AN INVESTIGATION OF $_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$

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The cross section for the reaction $_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$ is found to have a peak of $\sim 2.5 \times 10^{-31}$ cm^2 at 107 MeV (lab. system) and half-width ~ 11 MeV. Comparison is made with the cross sections for $_{94}Pu^{241}(_{6}C^{13}, 4n)_{100}Fm^{250}$ and $_{92}U^{238}(_{8}O^{16}, 4n)_{100}Fm^{250}$.

1. INTRODUCTION

THIS is a study of the production of transuranium elements in reactions between nuclei and multicharged ions. It was one of our most important purposes to account for the fact that different cross sections are obtained for the production of identical isotopes in reactions involving the same compound nucleus formed in different ways, i.e., by different projectile-target combinations. [1]

The most suitable isotope for our purpose was $_{100}Fm^{250}$, which is produced in the three analogous reactions:

$$_{94}Pu^{241} + {}_{6}C^{13} \rightarrow {}_{100}Fm^{254} \rightarrow {}_{100}Fm^{250} + 4n,$$
$$_{92}U^{238} + {}_{8}O^{16} \rightarrow {}_{100}Fm^{254} \rightarrow {}_{100}Fm^{250} + 4n,$$
$$_{90}Th^{232} + {}_{10}Ne^{22} \rightarrow {}_{100}Fm^{254} \rightarrow {}_{100}Fm^{250} + 4n.$$

$_{100}Fm^{250}$ has been well studied and can be detected through registration of its α activity ($T_{1/2} = 30$ min, $E_\alpha = 7.43$ MeV). The first two reactions have been investigated in [1-3], and the third reaction is studied in the present work.

2. EXPERIMENTAL TECHNIQUE

In preliminary experiments on the irradiation of thorium targets with $_{10}Ne^{22}$ ions, considerable yields were observed [4] for reactions resulting in the production of the actinium isotopes Ac^{226}, Ac^{225}, and Ac^{224}. The α activities of the series for which these isotopes are the parents, created a number of difficulties for the study of the reaction yielding Fm^{250}. The principal difficulty was associated with the background at 7.43 MeV due to the low-energy tail of the strong 7.65 MeV Po^{214} line resulting from Ac^{226} decay:

$$\begin{array}{l} {}_{89}Ac^{226} \\ \beta\text{-}80\% \downarrow 29\ \text{hr} \\ {}_{90}Th^{226} \xrightarrow[30\ \text{min}]{\alpha 6{,}33\text{MeV}} {}_{88}Ra^{222} \xrightarrow[38\ \text{sec}]{\alpha 6{,}55\text{MeV}} {}_{86}Rn^{218} \xrightarrow[0.019\ \text{sec}]{\alpha 7{,}13\text{MeV}} \\ \qquad {}_{84}Po^{214} \xrightarrow[1{,}6\cdot 10^{-4}\text{sec}]{\alpha 7{,}65\ \text{MeV}} {}_{82}Pb^{210}\ . \end{array}$$

The reaction producing Ac^{226} has a cross section of the order of a few microbarns near the Coulomb barrier; the cross section grows rapidly with increasing Ne^{22} energy. An attempt was made to separate Fm^{250} from the actinium by using the difference in nuclear ranges. It was found, however, that for actinium nuclei the momentum component in the beam direction does not differ greatly from the momentum of the compound nucleus.[1)] The fermium was therefore separated chemically in conjunction with the use of an α spectrometer having high energy resolution.

Irradiation with accelerated $_{10}Ne^{22}$ ions took place in the internal beam of the 300-cm cyclotron of the Joint Institute for Nuclear Research. The targets were mainly metallic thorium having thicknesses 2—2.6 mg/cm^2. The reaction products were separated from the target material by collecting recoil nuclei on 3μ silver foil. The Ne^{22} current was ~ 1—$1.5\,\mu$A; bombardment lasted about one hour. The beam energy was varied by placing aluminum absorbers of suitable thicknesses in front of the target. [5]

The rapid chemical treatment of the collectors of recoil nuclei, with maximum possible separation from background activities, was based on fermium extraction by tenoil trifluoracetone (TTA). Two extractions were performed, at pH ~ 2.5 and ~ 3.5, after which the fermium atoms were separated from the organic phase by electrodeposition on a gold anode. Separation from the silver collector occurred during the extraction (to a $\sim 1\%$ level) and during electrodeposition (through silver deposition on the cathode). The product of this procedure was an extremely thin film containing fermium, whose chemical yield was determined by adding Cm^{242} to the original solution. The fermium yield was $\sim 50\%$ in the different runs. All chemical

[1)] Results obtained in a detailed study of reactions producing actinium isotopes will be published separately.

procedures combined required 12—15 min.

