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EXPERIMENTS ON THE PRODUCTION OF FERMIUM NEUTRON-DEFICIENT ISOTOPES AND NEW POSSIBILITIES OF SYNTHESIZING ELEMENTS WITH Z>100

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Эксперименты по получению нейтронодефицитных изотопов фермия и новые возможности синтеза элементов с Z>100

Приводятся экспериментальные результаты и расчетные данные по получению нейтронодефицитных изотопов ^{244}Fm и ^{246}Fm, образующихся в ядерных реакциях при облучении изотопов Pb и Bi ускоренными ионами ^{40}Ar и ^{37}Cl. На различных изотопах Pb измерены сечения реакций (^{40}Ar,xn) при x =1,2,3,4.

Показано, что если в качестве мишени используются "магические" ядра ^{208}Pb или его соседей, которые бомбардируются ионами с массой ≥ 40 а.е., то составные ядра оказываются слабовозбужденными и переходят в основное состояние путем испускания 2-х или 3-х нейтронов.

В свете полученных данных обсуждаются новые возможности синтеза элементов с атомным номером Z > 100.

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Experiments on the Production of Fermium Neutron-Deficient Isotopes and New Possibilities of Synthesizing Elements with Z> 100

See the summary on the reverse side of the title-page.

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1. Introduction

One of the main methods of synthesizing transfermium elements is based on using nuclear reactions induced by heavy ions. Different isotopes of heavy elements with Z = 102-105 have been produced by reactions proceeding via compound nucleus formation in the bombardment of the isotopes of elements ranging from U through Cf by the accelerated ions of ^{11}B, ^{12}C, ^{16,18}O, and ^{22}Ne (ref. /1/).

The use of this method for reaching the region of the heavier elements with Z > 105 and the attempts to synthesize superheavy elements of Z≈110-126 require heavier ions. However, numerous experiments with ^{31}P, ^{40}Ar, ^{68}Zn, ^{76}Ge, and ^{84}Kr, carried out at different laboratories have not yet lead to positive results. For instance, the upper limit in the production cross section for the spontaneously fissioning isotopes of element 107 in the ^{238}U(^{31}P,xn)$^{269-x}$107 reaction turned out to be douzens of times smaller than the production cross section for the known nuclides with Z=104 and 105, which may be produced in reactions induced by ^{18}O and ^{22}Ne ions /2/. The same situation occurs also in the case of the synthesis of superheavy elements in the reactions ^{248}Cm(^{40}Ar,xn)$^{288-x}$114 (ref. /3/), ^{243}Am(^{68}Zn,xn)$^{311-x}$125 (ref. /4/), ^{232}Th(^{84}Kr,xn)$^{316-x}$126 (ref. /5/) and ^{232}Th(^{76}Ge,xn)$^{308-x}$124 (ref. /6/). In these reactions, only the upper limits on the cross sections have been obtained to lie between 5×10^{-30} cm^2 and 10^{-34} cm^2.

The fact that no new elements have been observed in these experiments may be accounted for by the properties of the nuclei being synthesized. At the same time, it is not excluded that in the case of such heavy ions some factors prevent them from fusing with a heavy target nucleus /7-10/ . Unfortunately the experimental data available in this field are rather limited and their interpretation is ambiguous.

From our point of view, a direct answer to the question of whether or not the classical compound nucleus is produced is provided by the use of the conventional method of measuring the cross sections of reactions involving the emission of x neutrons by the compound nucleus. This method can also be employed to investigate the properties of the compound nucleus produced and, in the first place, its excitation energy E^*. The cross section for the production of heavy and superheavy nuclei in the ground state is strongly dependent on the fission barrier height, which is mainly determined by the shell effects. Since the shell effects vanish at high excitation energies /11/ , the investigation of this phenomena is of special interest in resolving the problem of the synthesis of new elements.

Up to now, these experiments on the investigation of the production of highly fissionable compound nuclei in reactions induced by very heavy ions were not carried out. The heaviest nuclides have been obtained in reactions with ions not heavier than ^{22}Ne , while the heaviest nuclei of Po , which have been produced in the (HI, xn) reactions induced by Ar , Kr and Xe ions, belong to the region of weakly fissionable nuclides.

The aim of this paper was to investigate the production of highly fissionable compound nuclei in reactions with ions heavier than neon. It was appropriate to begin experiments with accelerated ions of mass $A_I \approx 40$ atomic units, which could be accelerated to a fairly high intensity at the U-300 heavy ion cyclotron of the JINR Laboratory of Nuclear Reactions. The mechanism of the interaction with ^{40}Ar ions and heavier ions can be expected to show a noticeable difference from that observed in reactions with lighter ions. As a compound nucleus, a highly fissionable nucleus should be selected, whose barrier is to a considerable extent determined by the shell effects, similarly to the case of all transfermium and superheavy elements.

