SYNTHESIS OF THE ELEMENT 102 OF MASS NUMBER 256

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An α-active nuclide of the element 102 having mass number 256 has been synthesized in the nuclear reaction $^{238}\text{U} + (\text{Ne}^{22}, 4\text{n}) \rightarrow ^{256}\text{No}$. The nuclide was recorded and identified through the daughter nuclide $^{252}\text{Fm}$. The measured half-life of the nuclide $^{256}\text{No}$ was found to be $\approx 8$ sec.

The energy dependence of the formation cross section of nuclide $^{256}\text{No}$ in the $^{238}\text{U} + \text{Ne}^{22}$ reaction was studied. It peaks in the 112 MeV region. The cross section is $\approx 4.5 \times 10^{-22}$ cm$^2$ in the area of the peak.

This work was carried out using the internal beam of the three-meter cyclotron of the Nuclear Reactions Laboratory, a subdivision of the Dubna Joint Institute for Nuclear Research.

INTRODUCTION

At the present time, the principal technique used to synthesize new transuranium elements involves nuclear reactions resulting in the bombardment of uranium, plutonium, americium, curium, Californium, and einsteinium targets by intense fluxes produced by accelerated boron, carbon, nitrogen, oxygen, and neon ions. The reactions used predominantly have been fusion of the target nucleus and the nucleus of the bombarding ion with subsequent boiling off of several neutrons from the compound nucleus. The cross sections of those reactions in the region beyond the hundredth element are very small and constitute at most $10^{-29}$ to $10^{-23}$ cm$^2$. The reason for this is the high energy of excitation of the compound nuclei formed in the reaction, and the high fissionability of those nuclei.

The products of these nuclear reactions - the far transuranium elements - are neutron deficient to a pronounced extent, and this renders their α-decay time comparatively short. The low formation cross sections and the short decay times, as well as the large number of competing processes having higher probabilities, lead to the appearance of the most varied background activities in the products of interactions between these ions and the target nuclei, and are responsible for the difficulties encountered in producing and isolating new heavier elements. These difficulties increase still more precipitously as heavier and heavier elements are to be synthesized. This has stimulated the efforts of experimental physicists to search out still more effective ways of isolating new elements, bringing not only chemical but also physical techniques to bear on the problem of identifying trace quantities of new elements.

Experiments have been underway since 1957 on the synthesis of the element 102. During that time, findings of research projects conducted at laboratories in different countries have appeared in print. However, the actual proof of successful synthesis of element 102 to any extent as convincing as the evidence offered in connection with the synthesis of preceding elements has been lacking in the published reports.

The first communication on record on the synthesis of element 102 appeared in the summer of 1957 [1]. A team of scientists from Sweden, Britain, and the USA published a report on work which they carried out at the Nobel Institute of Physics in Stockholm. A curium target (isotope composition: $^{244}\text{Cm} \approx 95\%$; $^{246}\text{Cm} \approx 1\%$; $^{248}\text{Cm} \approx 4\%$; $^{247}\text{Cm} \approx 0.09\%$; and $^{244}\text{Cm} \approx 0.02\%$) was irradiated by $^{15}\text{C}$ ions in a cyclotron installation with cyclotron pole diameter 225 cm. The products of the nuclear reactions were separated out, after the exposure, on a chromatographic column. As a result, weak α-activity such that $E_\alpha = 8.5 \pm 0.1$ MeV and $T_1/2 = 10$ min was detected, the chemical behavior being what one would expect from theoretical prediction on element 102. The total number of recorded decay events apparently did not exceed 25.

On the basis of the data so obtained, the authors inferred that the observed α-activity was due to an isotope of the element 102, of mass number 251 or 253. These isotopes may be synthesized in the reactions $^{244}\text{Cm} + (\text{C}^{19}, 6\text{n}) \rightarrow ^{251}\text{Cm}$ or $^{244}\text{Cm} + (\text{C}^{19}, 4\text{n}) \rightarrow ^{253}\text{Cm}$, respectively. It is not excluded that this activity may even belong to products obtained as a result both of spallation reactions and of reactions taking place on impurities in the target material. As
was shown in other contributions to the literature \([2-4]\), these processes have a sufficiently high rate to present a troublesome background. This is particularly the case when we remember that the chemical procedure utilized by the authors of \([1]\) did not enable the researchers to reliably isolate element 102 from other elements present.

In February 1958, a staff team of the I. V. Kurchatov Institute of Atomic Energy published a paper describing an attempt to synthesize the nuclide \(^{253}\)No wherein a physical method of identification was used \([4]\).

The \(^{241}\)O \((\alpha, 4\text{ n}) \) \(^{255}\)No was decided upon for synthesizing the nuclide \(^{255}\)No. A \(^{241}\)Pu target was bombarded by \(^{16}\)O ions accelerated to 100 MeV energy in a 1.5 meter cyclotron. The nuclear reaction products knocked from the target were led to an \(\alpha\)-particle detector, consisting of a nuclear emulsion stack. Short-lived \(\alpha\)-activity of about 8.9 MeV energy, which might have been a result of the synthesis of one of the isotopes of the element 102 (and most probably of \(^{255}\)No, in fact), was detected in these experiments. The experiments were greatly hindered by the presence of a large amount of hitherto unknown \(\alpha\)-emitters in the reaction products. It was shown that some of these \(\alpha\)-emitters appear as a result of reactions taking place in lead, bismuth, and other elements present in the form of impurities in the target material.

The experiments were extended into 1958 \([5]\). Painstaking removal of all possible impurities and a specially developed highly sensitive activation analysis procedure used on the plutonium targets employed in the experiments revealed that the contributions of the impurities remained below 40\%, and that the total background amounted to 50\% of the observed effect due to the \(\alpha\)-activity \(E_{\alpha} = 8.9 \pm 0.4\) MeV. Experiments were designed and conducted to aid in identifying the product responsible for this \(\alpha\)-activity.

