CROSS SECTION FOR THE PRODUCTION OF Fm^{250} *IN THE REACTIONS* Pu^{241} $(C^{13}, 4n)$ Fm^{250} *AND* U^{238} $(O^{16}, 4n)$ Fm^{250}

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The cross section for production of Fm^{250} in the reaction $Pu^{241}(C^{13}, 4n)$ and $U^{238}(O^{16}, 4n)$ has been determined as a function of the energy of bombarding particles. The comparison of the cross section for production of Fm^{250} with the fission cross section in these reactions shows that in the overwhelming majority of cases the excited compound Fm^{254} nucleus undergoes fission, and only in a few cases does deexcitation take place as a result of neutron emission. The maximum cross section for the production of Fm^{250} by irradiation with oxygen or carbon ions is 1×10^{-30} and 5×10^{-30} cm^2 respectively. The difference between the cross sections is probably due to the effect of the Coulomb barrier.

THE present work is a part of research done on the synthesis of transuranic elements with the aid of multiply-charged ions (see references 1 — 4).

The compound nucleus formed as a result of collision between a multiply-charged ion and a heavy nucleus disintegrates essentially either by fission[5] or by neutron emission.[1-4,6] A study of the competition between these processes as a function of the energy and nuclear characteristics (Z and A) of the colliding particles is of great interest, particularly for the synthesis of new transuranic elements.

1. THE REACTION $Pu^{241}(C^{13}, 4n)Fm^{250}$

In the present investigation we studied the reaction $Pu^{241}(C^{13}, 4n)Fm^{250}$ with the aid of the same Pu^{241} targets as were used in the experiments on the production of the 102nd element.[2] The Pu^{241} was deposited on thin (1.5 — 2) niobium foils; the layer thickness amounted to 90 and 200 $\mu g/cm^2$. To prevent possible crumbling of the substance, the Pu^{241} was covered from above with a layer of copper approximately 70 $\mu g/cm^2$ thick, deposited by evaporation in vacuum. The targets were irradiated in the internal beam of the cyclotron. The reaction products were gathered by the same procedure as used by Flerov et al.[2] to obtain the 102nd element. This procedure is based on causing the heavy ions to impart to the compound nucleus so large a momentum that the reaction products are knocked out from a layer of target of noticeable thickness. The scheme of the experiment is shown in Fig. 1.

Such a procedure has made it possible to employ the same target many times and to avoid working with highly active matter. The reaction products were gathered on a 15 μ aluminum foil, placed several millimeters from the target. The irradiation was at different cyclotron radii. The energy of the $^{+4}C^{13}$ ions was determined from the absorption in aluminum filters. The intensity of the current of the $^{+4}C^{13}$ ions was 0.3 — 0.5 μa.

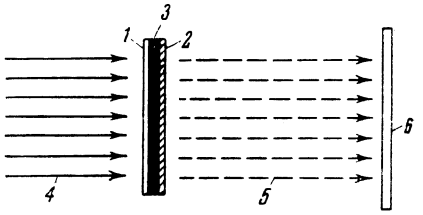

FIG. 1. Arrangement of the experiment. 1 — niobium foil 1.5 μ thick; 2 — protective copper layer (70 $\mu g/cm^2$); 3 — layer of Pu^{241} (90 or 200 $\mu g/cm^2$); 4 — $^{+4}C^{13}$ ions; 5 — Fm nuclei and other reaction products; 6 — aluminum collector 15 μ thick.

After irradiation, which lasted for 45 — 60 minutes, the collector with the reaction products was removed from the cyclotron and subjected to radiochemical analysis. The collector was dissolved in concentrated hydrochloric acid, to which 400 μg of lanthanum and known amounts of Am^{241} were introduced as a carrier to determine the fermium chemical yield; the lanthanum fluoride was then precipitated. The fluorides were decomposed with nitric acid. The nitrate solution was deposited on a platinum disc, which after drying and roasting was placed in an ionization chamber with spherical electrodes. The pulses from the ionization chamber were fed to a 50-channel amplitude analyzer. The Fm^{250} was identified by the energies of the α particles and by the half-life (E = 7.43 Mev, $T_{1/2}$ = 30 min[7]). In the calculation of the reaction cross section, we took into account the effectiveness with which the Fm^{250}