The analysis of the rather limited number of accessible target-projectile combinations leads to the choice of the ^{208}Pb(^{40}Ar,4n)^{244}Fm reaction. ^{244}Fm is one of the most highly fissionable known nuclides. This isotope undergoes spontaneous fission with a probability close to 100% and has a half-life of 3.3 msec. The properties of ^{244}Fm have been established by Nurmia et al. /12/ , who synthesized it in the ^{233}U(^{16}O,5n)^{244}Fm reaction with a cross section of 1×10^{-32} cm^2. Since the compound nucleus cross section might considerably decrease in going from ^{16}O to ^{40}Ar , it was necessary to provide the highest possible sensitivity of the experimental technique designed to detect short-lived spontaneous fission nuclei.

II. Description of Experiments and Experimental Technique

The block diagram of the experimental apparatus is shown in fig. 1. The beam of six-charged ^{40}Ar ions with the energy of 220 MeV and intensity up to 10 μA passed through diaphragms to strike a water-cooled Dural disk serving as a target and having the shape of the frustrum of a cone with a base angle of 20° and maximum diameter of 250 mm. By vacuum evaporation a lead layer was deposited onto the lateral face of the disk, the thickness of the layer being varied in the range of 2 to 5 mg/cm^2 in different experiments. The maximum rotation velocity of the disk was 2800 rev/min (1 revolution per 20 msec). The disk temperature was controlled during the experiments using special detectors and did not exceed 60 °C. At a distance of 3 mm, the target was surrounded by dielectric detectors for fission fragments, which were mica plates with the uranium and thorium content of $< 10^{-7}$ g/g.

In the experiment described the lead layer served as both a thick target in which the excitation functions of the

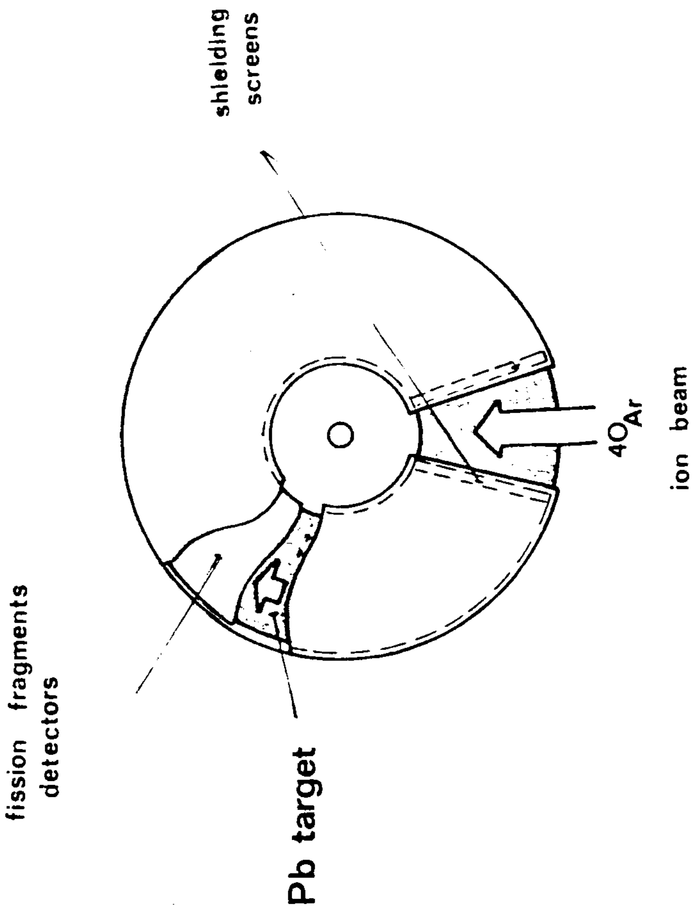

Fig. 1. Schematic view of the experimental device for detecting short-lived spontaneously fissioning nuclei.

Pb(^{40}Ar,xn) reactions were integrated, and a recoil catcher foil. At the ^{40}Ar ion energy of 220 MeV, recoil nuclei stop at a depth of 1 to 3 mg/cm^2 in the direction perpendicular to the plane of the detectors. The detection efficiency under these conditions was determined experimentally to be about 50%.

A special scanning device placed in front of the diaphragms controlled the distribution and intensity of ^{40}Ar ion beam. The integral flux of ^{40}Ar ions was determined in each experiment, using a Ge(Li) gamma-spectrometer, from the yield of terbium isotopes produced by the reactions $^{114,\,116}$Cd(^{40}Ar,xn)Dy$\xrightarrow{e.c.}$Tb. For this purpose a cadmium target about 30 mg/cm^2 thick and 1% of the total area of the lead target was glued upon the lateral face of the disk.

The apparatus sensitivity permitted observation of one track of spontaneous fission in detectors after a 10-hour bombardment by ^{40}Ar ion beam with an intensity of $5\,\mu A$, which corresponds to a production cross section of 2×10^{-36} cm^2. This high sensitivity was due to a low background which resulted from the use of shielding screens preserving detectors from scattered ions, and from the special procedure of annealing and etching the mica to make fission fragments observable.