It could be safely assumed, on the basis of the results of a study of the dependence of the yield of this reaction product on the energy of \(^{16}\)O ions, that the product forms in a reaction having a typical excitation function for evaporation reactions. When \(^{249}\)Pu targets are bombarded by oxygen ions, no yield of this product is observed. The results of the experiments on record back up the conclusion that the product responsible for this \(\alpha\)-activity is indeed the nuclide \(^{253}\)No.

As a result of the experiments carried out in this project, the half-life of the element \(^{253}\)No has been found to lie in the range 3-40 sec. The presence of background \(\alpha\)-emitters, and in particular of an isomer of \(^{251}\)Pu \((E_{\alpha} = 8.8\) MeV; \(T_{1/2} = 25\) sec) produced in nuclear reactions which occur in the lead impurities present in the target, enabled us to determine no more than the lower and upper bounds of the half-life.

The discrepancy in the results reported in \([1]\) and in \([4, 5]\) may be accounted for by the fact that no unambiguous determination of the mass number of the synthesized nuclide was performed in the Stockholm experiments. The curium targets had a rather complicated isotope composition, and it is not at all excluded that the nuclide \(^{255}\)No was synthesized in these experiments in the reaction \(^{244}\)Cm \((\text{Cm, 4 n}) \) \(^{255}\)No, or that some even heavier nuclide was formed \([6]\). However, Berkeley experiments have demonstrated on the other hand that this supposition lacks any substantial basis.

Experimental results on the synthesis of element 102 at the Radiation Laboratory of the University of California at Berkeley, on the linear heavy ion accelerator, were published in May 1958 \([7, 8]\). The experiments of the Stockholm group were repeated under similar conditions, but with much higher sensitivity. A curium target having the same isotope composition as that used in the Stockholm experiments was bombarded by a monochromatic beam of both \(^{13}\)C ions and \(^{12}\)C ions, while the ion energy was varied over a wide range. The accelerator beam intensity was many times in excess of the ion beam intensity of the Stockholm cyclotron. However, a careful and thorough investigation turned up no products of the family of nuclear reactions \((\text{C, 13, 4 n})\) of \(\alpha\)-activity \(E_{\alpha} = 8.5\) MeV and \(T_{1/2} = 10\) min. This provided once more a convincing demonstration of the fact that some important error must have crept into the work done at Stockholm.

Experiments on the synthesis of the shorter-lived isotopes of the element 102, in particular the nuclide \(^{254}\)No, were being carried out in California simultaneously with these above experiments \([8]\). The method used in these latter cases permitted investigators to record and identify the short-lived \(\alpha\)-active isotopes in terms of their relatively short-lived daughters. In the case in point, \(^{254}\)No was obtained in the reaction \(^{244}\)Cm \((\text{Cm, 4 n}) \) \(^{254}\)No, and was identified by the \(^{260}\)Fm present (this is an isotope whose properties have been studied extensively). The half-life of \(^{254}\)No was measured by this procedure, and found to be 3 sec. This work was completed with greater precautions than the preceding projects, and the fact of the synthesis of the isotope of element 102 having mass number 254 was backed up by sufficiently rigorous and airtight arguments.
Joint Institute for Nuclear Research brought with it renewed opportunities in the synthesis of the isotopes of the element NJ ~ is of special interest since, according to theoretical predictions [15], this was a very important point to consider in our work, once we remember that in proceeding to heavier and still heavier elements, the cross sections of the reactions in which these isotopes are formed decline drastically. Secondly, the heavier isotopes in the reactions involving evaporation of neutrons is much greater than that for lighter isotopes [4].

Element 102 having mass numbers covering the range from 249 to 256. Alongside the experiments conducted on the synthesis of new elements, the mechanisms underlying the interaction between multiply charged ions and heavy nuclei were also studied. This yielded a wealth of new information which laid the groundwork for taking a different slant to the problem of the synthesis of new elements. Reactions leading to the formation of α-active and spontaneous fissioning isomers were studied [12, 13], as well as several spallation reactions in which α-active nuclei in the Po - Ac range were formed as a result of the stripping of a large number of nucleons from the target nuclei. These phenomena have the effect of greatly complicating the background problem in the synthesis of new elements.

In 1959, some results were published on subsequent experiments on the synthesis and study of the properties of the nuclide No 254 [9]. The procedure employed in the preceding experiments was somewhat modified in this instance, making it possible to measure the energy of the α-particles of the nuclear reaction products directly. In these experiments, the authors detected a three-second α-emitter with $E_\alpha = 8.3$ MeV, which was identified with the nuclide No 254 observed earlier [8]. It was reported at that same time that an isotope emitting $E_\alpha = 8.8 \pm 0.1$ MeV alphas of half-life $T_{1/2} = 10-20$ sec had been obtained in these experiments. According to the suggestion put forth by the authors, this group of α-particles may be related to the decay of the No 254 obtained in [4]. However, subsequent experiments conducted by these same authors failed to provide confirmation of this result [10].

Later on, in [9], the authors report that the spontaneously fissioning product of half-life $\approx 3$ sec which they recorded, was found to coincide with the half-life reported for No 254, while the number of spontaneous fission events was only one half the number of α-decay events at 8.3 MeV α energy. Using this as their point of departure, the authors drew the inference that the nuclide No 254 may possibly undergo spontaneous fission in 30 cases out of a hundred. This yielded $T_{sf} \approx 7$ sec, which differs by a factor of $10^5$ from the values predicted on the basis of available spontaneous fission data, and is on that account highly astonishing.

Soon thereafter, staff members of the I. V. Kurchatov Institute of Atomic Energy made an attempt to check the results of the experimental work reported in [9] on spontaneous fission of No 254, obtaining this nuclide in the reaction Pu 235 (O 16, 4 n) 102 254 [11]. However, the effect in question was not discovered then. It was demonstrated, as a result of this experiment, that if $T_{sf}/T_\alpha \approx 2$ for this nuclide, then its formation cross section in the reaction mentioned above must be far less than would be expected from an examination of all the available data.