The α spectra of the reaction products were measured with a two-grid ionization chamber filled with argon plus a small amount of acetylene. The high-stability electronic equipment permitted lengthy runs with 25—30 keV energy resolution. The ionization chamber was equipped with a special lock for rapid transfer of samples without change of the gas.

All preparatory procedures from the termination of irradiation to the initiation of measurements usually required 30—35 min, which is about one half-life of Fm^{250}.

3. EXPERIMENTAL RESULTS

As a check of the entire technique, the excitation function of the reaction $_{92}U^{238}(_8O^{16}, 4n)_{100}Fm^{250}$ was measured. The result is consistent with the $\sim 10^{-30}$ cm^2 peak cross section for this reaction, in agreement with other investigations.[1,3]

In our main study of the reaction $_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$ we identified Fm^{250} from its half-life and α-particle energy. Figure 1 is a portion of the α spectrum around the Fm^{250} line, which is accompanied on both sides by lines representing Rn^{218} and Po^{214} decays having intensities that did not interfere with the registration of Fm^{250} α decay. At the same time these background lines furnished good calibration points for determining the principal α-particle energy $E_\alpha = 7.440 \pm 0.020$ MeV. This is in good agreement with the tabular value 7.43 MeV.

Figure 2 demonstrates the decay of the 7.44-MeV α activity. The experimental half-life $\sim$ 33 min also agrees well with the tabular 30-min half-life of Fm^{250}.

Figure 3 shows the dependence of the cross section for $_{100}Fm^{250}$ production on the energy of incident $_{10}Ne^{22}$ ions in the laboratory system. Because of the considerably enhanced cross section for Ac^{226} production above 120 MeV it was possible to obtain only the upper limit of the cross section for Fm^{250} production. The $_{10}Ne^{22}$ energy was determined to within 5 MeV; the experimental half-width of the curve is $\sim$ 11 MeV. The peak cross section $\sim 2.5 \times 10^{-31}$ cm^2 for $_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$ is attained at about 107 MeV.

In calculating cross sections an effective thickness of 1 mg/cm^2 was assumed for the Th^{232} layer emitting Fm^{250}. This value was obtained by using data in [6].

A remeasurement of the excitation function agreed with the foregoing within experimental error.

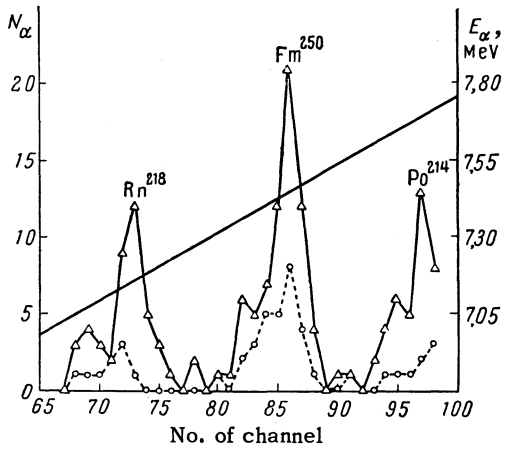

FIG. 1. Part of α spectrum from products of the reaction $_{90}Th^{232} + _{10}Ne^{22}$. The solid curve represents the spectrum registered in the first 15 min following bombardment; the dashed curve represents the total spectrum in 7 min of measurements. The straight line is a calibration curve for α-particle energies.

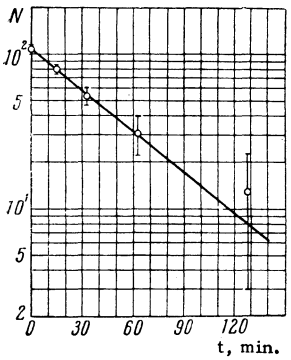

FIG. 2. Decay of 7.44-MeV α-activity.