III. Discussion of Experimental Results

The first experiment was carried out using a lead target with natural isotopic composition, which was bombarded with ^{40}Ar ions at a rotation velocity of 2800 rev/min. At the integral flux of 1.1×10^{17} ions, 662 tracks of spontaneous fission fragments have been recorded. On the basis of the time distribution of events, which is presented in fig. 2, one can determine the half-life of the spontaneous fission activity to be equal to 4.0 ± 0.5 msec. This value agrees with the data obtained for the ^{244}Fm isotope previously. By assuming the observed activity to be produced by the ^{208}Pb(^{40}Ar,4n)^{244}Fm reaction,

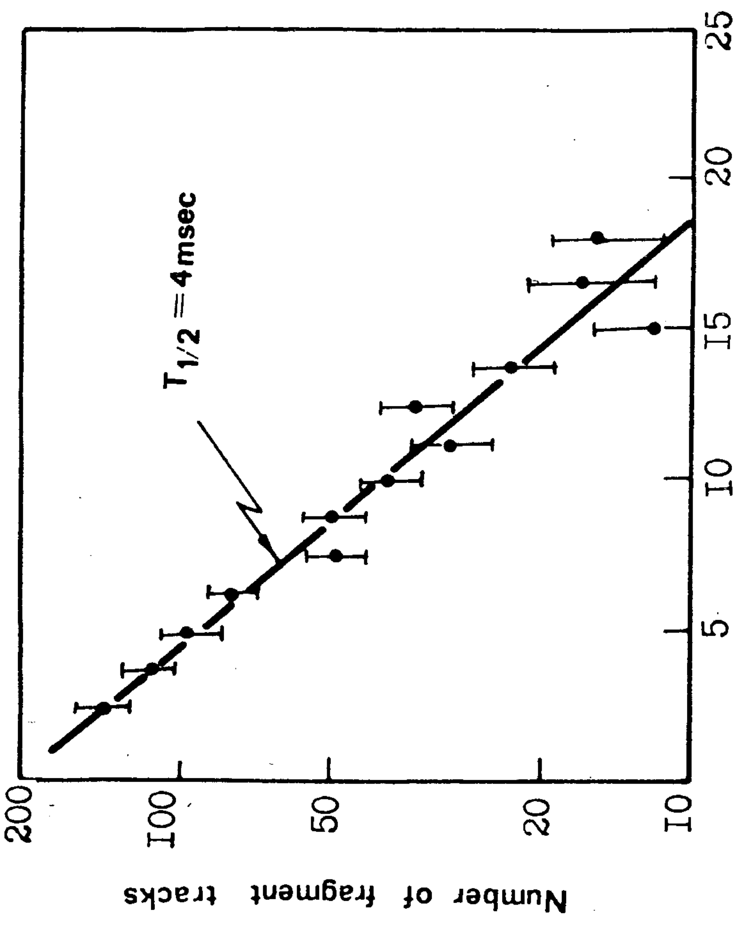

Fig. 2. Decay curve for ^{244}Fm produced by bombarding lead with ^{40}Ar ions.

it is possible to determine the yield of this reaction to be equal to $(3.4 \pm 0.7) \times 10^{-14}$ per particle.

Subsequently the experiment was repeated with a target of the enriched ^{208}Pb isotope (98% ^{208}Pb). With the integral flux of 6×10^{16} ions, 214 tracks of spontaneous fission fragments have been recorded. This corresponds to the yield of $(1.0 \pm 0.2) \times 10^{-14}$ per particle from the ^{208}Pb(^{40}Ar, 4n)^{244}Fm reaction.

In comparing the results of the two experiments, one should note a discrepancy in the yields of the reaction ^{208}Pb(^{40}Ar, 4n) ^{244}Fm determined using targets of the natural mixture of lead isotopes and target from the enriched ^{208}Pb isotope. This discrepancy leads to the assumption that the reactions involving the evaporation of neutrons less than 4 contribute substantially to the formation of ^{244}Fm . These reactions are ^{207}Pb(^{40}Ar,3n) and ^{206}Pb(^{40}Ar, 2n) . In order to test this assumption, we have performed direct experiments to determine the cross sections for reactions with 1, 2 and 3 neutrons emitted.

At the bombardment of targets from the enriched ^{207}Pb isotope (83% ^{207}Pb) by an integral flux of 2×10^{16} ^{40}Ar ions, 111 tracks were recorded, whereas 35 tracks were revealed in the experiment with a ^{206}Pb target (90.4% ^{206}Pb) at an integral flux of 1×10^{16} ions. The time distribution of tracks in these experiments corresponded to the decay of ^{244}Fm.