Consequently, a series of experimental works in which attempts were undertaken to synthesize the isotopes of the element 102 were carried out in 1961 by laboratories of a large number of countries. The results reported in [1] received no confirmation from the subsequent experiments completed in Moscow and Berkeley. Subsequent experiments yielded experimental data on the basis of which the authors drew the conclusion that what they had synthesized were the isotopes No 253 and No 254. However, attempts to achieve mutual verification of the results obtained under other conditions did not meet with success.

Alongside the experiments conducted on the synthesis of new elements, the mechanisms underlying the interaction between multiply charged ions and heavy nuclei were also studied. This yielded a wealth of new information which laid the groundwork for taking a different slant to the problem of the synthesis of new elements. Reactions leading to the formation of α-active and spontaneous fissioning isomers were studied [12, 13], as well as several spallation reactions in which α-active nuclei in the Po - Ac range were formed as a result of the stripping of a large number of nucleons from the target nuclei. These phenomena have the effect of greatly complicating the background problem in the synthesis of new elements.

The commissioning of the three-meter cyclotron designed to accelerate multiply charged ions at the Dubna Joint Institute for Nuclear Research brought with it renewed opportunities in the synthesis of the isotopes of the element 102. The high intensity of the beams of multiply charged ions right up to neon (tens of microamperes beam current) rendered possible a significant increase in the yield of transuranium elements. By using U 233, U 235, U 238 as target materials and Ne 20 and Ne 22 as bombarding missiles, it became possible in principle to produce isotopes of the element 102 having mass numbers covering the range from 249 to 256.

From among these isotopes, we chose No 256 for the following reasons. First, the formation cross section of the heavier isotopes in the reactions involving evaporation of neutrons is much greater than that for lighter isotopes [14]. This was a very important point to consider in our work, once we remember that in proceeding to heavier and still heavier elements, the cross sections of the reactions in which these isotopes are formed decline drastically. Secondly, the study of the properties of the element No 256 is of special interest since, according to theoretical predictions [15], an abrupt jump in the direction of increased rate of spontaneous fission (as compared to the properties of fermium, for
Fig. 1. Design of device used in the synthesis of the nuclide No $^{256}$ and in accumulating its daughter Fm $^{258}$: 1) copper disk with annular recess along periphery; 2) mechanical plugs bounding the collecting volume for nuclear reaction products; 3) uranium target on aluminum foil substrate; 4) collector for a-decay products; 5) "electrical plugs" designed to safeguard collector from impacting of primary products of nuclear reactions.

instance) should be observed in the properties of the isotopes of the element 102. This has been expressed most conspicuously in research on the properties of the isotope No $^{256}$. Thirdly, experimental information on the formation cross section of the isotope No $^{256}$ and on its decay properties might enable research workers to get a clear idea of the possibility of synthesizing still heavier elements, and in particular the element 104.

The reaction U $^{238}$ (Ne $^{22}$, 4 n) No $^{256}$ was selected for synthesizing the isotope No $^{256}$.

**EXPERIMENTAL PART**

**1. Experimental Procedure**

The choice of the procedure to be followed was dictated by the following considerations. Taking cognizance of the fact that reactions accompanied by the formation of transuranium elements in the irradiation of heavy nuclei by multiply charged ions proceed with extremely small cross sections, it was found necessary to devise a sufficiently sensitive experimental technique for our work. This task was in turn complicated by the fact that the exposures had to be carried out on the internal beam of the cyclotron. It was this, more than anything else, which dictated the specific features of the procedure which we followed in this project.

In our experiments on the synthesis of the nuclide No $^{256}$, we employed the technique of recording and identifying a-active products of nuclear reactions from their daughter products. This technique was first used in order to produce new elements in the work described in [8].

According to the systematics of a-active even-even nuclei, the half-life of No $^{256}$ should be $\approx 15$ sec. When this isotope is recorded directly by its a emission, we invariably encounter a background established by the a emitters formed in nuclear reactions by the greatest disparity of techniques, and in quantities which are truly enormous compared to the expected effect. This throws a cloud over the interpretation of the experimental findings which is difficult to dispel. We therefore decided on a method which would enable us to record the a-decay of the nuclide No $^{256}$ by its decay product Fm $^{258}$, the half-life of which is $\approx 30$ h according to tabulated data. This in turn made it possible to accumulate Fm $^{258}$ over a protracted period in amounts sufficient to perform the analysis. Moreover, it became possible to carry out a painstaking and thorough chemical separation of fermium nuclei from all other products whose a-activity might give rise to an undesirable background. Another major advantage to be found in this method is the unambiguity in the determination of Z and A for the nuclide under investigation. By using this technique, we were able to measure the half-life of nuclide No $^{256}$ successfully. It is quite natural that the a-decay energy remained inaccessible to measurement by this method.

The basis of the method is the collection of recoil nuclei following an a-decay event. The kinetic energy of the recoil nucleus is $\approx 100$ keV. The recoil nuclei are ionized and may be collected by an electric field established throughout a gaseous medium, being collected on a special substrate. If the nuclei experiencing a-decay lie on some surface, then an energy of $\approx 100$ keV will be entirely adequate to free the recoil nuclei from that surface.

