{252}102$ reaction without changing the experimental technique. The isotope ^{204}Pb with a 99.80% enrichment was used as a target. In this experiment, three spontaneous fission fragments were detected, and all of them can be assigned to the $^{206}Pb(^{48}Ca, 2n)^{252}102$ reaction on the ^{206}Pb admixture of the target material. This determines the upper limit of the cross section for the $^{208}Pb(^{48}Ca, \gamma)$ reaction to be about 5×10^{-34} cm^2, i.e., a factor of 1000 smaller than the cross sections for reactions with the emission of two neutrons.

The problem of cross section magnitudes for heavy ion radiative capture reactions presents a separate interest in terms of the competition between neutron and γ-ray emissions in the region of highly fissionable nuclei. In the future we are planning to carry out similar experiments with a higher sensitivity.

The results obtained in experiments using accelerated ^{48}Ca ions lead one, in our opinion, to conclude that the use of these ions in fact offers unique possibilities for the synthesis of new transuranic and superheavy elements. One should, however, bear in mind that although the replacement of lead isotopes by U, Pu or Cm nuclei should lead to some increase in the minimum excitation energies of compound nuclei, we estimate them not to exceed 20-25 *MeV*. At such energies, it is not excluded that there is a certain probability for compound nuclei to proceed to the ground state with the emission of a small number of neutrons. On the other hand, with the ion beam intensity of about 10^{12} *particles/sec* it is possible to record the formation of superheavy nuclei if the production cross section is equal to 10^{-34} cm^2 or even 10^{-35} cm^2.

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