The comparatively large yield of the ^{206}Pb(^{40}Ar, 2n) reaction permits the investigation of the reaction involving the evaporation of 2 neutrons in another combination, $^{208}\text{Pb} + {}^{40}\text{Ar} \rightarrow {}^{246}\text{Fm}$, where the ^{246}Fm isotope ($T_{1/2}$= 1.2 sec) undergoes spontaneous fission with an about 8% probability /12,13/ . To provide the detection of the ^{246}Fm decay, the rotation velocity of the target disk was decreased to 8 rev/min (one revolution per about 7.5 sec). In this case an enriched ^{208}Pb target was used. Figure 3 shows the time distribution of spontaneous fission tracks recorded during this experiment.

These data indicate that the half-life of ^{246}Fm is 0.9 ± 0.3 seconds, which agrees with the previous results. The

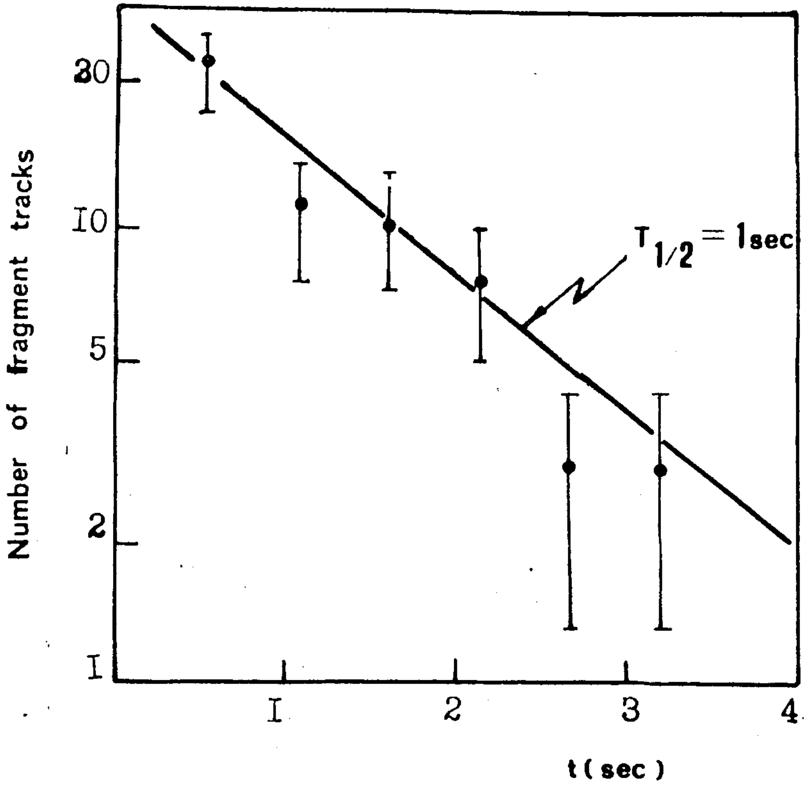

Fig. 3. Decay curve for ^{246}Fm produced by the reaction ^{208}Pb(^{40}Ar, 2n)^{246}Fm .

yield of the ^{208}Pb(^{40}Ar, 2n)^{246}Fm reaction is approximately 3 x 10^{-14} per particle. The error in this value, which is estimated to be a factor of 2, is mainly due to the uncertainty in the spontaneous fission branch in the ^{246}Fm decay.

It is of interest to study the reaction involving the evaporation of 2 neutrons using the lighter bombarding ions, e.g., in the combination ^{209}Bi(^{37}Cl, 2n) ^{244}Fm. The initial energy of six-charged ^{37}Cl ions is about 240 MeV, i.e., considerably higher than the ion energy for the ^{209}Bi(^{37}Cl, 2n) reaction. This necessitated the use of an aluminium absorber, which at the same time provided vacuum separation between the experimental chamber and ion guide. The chamber was filled with helium (30 mm Hg) to cool the absorber. The integral flux of ^{37}Cl ions bombarding the bismuth target was 5 x 10^{16} ions. As a result , only 18 tracks have been recorded , whose distribution permitted their assignment to ^{244}Fm decay. The yield of the ^{209}Bi(^{37}Cl, 2n) ^{244}Fm reaction was equal to 6 x 10^{-16} per ion.

An attempt has also been made to determine the yield of the reaction with single neutron emitted. For this purpose an experiment has been performed in which the spontaneous fission of ^{246}Fm produced by bombarding ^{207}Pb with ^{40}Ar ions was detected. In this experiment use was made of a target from enriched ^{207}Pb (98% ^{207}Pb , 1.3% ^{208}Pb). With an integral flux of 6 x 10^{16} ^{40}Ar ions, only one track has been detected which might be due to the ^{208}Pb(^{40}Ar, 2n) ^{246}Fm reaction on the ^{208}Pb admixture in the target. Thus only the upper limit on the ^{207}Pb(^{40}Ar, 1n) reaction yield can be determined to be equal to 5 x 10^{-16} per ion.