It is no easy matter to obtain absolutely thin layers of nuclear reaction products. This problem was resolved in the following manner in [8]. The nuclei which are nuclear reaction products possessing a reasonably high momentum are knocked out of the target and are slowed down in their passage through the gas. Being ionized, they drift in the direction of the electric field onto the surface of the special substrate. At first glance, this method would seem to be a highly efficient one, since it makes it possible to effect a fairly complete collection of the nuclear reaction products. But under the conditions which we had to cope with, it was hardly a suitable procedure. The trouble was that the collection took place in a volume where the ionization density of the gas was very high because of the beam
Experimental results on a check of the reliability of the method used to record \(\alpha\)-active nuclear reaction products in terms of their daughter products:  
1) energy dependence of the cross section of the reaction \(\text{U}^{238}\) (Ne\(^{20}\), \(\alpha\)4n) \(\text{Fm}^{259}\), obtained by recording the \(\text{Fm}^{259}\) present;  
2) the same dependence obtained by recording the \(\text{Cf}^{246}\) (daughter of \(\text{Fm}^{259}\));  
3) the energy dependence of the \(\text{Cf}^{246}\) yield resulting from irradiation of \(\text{U}^{238}\) by Ne\(^{20}\) ions.

traversing the region, and could be counted on to effect a severe distortion of the collecting electric field. An obscure phenomena related to this mode of collection may be found in [16], since the sign of the applied electrical voltage is almost without effect on the collecting efficiency. Bearing in mind the fact that the ionization density of the decelerating gas was much greater under our experimental conditions, we declined to rely on that method. All of these difficulties were found to be avoidable by using the diffusion of the nuclei decelerated in the gas for effective collection of the nuclear reaction products, with subsequent adsorption on a cold metal surface.

**Experimental arrangement.** The device in which the \(\text{Fm}^{255}\) was accumulated was mounted in a gas-filled probe (the design of which may be seen in Fig. 1). It operates on the basis of a rotating massive copper disk measuring 100 mm in diameter, which is cooled by water. The annular recess of rectangular cross section, \(20 \times 10\) mm in dimension, is seen on the periphery of the disk. Fixed mechanical plugs of teflon cut off a portion of the volume of this recess above and below. An uranium target which closes this portion of the recess can be moved forward. The reaction products are knocked out of the target into this closed volume, are slowed down in the gas and diffuse to the walls bounding the volume. The nuclei adsorbed on the surface of the annular recess are transferred, as the disk rotates, from the irradiation zone to the zone where the recoil nuclei are collected after the \(\alpha\)-decay of the nucleus of the nuclear reaction products. The collector device for the recoil nuclei (\(\text{Fm}^{255}\)) comprises a metal base shaped like an arc on which is mounted a silver foil 3 to 5 \(\mu\) thick. The length of the collector arc extends to 70\% the length of the circumference of the disk. A voltage of 80 volts was applied across the collector. This voltage was entirely adequate to promote an efficient collection of recoil nuclei following \(\alpha\)-decay.

The volume of the probe was filled up with argon gas to a pressure of 500 mm Hg. The choice of gas and pressure was dictated by the consideration that the recoil nuclei released from the target might become slowed down as they traversed the gas and might then diffuse to the walls of the enclosure and become adsorbed on those walls.

Since the products found on the collector served as evidence for any conclusion as to the synthesis of a particular nuclide in the nuclear reaction, it became a decisive point to provide assurance that only those atoms which were products of the \(\alpha\)-decay, and by that token were secondary atoms, would arrive at the collector.

The greatest possible nuisance to the experimental results was offered by the direct penetration to the collector of nuclear reaction products which were not products of \(\alpha\)-decay, i.e., primary products. The vexing problem to cope with here is that reactions of the \((\text{I, } \alpha\text{xn})\) type take place in the fermium mass region with cross sections several times larger than the cross sections of \((\text{I, xn})\) type reactions. We found in particular that the maximum formation cross section of \(\text{Fm}^{255}\) in the reaction \(\text{U}^{238}\) (Ne\(^{22}\), \(\alpha\)4n) \(\text{Fm}^{258}\) was \(\approx 2.5 \cdot 10^{-21}\) cm\(^2\).

This explains why so much emphasis was placed on leakproofing the volume in which reaction products arriving on the walls via diffusion and adsorption were to be collected in the design and fabrication of the device described above. To achieve this purpose the spaces between the walls of the disks and mechanical plugs and between the target plane also were made \(\approx 0.1\) mm across and the length of the spaces was not less than 20 mm. Electrical plugs were used to back up the mechanical plugs, and a voltage of 80 V was placed across the former. This eliminated any possibility of the charged primary reaction products arriving at the collector and thus vitiating the results.

The disks were rotated at constant speed, variable over a wide range. The data on the distribution of daughter product activity on the collector and speeds at which the disk was rotated were useful in estimating the half-life of the parent activity.

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The volume of the probe was kept separated from the volume of the cyclotron chamber by means of a vacuum-tight aluminum foil 10 µ thick, which served at the same time as the substrate in the uranium target. In the cooling system used in the probe assembly, the foil was able to retain its vacuum tightness for a span of ≈ 15 h of exposure at a beam current of 10 µA incident upon the target. The beam intensity was determined by the current of ions impinging on the collector placed behind the disk. Slits through the disk, stopped up by aluminum foil, were provided for that purpose. Errors in beam current measurement were eliminated by separating the collector from the gas volume. The current impinging on the target was recorded to 2.5% efficiency.

An Au–Si semiconductor detector was placed in the probe to monitor the ion energy. The probe was positioned along the radius of the cyclotron in order to vary the energy of the beam impinging on the target.

The targets were fabricated for the exposure by electrodeposition of uranium from a solution of uranyl nitrate in acetone. Aluminum foil was employed as substrate. The target thickness was 1-1.5 mg/cm².

Chemical separation. A silver foil, on which recoil nuclei were collected after the α-decay of the primary products of the nuclear reaction, was dissolved in 1 ml of hot 14 N HNO₃ in the presence of a carrier (50 µg lanthanum) for transuranium elements. The solution was allowed to cool, and the lanthanum hydroxide formed was precipitated out using an excess of 6 N ammonium solution. The hydroxide residue was flushed twice with twice-distilled water, was redissolved in a single drop of 2 N HCl, and this solution was applied to a Dowex-50X12 ion exchange resin column. The column was washed down to completely remove any lead or bismuth. The americium, curium, and transcurium elements were then eluted using 6 N HCl.