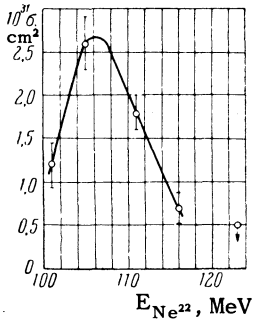

FIG. 3. Dependence of cross section for $_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$ on neon ion energy (lab. system). Statistical errors are indicated. The upper limit of the cross section was obtained at $\approx$123 MeV.

4. DISCUSSION

From a comparison of the experimental cross sections for the production of Fm^{250} in the reactions $Pu^{241} + C^{13}$, $U^{238} + O^{16}$, [1-3] and $Th^{232} + Ne^{22}$ we conclude that the cross section decreases considerably with increasing projectile mass (see the table). We shall now consider the possible causes of this effect.

The cross section σ_{4n} for a reaction resulting in the evaporation of four neutrons can be represented by

Reaction	σ_{4n} max, 10^{-30} cm²		Γ_n/Γ_f (experimental)
	Experimental	Calculation for $\Gamma_n/\Gamma_f = 0.12$	
$_{94}Pu^{241}(_6C^{13}, 4n)_{100}Fm^{250}$	6	6	0.12
$_{92}U^{238}(_8O^{16}, 4n)_{100}Fm^{250}$	1	3	0.09
$_{90}Th^{232}(_{10}Ne^{22}, 4n)_{100}Fm^{250}$	0.25	2	0.07

$$\sigma_{4n} = \sigma_c(E)\,\overline{[\Gamma_n/(\Gamma_n+\Gamma_f)]^4}\,P_{4n}(E^*), \qquad (3)$$

where $\sigma_c(E)$ is the cross section for the formation of a compound nucleus, $\overline{\Gamma_n/(\Gamma_n+\Gamma_f)}$ is the mean ratio of the neutron width to the sum of the neutron and fission widths, and $P_{4n}(E^*)$ is the probability of the evaporation of four neutrons from a nucleus having excitation energy equal to the ion energy E.

The product $\sigma_c(E)\,P_{4n}(E^*)$ can obviously vary, depending on the projectile-target pair. This results from the fact that a single value of the cross section for compound-nucleus formation can correspond to different excitation energies, i.e., to different values of $P_{4n}(E^*)$. However, this factor does not take into account the entire difference between the experimental cross sections for the given reactions. The table gives the calculated peak cross sections obtained with the variation of $\sigma_c(E)\cdot P_{4n}(E^*)$ taken into account. The required values of $\sigma_c(E)$ were taken from [7]. The constant value 0.12 was taken for $\overline{\Gamma_n/\Gamma_f}$; this was calculated using the experimental cross section for $Pu^{241}(C^{13}, 4n)Fm^{250}$ obtained from the foregoing formula. The difference between the calculated and experimental results indicates the existence of other causes for the diminished cross section in the case of heavier bombarding particles.

Pik-Pichak has shown [8] that the fission width Γ_f depends on the nuclear angular momentum. The aforementioned diminution of the cross section can possibly be associated with an increased probability of fission of the compound nucleus, since systems incorporating heavier ions have larger angular momentum. On this basis a slight change in the value of Γ_n/Γ_f would generally be sufficient to account for the experimental results. The last column of the table gives the values of Γ_n/Γ_f obtained from the formula for σ_{4n} using the experimental cross sections.

Our estimates of the effect of higher angular momentum show that this factor can account for only a small part of the decrease of σ_{4n} as we go from C^{13} to Ne^{22}. There are two other possible causes of cross section variation:

1. During the collision process nuclei could be deformed in the Coulomb field. This would elevate the Coulomb barrier and thus reduce the value of $\sigma_c(E)\,P_{4n}(E^*)$.

2. At the instant of collision oscillations of the system could be excited, thus increasing the probability of fission before the first neutron is ejected. We can expect these oscillations to be stronger for heavier projectiles.

In the absence of detailed calculations there is no basis for preferring either of the two possible explanations.

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