The experimental results on the production of the ^{244}Fm and ^{246}Fm isotopes in reactions induced by ^{40}Ar and ^{37}Cl ions are presented in the table. The experimental values of the reaction cross sections corresponding to the maximum excitation function, $\sigma_{max.exp.}$, are also listed there. These values were estimated on the basis of the measured yields from a thick target and the calculated values of excitation function widths, which are

Table 1.

Reaction	Integral ion flux x 10^{16}	Reaction yield/ion x 10^{-14}	$\sigma_{\text{max. exp.}}$ cm^2	$\sigma_{\text{max. theor.}}$ cm^2
$^{208}Pb + {}^{40}Ar \rightarrow {}^{244}Fm + 4n$	6	1.0	1.5×10^{-33}	1.5×10^{-32}
$^{207}Pb + {}^{40}Ar \rightarrow {}^{244}Fm + 3n$	2.4	2.5	5×10^{-33}	1.4×10^{-32}
$^{206}Pb + {}^{40}Ar \rightarrow {}^{244}Fm + 2n$	0.9	1.6	3×10^{-33}	1.3×10^{-33}
$^{208}Pb + {}^{40}Ar \rightarrow {}^{246}Fm + 2n$	10	3	7×10^{-33}	3.6×10^{-33}
$^{209}Bi + {}^{37}Cl \rightarrow {}^{244}Fm + 2n$	5	0.06	1.3×10^{-34}	4.3×10^{-34}
$^{207}Pb + {}^{40}Ar \rightarrow {}^{246}Fm + 1n$	6	< 0.05	$<1\times10^{-34}$	3.6×10^{-36}

varied in the range of 8 MeV for the $^{207}Pb(^{40}Ar,1n)$ to 15 MeV for the $^{208}Pb(^{40}Ar,4n)$ reaction *. In estimating $\sigma_{\text{max.exp.}}$ in this way, the main uncertainty lies in the possible discrepancy between the calculated and actual shapes of excitation functions. According to our estimates, this discrepancy cannot lead to an over a factor of 2 error in determining the absolute values of $\sigma_{\text{max. exp.}}$. The relative error in comparing $\sigma_{\text{max.exp.}}$ for different reactions is substantially smaller and mainly determined by an about 30% inaccuracy in the measured yields of the reactions

In order to interprete the results presented and to compare them with the data obtained previously for reactions with the lighter ions, we shall make use of the method of Jackson and Sikkeland intended for calculating the xn -reaction cross sections (ref. /15/). This method describes satisfactorily a large amount of experimental data on the production of heavy nuclei with $Z < 106$ by reactions induced by ions with $A_I < 22$ (ref. /16/). In this case we assume that the mechanism of nuclear fusion does not change considerably as one goes from relatively light projectiles (^{12}C, ^{16}O, ^{22}Ne) to ^{40}Ar.

Then the cross section for the (HI, xn) reaction can be presented in the following form

$$\sigma_x(E) = \{ \prod_{i=1}^{x} [\Gamma_n/(\Gamma_n+\Gamma_f)]_i \} \sum_{L=0}^{L_{CN}} \sigma_L(E) P_{x,L}(E^*), \qquad /1/$$

where E is the ion energy, σ_L is the cross section of the L – the partial wave, and $P_{x,L}(E^*)$ is the probability for emission of x neutrons from the compound nucleus with excitation energy E^* and angular momentum L.

In order to find the magnitude of the critical angular momentum L_{CN}, we make use of the empirical relation obtained from measurements of the angular correlations

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* The excitation function measured by us in the reaction $^{207}Pb(^{40}Ar,3n)^{244}Fm$ is in good agreement with the calculated one. For the estimation of $\sigma_{\text{max.exp.}}$ use was made of the data on the stopping power of argon and chlorine ions from the tables of Northcliffe and Schilling (ref. /14/).

of fission fragments in the bombardments of ^{238}U with ^{12}C, ^{16}O, ^{20}Ne, and ^{40}Ar ions [17]. This gives

$$\sum_{L=0}^{L_{CN}} \sigma_L \Big/ \sum_{L=0}^{\infty} \sigma_L = (1 + 0.03 A_I)^{-1} . \qquad /2/$$

The partial cross section σ_L is determined by the relation

$$\sigma_L = \pi \lambda\!\!\!^{-2} (2L+1)\, T_L , \qquad /3/$$

where T_L is the coefficient of transmission of the L–th partial wave through the potential $V_L(r)$ for the interacting nuclei [18]

$$V_L(r) = \frac{z_I z_T e^2}{r} + \frac{\hbar^2 L(L+1)}{2\mu r} + V_0 \exp \frac{r_0 (A_I^{1/3} + A_T^{1/3}) - r}{d} . \qquad /4/$$

For the potential parameters the following values are taken: $V_0 = -70$ MeV, $r_0 = 1.25 \times 10^{-13}$ cm and $d = 0.44 \times 10^{-13}$ cm (ref. [19]). The transmission coefficients T_L are calculated in the inverted parabola approximation [20].