α-Spectrometric measurements of the curium fraction were usually taken after this separation was completed. In some cases, an additional separation of the fraction of transcurium elements, using ammonium lactate, was accomplished on a column of Dowex-50X12 resin. The position of fermium was found on the chromatogram by the α-active isotope of yttrium, which was added before the solution was transferred to the column. Cm²⁴² was usually employed to determine the chemical yield. The average chemical yield was ≈ 65%.

The substrate with the fraction of transuranium elements coated on it was placed in a grid ionization chamber. The chamber was filled with argon and a small amount of acetylene additive. The signal from the amplifier and expander is fed across an AI-100-1 multichannel analyzer. A special electronic device designed to separate out signals according to pulse shape blocks out signals which deviate from the shape of α-particle signals. This substantially reduces the background of electrical noise.

The energy resolution of this chamber was ≈ 30 keV. The half-width of the α-lines was ≈ 60 keV for the samples obtained after completion of the chemical separation step, and was determined by the layer thickness. The high stability of the associated electronic equipment made for reliable operation over many days of continuous measurements, during which line broadening stayed within 25 keV. The background amounted to ≈ 0.3 pulse per MeV·h in the 6-8 MeV region.

Recording efficiency. The recording efficiency attained in using the method described here was a function of two variables: the precipitation factor of the nuclear reaction products (with respect to their deposition on the effective walls of the disk) and the effectiveness with which α-decay products were collected on the collector walls. These quantities could be determined accurately only by experimental means.

We made use of nuclear reactions involving the formation of α-active products in the rare-earth region for certain aspects of experimentation in technique. Even with the limited number of such α-emitters at our disposal, we were able to identify without ambiguity not only the product itself, but also the reaction responsible for its formation. This created certain conveniences for us in our investigation of the specific features of the method which were of greatest interest.

The nuclear reaction Ba¹³⁸ (Ne²⁰, 8 n) Dy¹⁸⁰ was utilized in our determination of the precipitation factor. It was found that this factor corresponds more or less to the geometric position of the portion of the surface on which the precipitation takes place, while the total coefficient for precipitation onto the effective walls of the disk was ≈ 0.7.

The effectiveness with which the α-decay products were collected in the probe was not measured directly. However, a multiplicity of experiments on the collection of α-decay products of Th²³⁴ have revealed it to be rather high and in fact close to 100%.
We used two different methods to measure the energy dependence of the cross section of the nuclear reaction $^{238}$U ($^{20}$Ne, $\alpha$4n) $^{239}$Fm in our work on determining the total recording efficiency and in checking the reliability of the entire experimental procedure as a whole: we studied the $^{239}$Fm yield directly in the reaction products, and the $^{246}$Cf yield (of the daughter product $^{237}$Fm) by using the approach discussed above. Figure 2 shows the results of these measurements. We find that the $^{246}$Cf yield curve for the daughter products repeats the behavior of the $^{239}$Fm yield curve within the limits of allowable error, and at the same time contrasts quite sharply with the yield curve of $^{246}$Cf in the primary products. These results provide us with an excellent proof of the reliability of the method we used. The recording efficiency as a whole (with the chemical yield left out of account) determined in these experiments was $\approx 15\%$, which is in agreement with the amount obtained by theoretical prediction.

By taking advantage of the high beam intensity of $^{22}$Ne ions and keeping track of the fact that the daughter nuclide $^{239}$Fm resulting from the $\alpha$-decay of $^{239}$No has a $T_{\frac{1}{2}}$ longer than 20 h, we were able to accumulate $^{239}$Fm in amounts sufficient to facilitate reliable recording and identification, even though the formation cross section of $^{239}$No was found to be as low as $10^{-20}$ cm$^2$. However, in view of the protracted half-life of $^{239}$Fm and the expected low yield of the nuclide $^{239}$No, stable operation of the $\alpha$-spectrometer over a period of many days of continuous measurements was required along with an exceptionally low background level.

Experiments on the determination of the possible background level. As was mentioned at one point above, the basic factor to which background may be related in the procedure employed here is the penetration of primary products of a nuclear reaction of the type (I, $\alpha$xn) onto the collector, in the case of $\alpha$-decay products (cf. Fig. 1).

For that reason, we conducted several experiments designed to determine what is known as the "leakage factor" (i.e., the ratio of the number of atoms of any given reaction product arriving on the collector to the total number of atoms of this product obtained in the reaction).

When barium targets were irradiated by $^{22}$Ne ions and cesium targets were bombarded with $^{16}$O ions, reactions involving the formation of the $\alpha$-active nuclides $^{150}$Dy and $^{181}$Dy, whose daughters are not $\alpha$-active, proceeded at high cross sections. The leakage factor was found to remain within 1/2000 when the $\alpha$-activity of the collector placed directly behind the target was compared to the $\alpha$-activity of the collector for $\alpha$-decay products. This is entirely in accord with the requirements imposed on this method, since the cross section of a (I, $\alpha$4n) reaction exceeds the cross section of a (I, 4n) reaction by a factor of not greater than 20.

Accordingly, a procedure followed in the form in which it was worked out for these experiments would not yield an appreciable background attributable to the penetration of primary reaction products to the collector, in the
Fig. 4. Chemical identification of Fm\textsuperscript{258}: a) chromatogram on which secondary products were separated in HCl; b) \(\alpha\)-spectrum of fraction containing curium; c) chromatogram of further separation of the transuranium elements by ammonium lactate; d) \(\alpha\)-spectrum of the fermium fraction (determined with respect to the yttrium). (The shape of the Cm\textsuperscript{248} \(\rightarrow\) \(\alpha\)-lines is indicated to demonstrate the spectral broadening due to the thickness of the layer of sample obtained as a result of the separation using ammonium lactate).

case of recoil nuclei present after \(\alpha\)-decay. Control experiments carried out in the process of No\textsuperscript{256} synthesis revealed that this assertion, based on experimental findings involving dysprosium atoms, is likewise valid for fermium atoms.