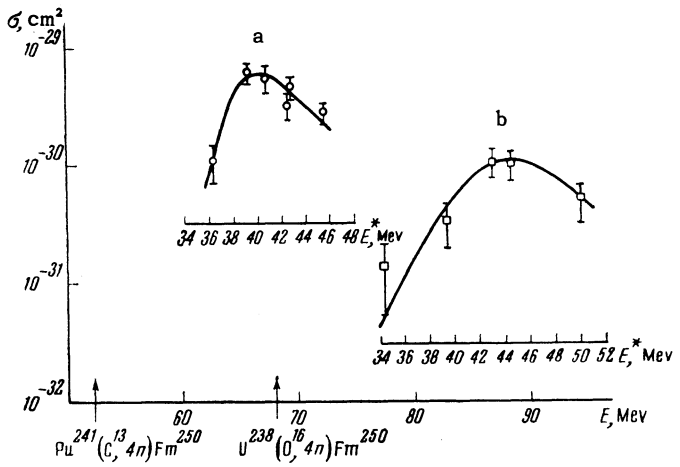

FIG. 2. Reaction cross sections for the production of Fm^{250} as a function of the energy E of the bombarding particles. a – The reaction $Pu^{241}(C^{13}, 4n)Fm^{250}$; b – the reaction $U^{228}(O^{16}, 4n)Fm^{250}$. The arrows mark the reaction thresholds.

nuclei were knocked out from the target matter. To estimate the fraction of the Fm^{250} nuclei knocked out from the target, we used experimental results on the determination of the range of the nuclei of the radon formed in the reaction $Au^{197}(N^{14}, xn)$, where $x = 4 - 6$, in aluminum and in copper. A recalculation of these data for the $Pu^{241}(C^{13}, 4n)Fm^{250}$ reaction was based on a relation derived by Firsov. The basic principles of this relation were verified in experiments on the ranges of the nuclei formed in the reactions under the influence of 14-Mev neutrons (see Appendix).

The values obtained for the cross section of the $Pu^{241}(C^{13}, 4n)Fm^{250}$ reaction as a function of the energy of bombarding particles are shown in Fig. 2.

2. THE REACTION $U^{238}(O^{16}, 4n)Fm^{250}$

In the investigation of this reaction we used targets comprising layers of uranium, deposited by evaporation in vacuum on thin (2μ) nickel foils. To avoid crumbling of the uranium, which is possible when operating with thick layers, we used "packets" of pairs of nickel foils with the uranium layers facing each other. The total thickness of the uranium layer reached ~ 1.3 mg/cm^2. The irradiation was with $^{+5}O^{16}$ ions. The irradiation procedure, the subsequent chemical processing, and the identification of the Fm^{250} were the same as in the investigation of the preceeding reaction. In individual cases, the resultant reaction products were separated chromatographically. A study of the Fm^{250} yield was also made by irradiating thick (15μ) uranium foils. The cross section for the production of Fm^{250} could be estimated in this case by differentiating the curve of the energy dependence of the yield. The data obtained were found to be in satisfactory agreement with the results of experiments on the irradiation of thin targets.

The cross section of the reaction $U^{238}(O^{16}, 4n)Fm^{250}$ is also shown in Fig. 2 as a function of the oxygen-ion energy. This figure shows, along with the energy of the bombarding particles, also the excitation energy (E*) of the compound Fm^{254} nuclei produced in the reactions $Pu^{241} + C^{13}$ and $U^{238} + O^{16}$. The errors indicated are statistical counting errors. Errors in the measurement of the ion current and of the chemical yields of the reaction products are insignificant. The total measurement error in the case of the $Pu^{241}(C^{13}, 4n)Fm^{250}$ may be 1.5 or 2 times greater, owing to inaccuracies in the determination of the fraction of the knocked-out Fm^{250} nuclei.

The results obtained in the present work for the cross sections of the reactions $Pu^{241}(C^{13}, 4n)Fm^{250}$ and $U^{238}(O^{16}, 4n)Fm^{250}$ are in agreement with those obtained by others.[8,9]

It must be noted that in the investigation of the products of the reaction $U^{238} + O^{16}$, the isotope Cf^{246} was identified in amounts considerably in excess of the Cf^{246} produced through α decay of Fm^{250}. It is obvious that in this case the Cf^{246} is produced directly via the reaction $U^{238}(O^{16}, \alpha 4n)Cf^{246}$, the cross section of which has tentatively been estimated to be ten times the cross section of the reaction $U^{238}(O^{16}, 4n)Fm^{250}$.