The value of $P_{x,L}(E^*)$ was calculated using formulae given in ref. [16]. The values of the parameters contained in these formulae were derived from the best agreement with experimental data for the shape of the excitation functions for the (HI,xn) reactions [15,16].

The empirical relation of Sikkeland [15] was used to calculate the evaporation-to-fission width ratio Γ_n/Γ_f.

The results of the calculations are presented in Fig.4, while comparison with experimental data is shown in the table. The magnitudes of the cross sections for xn -reactions and their agreement with the calculated ones indicate that the interaction of ^{40}Ar ions with a heavy nucleus leads to the formation of a compound nucleus with a fairly high probability.

It does not appear possible to make a more conclusive qualitative analysis of the data, since the cross sections for the production of highly fissionable nuclei in the ground state are the 10^{-7}-10^{-10} th part of the complete fusion

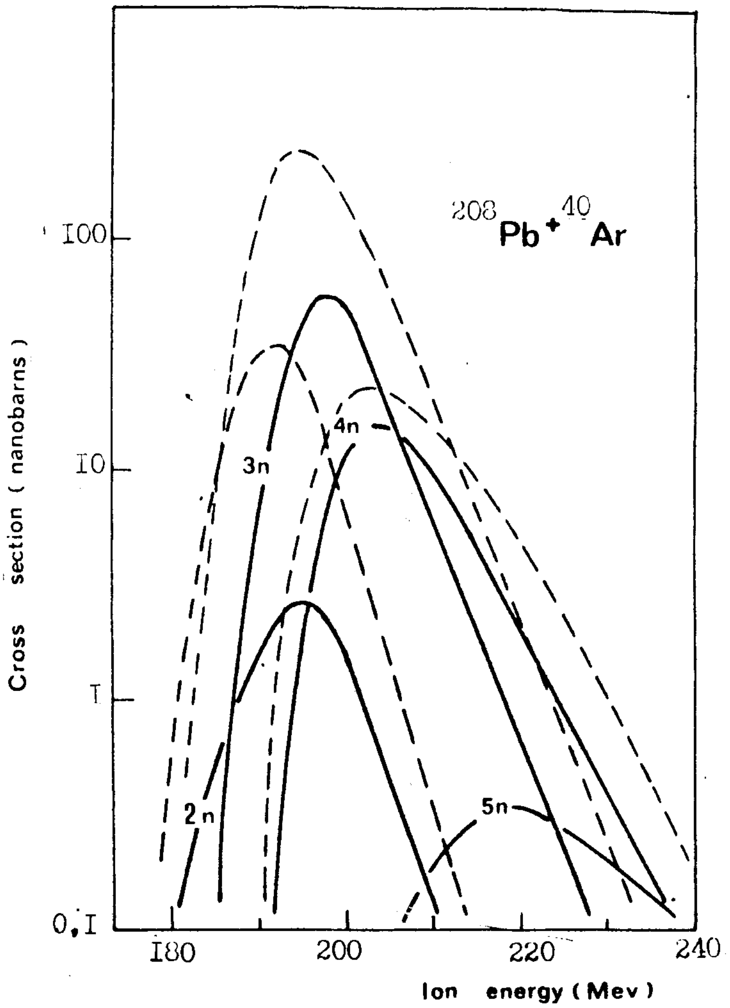

Fig. 4. Cross section for the reaction $^{208}Pb(^{40}Ar,xn)^{248-x}Fm$ as a function of the ion energy (lab. sys.). The solid and dashed curves show the results calculated using the d parameter equal to 0.34×10^{-13} cm and 0.44×10^{-13} cm, respectively.

cross section. Such an analysis requires the exact determination of the fraction of nuclei surviving fission, which in turn necessitates more detailed measurements of the Γ_n/Γ_f ratio as a function of the excitation energy and nuclear angular momentum.

One can see from the table that the experimental cross section for the $^{208}Pb(^{40}Ar, 4n)^{244}Fm$ is ten times smaller than the calculated one and 100 times smaller than the cross section of the $^{233}U(^{16}O, 4n)^{245}Fm$ reaction, which was determined by Nurmia et al. /12/. However, on the basis of the measured yields of the xn-reactions on the thick target it is difficult to answer the question of whether the mentioned discrepancies result from the suppression of compound nucleus formation, or they are a consequence of the influence of differences in the properties of the formed compound nuclei on the de-excitation process.

At the same time, after considering the Pb+Ar reaction separately, one can note an interesting feature, namely that the cross sections of reactions with two and three neutrons emitted are comparable with and even exceed the cross section for the reaction involving 4 neutrons evaporated. This fact seems to be rather important for both the production of weakly excited compound nuclei. and the mechanism of their production. Therefore we shall consider this problem in more detail.