The error in the interpretation of the data obtained may be traced back to the fact that not only \(\alpha\)-decay products but also products of \(\beta\)-decay, electron capture, and isomeric transition may be collected under the influence of the applied electric field. For that reason, we made sure to conduct some experiments to probe into these sources of possible background contributions.

In experiments on the collection of Bi\textsuperscript{212}, which is a product of \(\beta\)-decay [\(\text{Pb}^{212} \beta^- (900-600 \text{ keV}) \rightarrow \text{Bi}^{212}\)], it was shown that the collecting efficiency in this instance amounts to \(\approx 0.5\%\) and is independent of the sign of the collecting voltage.

An investigation of the collecting efficiency for products present after electron capture was made when Ce\textsuperscript{146} was exposed to irradiation by O\textsuperscript{16} ions. The nuclear reaction Ce\textsuperscript{146} (O\textsuperscript{16}, 7n) Dy\textsuperscript{149} \(\rightarrow\) Tb\textsuperscript{149}, which results in synthesis of Dy\textsuperscript{149}, a nuclide which then undergoes electron capture at high energies, was used in two instances: in obtaining Tb\textsuperscript{149} in both primary and secondary reaction products. The collecting efficiency for Tb\textsuperscript{149} in electron capture by Dy\textsuperscript{149} was found to be \(\approx 1\%\) in the particular geometry used.

On the basis of experimental findings relating to the collection of \(\beta\)-decay products and electron capture products by the electric field, we feel we may conclude that the collecting efficiency of the electric field in a gas of products of an isomeric transition apparently fails to exceed 1%.

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Fig. 5. Energy dependences of the reactions involving formation of the nuclides discussed here: () No\textsuperscript{256} (from Fm\textsuperscript{252} data); () Fm\textsuperscript{252} (from Fm\textsuperscript{252}); () Fm\textsuperscript{252} (from Cf\textsuperscript{252}); () Cf\textsuperscript{252} (from Cf\textsuperscript{252}). (The energy of the bombarding Ne\textsuperscript{22} ions is given in the laboratory system).

Taking into account the yield of Fm\textsuperscript{252} when U\textsuperscript{238} is irradiated by Ne\textsuperscript{22} ions, finding that this yield corresponds to a cross section \(\approx 2.5 \times 10^{-21}\) cm\(^2\), and also taking into account data obtained from control checks on the performance of the associated equipment used in the experiment, we may state that the background is so low that the nuclide No\textsuperscript{256} can be reliably recorded at reaction cross sections as low as \(10^{-33}\) cm\(^2\).

2. Experiments on the Synthesis of the Nuclide No\textsuperscript{256}

Experiments on the synthesis of the nuclide No\textsuperscript{256} consisted of protracted irradiation of uranium targets (6 to 10 h) in an intense beam of accelerated Ne\textsuperscript{22} ions. A current of 5 to 10 \(\mu\)A was utilized. The total flux of Ne\textsuperscript{22} ions through the target amounted to 40-70 \(\mu\)A/h in each of the experiments.

In the first irradiation experiments, which were performed in the spring of 1962, \(\alpha\)-activity ascribed to Fm\textsuperscript{252} was detected on the collector bombarded by secondary reaction products.

Figure 3a presents the \(\alpha\)-spectrum of the fraction of transuranium elements in the separation of secondary reaction products by using 6 N HCl, as obtained in one of the experiments involving irradiation by neon ions of \(\approx 115\) MeV energy. The energy of the \(\alpha\)-particles, \(7.04 \pm 0.02\) MeV, was in excellent agreement with tabulated values for Fm\textsuperscript{252}. Figure 3b shows the decay of this activity with a half-life of \(\approx 25\) h.

It is clear from inspection of Fig. 4 that the 7.04 MeV \(\alpha\)-activity unquestionably belongs to Fm\textsuperscript{252}. Figure 4a shows the chromatogram obtained in the separation of secondary products by HCl on a column of Dowex-50X12 resin, showing that the \(E_\alpha = 7.04\) MeV \(\alpha\)-activity became eluted in the company of the curium present.

After several hours of measurements, the activity was washed clear of the substrate, and a further separation of the fraction of transuranium elements was effected by using ammonium lactate to transfer the fraction to a Dowex-50Kil2 resin column. Yttrium was added to calibrate the chemical separation. Figure 4b shows a chromatogram of this separation, and Fig. 4c shows the \(\alpha\)-spectrum of the fermium fraction products after this separation was completed.
Fig. 7. Results of one of the experiments demonstrating the significant decay of the nuclide No\textsuperscript{256} (from Fm\textsuperscript{252} data) during a time \( \approx 10.8 \) sec, and the absence of any substantial decrease in Fm\textsuperscript{256} activity (from Cf\textsuperscript{246} data) during the same time span: a) \( t = 0 \); b) \( t \approx 10.8 \) sec.

It was found as a result that the \((7.04 \pm 0.02) \text{ MeV}\) \(\alpha\)-activity was the \(\alpha\)-activity of Fm\textsuperscript{252}, the presence of which constitutes evidence of synthesis of the \(\alpha\)-active nuclide No\textsuperscript{256}.

The amounts of Fm\textsuperscript{252} obtained on the collector correspond to cross sections \( \approx 10^{-32} \text{ cm}^2 \) for the reaction \(^{238}\text{U}(\text{Ne}^{22}, 4\alpha)\text{No}^{256}\). This rendered possible not only unambiguous identification of Fm\textsuperscript{252} as the \(\alpha\)-decay product, but also a study of the way No\textsuperscript{256} was formed in the reaction, measurement of the half-life of No\textsuperscript{256}, and enabled us to directly perform all control experiments, in the course of the No\textsuperscript{256} synthesis experiments, to ascertain possible reasons for the Fm\textsuperscript{252} background. Cf\textsuperscript{246} was also detected on the collector, and this furnished evidence of the synthesis of Fm\textsuperscript{252}, apparently in the reaction \(^{238}\text{U}(\text{Ne}^{22}, 6\alpha)\text{Fm}^{250}\).