DISCUSSION OF RESULTS

A comparison of the cross section for production of Fm^{250}, through bombardment of Pu^{241} or U^{238} by C^{13} and O^{16}, with the fission cross sections for these reactions shows that in the overwhelming majority of cases the excited compound nucleus Fm^{254} experiences fission, and only in a negligible number of cases is the excitation removed by emission of neutrons. Comparison of the cross sections of the various reactions (see references 3 and 4) shows that the cross section of neutron-evaporation reaction diminishes with increasing Z of the compound nucleus. Thus, for example, in bombardment by carbon ions the maximum cross section of the reaction of evaporation of four neutrons amounts to 8×10^{-29} cm^2 in the case of production of the compound nucleus Cm^{244} (reference 4), 6×10^{-29} cm^2 in the case of Cf^{250} (reference 3), and 5×10^{-30} cm^2 in the case of Fm^{254}. A detailed precise evaluation of the competition between the neutron-evaporation and fission processes requires not only the comparison of the magnitudes of the neutron-evaporation cross sections, but also allowance for such factors as the dependence of the cross section for the production of the compound nucleus on the energy and the probability of evaporation of

a given number of neutrons at a given excitation energy.

In the case of the $Pu^{241}(C^{13}, 4n)Fm^{250}$ and $U^{238}(O^{16}, 4n)Fm^{250}$ reactions we deal with the production of the same compound nucleus Fm^{254} with subsequent evaporation of four neutrons. As can be seen from the diagram, the cross section for the production of Fm^{250} by irradiation with oxygen ions is found to be several times smaller than in irradiation by carbon ions. The reduction in the cross section of the reaction in irradiation with oxygen ions is due to the influence of the Coulomb barrier. The large Coulomb barrier in the case of the reaction $U^{238} + O^{16}$ causes a large shift in the maximum of the reaction of evaporation of four neutrons, towards the higher energies. At these excitation energies the evaporation of four neutrons becomes less probable and takes second place to the more probable reaction of evaporation of five neutrons.

It should be noted that in the present experiments we observed no formation of other fermium isotopes, besides Fm^{250}. Therefore, the fermium isotope which we obtained earlier[10] by bombarding uranium with oxygen ions is obviously Fm^{250}.

In conclusion, the authors express their deep gratitude to Prof. G. N. Flerov for continuous attention and interest in this work.

APPENDIX

We give below the results of experiments on the determination of the ranges of the nuclei produced in nuclear reactions. In one of these experiments thin layers of Au^{197}, coated on the side opposite to that of the beam, with thin layers of aluminum or copper, were irradiated with N^{14} ions of known energy. The nuclei of the radon produced by the $Au^{197}(N^{14}, xn)$ reaction were knocked out of the layer of gold and, partially passing through the layer of absorber (Al or Cu), entered the collector. The distribution of the ranges of the radon nuclei in aluminum and copper was determined from the ratios of the intensities of the radon decay-product α radiations in absorber layers of different thicknesses to that in the collector.

Analogous experiments were carried out by A. F. Georgobiani, N. I. Tarantin, and G. N. Flerov in 1954. They determined the ranges of nuclei produced upon irradiation of various substances (Al, Si, Cu, Ag, and Sb) by 14-Mev neutrons. The experimental setup was similar to that shown in Fig. 1. The average range of the reaction products in the target substance was determined by comparing the numbers of radioactive nuclei produced in (n, 2n) and (n, p) reactions in the target and on a Plexiglas collector.

The results obtained, both in the case of irradiation with N^{14} ions and in the case of irradiation with 14-Mev neutrons, were found to be in satisfactory agreement with the formula obtained in 1954 by O. B. Firsov for the ranges of atoms at initial velocities of $\sim 10^7 - 10^8$ cm/sec. In the derivation of this formula the author described the interaction of two colliding atoms by means of a potential approximated by a function inversely proportional to the square of the distance.[11] The value obtained is

$$R = 0.5A_2(A_1 + A_2)(Z_1 + Z_2)^{1/2}E / A_1Z_1Z_2.$$

where R is the range of the atom, expressed in $\mu g/cm^2$, Z_1A_1 and Z_2A_2 are the atomic number and the mass number of the moving atom and of the atoms of the retarding medium, and E is the kinetic energy of the moving atom, expressed in kev. The mean square spread of the ranges of the radon nuclei, formed in the reaction $Au^{197}(N^{14}, xn)$ was found to be 0.4 of the average range.

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