As is seen from eq. /1/, the probability for the nucleus to be produced in the ground state is principally dependent on the excitation energy of the compound nucleus. The minimum value of the compound nucleus excitation energy in turn is determined by the barrier of the interaction and the Q value of the reaction, i.e.,

$$E^*_{min.} = B_{int.} + Q,$$

where $B_{int.} = z_I z_T e^2 / r_e (A_I^{1/3} + A_T^{1/3})$ and $Q = M_I + M_T - M_{CN}$. Figure 5 shows the $E^*_{min.}$ variation for the compound nucleus ^{248}Fm produced with different target-projectile combinations. In calculating $E^*_{min.}$ nuclear masses were taken from the paper by Myers and Swiatecki /24/, while

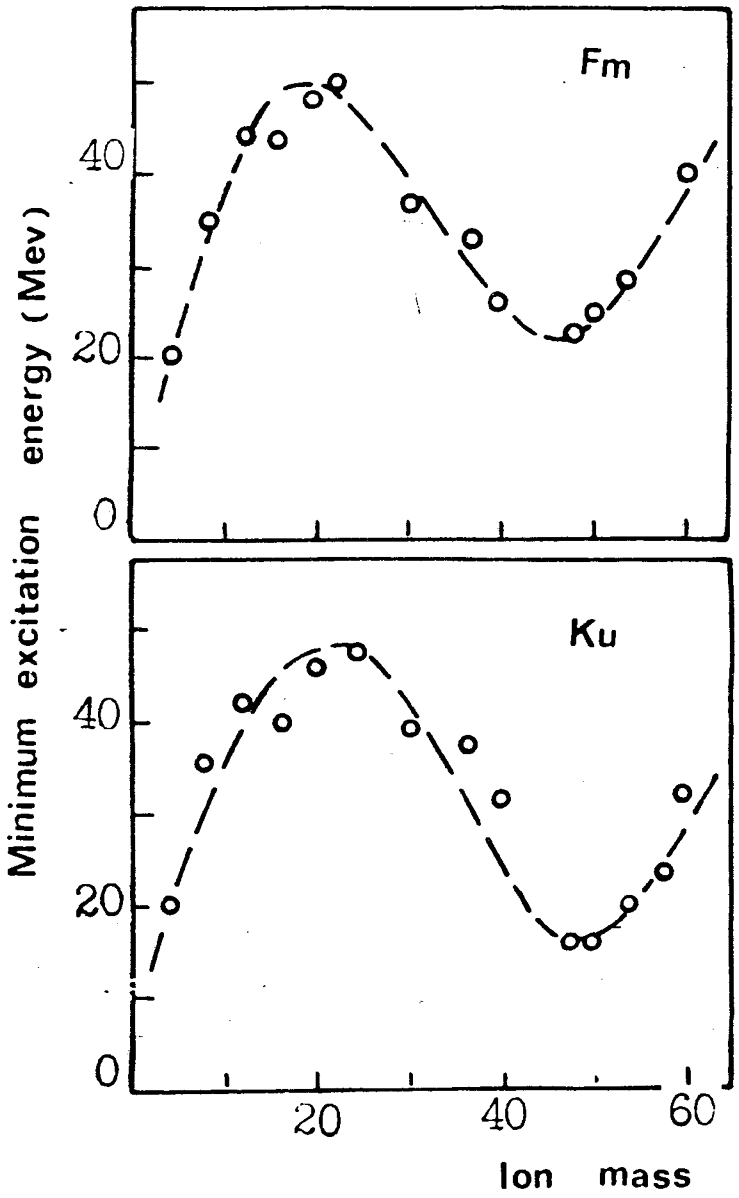

Fig. 5. Minimum excitation energy of the compound nuclei ^{248}Fm and ^{258}Ku formed in different target-projectile combinations. The dashed curves are drawn through the calculated E^*_{min} values shown by points.

the interaction effective radius r_e was taken to be equal to 1.45 x 10^{-13} cm.

One can see that as the mass of the bombarding particle increases, the excitation energy of the compound nucleus also increases and reaches the maximum value in the region of $A_I \approx 25$ to decrease then nearly twice in the region of $A_I \approx 40$-50.

This accounts for the well known experimental fact that in the synthesis of heavy elements with Z= 100-105 using ^{12}C, ^{14}N, ^{16}O, ^{22}Ne ions no reactions involving a small number of neutrons emitted were observed, as was in the case for $^{208}Pb(^{40}Ar, xn)$.

In view of the fact that the (^{40}Ar;2n, 3n) reactions occur at projectile energies close to the interaction barrier, their cross sections are extremely sensitive to the barrier value. As is shows in fig. 4, a 4 MeV increase in B_{int} reduces the cross section for the reaction with 2 neutrons emitted by a factor of 10. This makes it possible to determine the B_{int} value exactly enough from the experimental cross sections with $x \leq 3$. This gives an idea of the nature of the mechanism of fusion of these heavy complex nuclei.