Measurement of energy relationships. After the fact of the synthesis of No\textsuperscript{256} had been clearly established, experiments were conducted to measure the excitation functions for the reaction \(^{238}\text{U}(\text{Ne}^{22}, 4\alpha)\text{No}^{256}\) with respect to the Fm\textsuperscript{252} in the secondary products. The experimental results are displayed in Fig. 5. The solid curve for Fm\textsuperscript{252} (No\textsuperscript{256}) has the slope typical of evaporative reactions, peaking at \( E_{\text{Ne}^{22}} \approx 112 \) MeV with maximum cross section \( \approx 4.5 \times 10^{-32} \text{ cm}^2 \). That diagram also shows curves for the formation cross sections of Fm\textsuperscript{252} and Cf\textsuperscript{246} in the primary products and for Cf\textsuperscript{246} in the secondary products.

A comparison of the yield curves of Fm\textsuperscript{252} in the primary and secondary reaction products reveals that the Fm\textsuperscript{252} yield in the secondary products may be determined uniquely by the yield of No\textsuperscript{256}:

1. The leftward branch of the excitation function of the reaction \(^{238}\text{U}(\text{Ne}^{22}, 4\alpha)\text{No}^{256}\) coincides with the yield curve of Fm\textsuperscript{252} in the primary reaction products.
2. The rightward branch of the curve slopes downward steeply, while the $\text{Fm}^{252}$ climbs upward, in the primary products. This substantiates the fact that the background due to the penetration of primary reaction products directly to the collector is not significant in the case of products of $\alpha$-decay.

3. The $\text{Fm}^{252}$ yield in the secondary products cannot be ascribed to electron capture by $\text{Md}^{252}$ for the following reasons:

   a) synthesis of $\text{Md}^{252}$ may occur only through the reaction $\text{U}^{238} (\text{Ne}^{22}, \text{p})\text{Md}^{252}$, which is forbidden by energy considerations in the 110-120 MeV energy range;

   b) the cross sections of reactions of this type are very small, and in fact are $\approx 10^{-23}$ cm$^2$ [17];

   c) even were we to suppose that this reaction actually occurred, when we take into account the effectiveness of the collecting step in the case of electron capture, we would find that the yield of $\text{Fm}^{252}$ in the primary products would have to be several tens of times larger than that observed.

All other modes of decay are excluded from consideration by the same arguments.

Measurement of the half-life of the nuclide $\text{No}^{256}$. The speed of rotation of the disk was varied in each experiment, as the half-life of the nuclide $\text{No}^{256}$ was measured. Following the exposure, the collector was split in half. The number of $\text{Fm}^{252}$ nuclei recorded on the half of the collector closer to the target (in the direction of rotation of the disk) was taken as the unit and was referred to the initial instant of time. The number of $\text{Fm}^{252}$ nuclei recorded on the farther half was equal to a fraction of unity and was referred to the instant of time dependent on the speed of rotation of the disk. The experimental results on measurement of the half-life of $\text{No}^{256}$ are plotted in Fig. 6. The half-life was established as close to 8 sec.

The validity of the experiments on measurement of the half-life was confirmed by the following fact. The distribution of activity of the nuclide $\text{Cf}^{244}$ as a daughter of $\text{Fm}^{252}$ ($T_1 = 30$ min) along the collector was found to be independent of the speed at which the disk was rotated (in the interval 1 to 1 rpm). This is seen clearly in Fig. 6 and Fig. 7.

Control experiments. In order to obtain confirmation of the successful synthesis of the nuclide $\text{No}^{256}$, a repeated measurement of the yield of $\text{Fm}^{252}$ on the collector and directly in the products of the $\text{U}^{238} + \text{Ne}^{22}$ reaction was carried out, and the points corresponding to the same neon energy on both curves were obtained in a single experiment. The need for this experiment was dictated by the fact that the experiments from which the yield curve of $\text{Fm}^{252}$ was plotted, based on the yield obtained directly in the $\text{U}^{238} + \text{Ne}^{22}$ reaction (cf. Fig. 5), were carried out without a careful control to monitor the energy of the $\text{Ne}^{22}$ ions.

The volume in which the reaction products were to be collected was made as a fixed-wall enclosure, in order to arrive at the two curves simultaneously as the experiments were being carried out. Silver foil was adhered to the walls of the enclosure.

All of the remaining steps were carried out in a manner similar to the procedure described above. Figure 8 shows the results of these experiments. The $\text{Fm}^{252}$ curve normalized at a single point (since the amount of primary reaction products precipitated on the fixed enclosure walls was not known exactly) matches the $\text{Fm}^{252}$ curve in Fig. 5.

The experiment carried out at low pressure (40 mm Hg) inside the probe confirms the diffusion of $\text{Fm}^{252}$ nuclei to the enclosure walls, and invalidates the hypothesis of direct impinging of the $\text{Fm}^{252}$ nuclei on the walls as a result of a broad angular distribution. This provides evidence in support of the validity of the earlier analysis of the slope of
the curves plotted in Fig. 5, in which case no account was taken of the variation in angular distribution of $\text{Fm}^{252}$ nuclei with variation in energy of the $\text{Ne}^{22}$ ions, in the $\text{U}^{238}(\text{Ne}^{22}, \alpha 4n)\text{Fm}^{252}$ reaction. The result of this experiment could have been predicted by considering, as point of departure, the fact that the escape of an $\alpha$-particle could not significantly broaden the angular distribution, inasmuch as capture of the heavy nucleus $\text{O}^{18}$ would ensue, but we felt that an experimental verification would stand us in good stead.

As a result of our control experiments, we compiled the following evidence:

1. It has been demonstrated that the background due to the penetration of $\text{Fm}^{252}$ nuclei produced directly in the $\text{U}^{238} + \text{Ne}^{22}$ reaction on the collector, when the nuclide $\text{No}^{256}$ is to be recorded and identified through its daughter $\text{Fm}^{252}$, does not exceed 1/2000 in the case of recoil nuclei after $\alpha$-decay.

2. The effectiveness of the procedure employed in this project was determined through the investigation of the reaction $\text{U}^{238}(\text{Ne}^{20}, \alpha 4n)\text{Fm}^{252}$.

3. The curves plotted for the yield of $\text{Fm}^{252}$ on the collector for recoil nuclei after $\alpha$-decay and directly in the $\text{U}^{238} + \text{Ne}^{22}$ reaction furnish useful information. A sharp contrast is discerned in the behavior of the curves; the slope of the $\text{Fm}^{252} (\text{No}^{256})$ with a half-width $\approx 8$ MeV and a maximum in the $112$ MeV region confirming the fact that we are dealing here with a reaction in which four neutrons are evaporated.

4. The possibility of collecting recoil nuclei following $\beta$-decay and electron capture was explored. It was shown that these modes of decay cannot be the causes of any $\text{Fm}^{252}$ impinging directly on the collector, in the case of recoil nuclei.

5. The distribution of $\text{Fm}^{252}$ nuclei on the collector corresponds to the $\alpha$-radioactive decay of the nuclide $\text{No}^{256}$ having a half-life close to 8 sec.

The results of the control experiments carried out in our work confirm the conclusion that the $\alpha$-active nuclide $\text{No}^{256}$ was indeed synthesized in the $\text{U}^{238} + \text{Ne}^{22}$ reaction.

**DISCUSSION OF THE RESULTS**

1. **Radioactive Properties of the Nuclide No$^{256}$**

   The fact that the nuclide $\text{No}^{256}$ is $\alpha$-active and has a half-life $\approx 8$ sec is not at all unanticipated from the standpoint of the systematics of even-even $\alpha$-emitters.

   It should be duly noted, however, that a comparison of the half-lives of the isotopes $\text{No}^{254}$ ($T_{1/2} = 3$ sec) and $\text{No}^{256}$ ($T_{1/2} = 8$ sec) clearly implies that the total $\alpha$-decay energy of the isotope $\text{No}^{256}$ should be greater than the total $\alpha$-decay energy of the isotope $\text{No}^{254}$. Once we remember that the isotope $\text{No}^{256}$ has a closed neutron subshell 152, we may apparently entertain the assumption that the effect of this subshell on the $\alpha$-decay energy is far less pronounced in the case of the isotopes of element 102 than in the case of fermium isotopes, and is also far less pronounced than the effect derived from theoretical estimates [18].

   The problem of the spontaneous fission period of the nuclide $\text{No}^{256}$ is also an interesting one. We find that $T_{sf} \geq 8$ sec, directly from our results. This lower bound for the spontaneous fission period of $\text{No}^{256}$ is not at variance with the value arrived at by extrapolations on graphs ($T_{sf} \approx 3 \cdot 10^9$ sec), nor with the value computed by using the Swiatecki-Dorn formula [19] ($T_{sf} \approx 2 \cdot 10^8$ sec). However, this result stands in stark contradiction to the theoretical estimate offered by Johansson [15], which yields $T_{sf} \approx 10^{-2}$ sec for $\text{No}^{256}$.

   It should be stressed that Johansson's theoretical estimates for $\text{No}^{256}$ are in excellent harmony with the suggestion [9] that the spontaneous fission observed in this work in the synthesis of the nuclide $\text{No}^{254}$ is related precisely to that nuclide.

   The excellent agreement between theoretical prediction and experimental evidence for the $T_{sf}$ values of 102$^{254}$ and the striking difference (by three to four orders of magnitude) in those values for $\text{No}^{256}$ are truly astonishing. This discrepancy confers added importance on the necessity of determining $T_{sf}$ directly for $\text{No}^{256}$.

2. **Cross section of the reaction $\text{U}^{238}(\text{Ne}^{22}, 4n)\text{No}^{256}$**

   Calculations of the energy characteristics of the reaction $\text{U}^{238}(\text{Ne}^{22}, 4n)\text{No}^{256}$ show that the maximum probability that four neutrons will be boil off the compound nucleus is attained when the energies of the impinging neon ions are 4 to 6 MeV below the coulomb potential barrier of the $\text{U}^{238} + \text{Ne}^{22}$ system.
This explains the position of the maximum of the formation cross section of No\textsuperscript{256} on the energy axis (the value $E_{\text{O max}} = 112$ MeV is in reasonable agreement with theoretical prediction). This accounts in considerable measure for the likewise low value of the cross section at the maximum ($\sigma_{\text{max}} \approx 4.5 \times 10^{-32}$ cm$^2$), but cannot account for the entire course of the decline in the cross section in the transition from light bombarding particles to the heavier particles, as reported by Donets et al., [20].

However, the cross section value so obtained is nevertheless large enough, particularly when we recall that the effect may become enhanced by the increased sensitivity brought about through this procedure.

In separate experiments, we secured results indicative of the presence of Fm\textsuperscript{251} in the secondary reaction products, and Fm\textsuperscript{251} may be a product of the decay of No\textsuperscript{255}. The sensitivity of our method is not adequate for confident identification of this nuclide, since Fm\textsuperscript{251} undergoes $\alpha$-decay only in one case out of a hundred. Nevertheless, this result permits us to hope that the synthesis of lighter isotopes of element 102 may be realized within the limits of presently mastered experimental techniques.

In conclusion, we take this opportunity to express our heartfelt acknowledgements to G. N. Flerov, under whose expert guidance and with whose warm cooperation this project was completed. We also express our indebtedness to the subdivision heads Yu. Ts. Oganesyan, A. N. Filipson, and A. S. Pasyuk for making available such intense beams of accelerated neon ions for our experiments.

LITERATURE CITED


All abbreviations of periodicals in the above bibliography are letter-by-letter transliterations of the abbreviations as given in the original Russian journal. Some or all of this periodical literature may well be available in English translation. A complete list of the cover-to-cover English translations appears at the back of this issue.