Figure 6 shows a comparison between the calculated and experimental variations of compound nucleus cross sections for the reaction $^{40}Ar + ^{208}Pb$. The results of measurements /22/ of cross sections for the formation of fission fragments resulting from the fission of the compound nucleus ^{248}Fm are shown by points. The theoretical curves have been calculated for the interaction potential parameters $V_0 = -70$ MeV, $r_0 = 1.25 \times 10^{-13}$ cm and at different diffuseness parameters $d = 0.44 \times x10^{-13}$ cm and $d = 0.34 \times 10^{-13}$ cm. The calculated dependences are seen to agree well with the experimental values. On the basis of the comparison with the experimental cross sections for the 2n and 3n reactions (see the table), one should give preference to the calculation with $d = 0.34 \times 10^{-13}$cm.

It is noteworthy that the variations in the masses of nuclei involved in the reactions cause irregular changes in the Q value. Therefore close target-projectile combi-

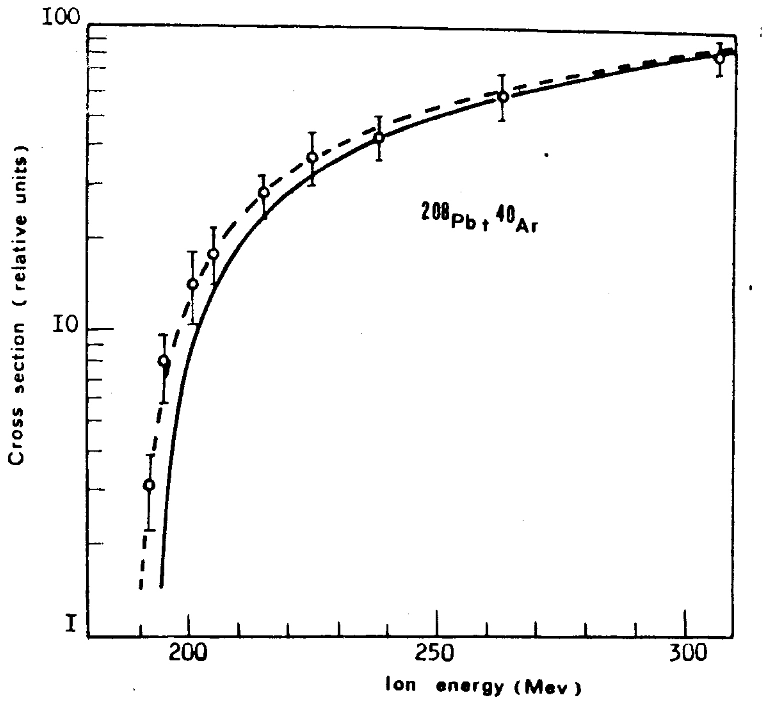

Fig. 6. Cross section for the formation of the compound nucleus ^{248}Fm by the reaction $^{208}Pb + ^{40}Ar$ as a function of the ion energy. The dashed and solid curves show the results calculated using the d parameter equal to 0.34×10^{-13}cm and 0.44×10^{-13}cm, respectively. Experimental data obtained in ref. /22/ are shown by points.

nations may display deviation from the smooth E^*_{min} dependence, shown in fig. 5, by several MeV. This in turn is expected to lead to a noticeable difference in the cross sections for reactions with $x < 3$. As an example, one can mention the reactions $^{209}Bi(^{37}Cl,2n)^{244}Fm$ and $^{206}Pb(^{40}Ar,2n)^{244}Fm$, in which E^*_{min} taken on values of 30 MeV and 32 MeV, respectively. Both experimental and calculated cross sections for these reactions differ by more than 10 times. This is a consequence of this small difference in the E^*_{min} values since in both cases the same compound nucleus, ^{246}Fm, is formed.

Thus, the intrinsic self-consistency of the data describing the formation of compound nuclei in the reactions Cl + Bi and Ar + Pb permits the use of this method of calculation to analyse the possibilities of producing heavier compound nuclei. In this case the formation of the nuclei of heavy elements in reactions with $x \leq 2$ is expected to have great advantages as compared with the previously used reactions involving the emission of four and five neutrons, since a decrease in the number of neutrons evaporated by 2-3 units increases the fraction of nuclei escaping fission by several orders of magnitude (see eq. /1/ at $\Gamma_n / \Gamma_f < 0.1$).

For instance, if one plots the E^*_{min} dependence for the compound nucleus ^{258}Ku, it will have a minimum at $A_I \approx 50$. Calculations show that the production cross section for element 104 in the reaction $^{50}Ti + ^{208}Pb \to ^{256}Ku + 2n$ may reach a value of 10^{-31} - 10^{-32} cm^2, which tens and hundreds of times exceeds the cross section for the reaction $^{242}Pu + ^{22}Ne \to ^{260}104 + 4n$, used to synthesize the isotope $^{260}104$ for the first time.

IV. Conclusion

The investigations described in this paper indicate that the interaction of ions with $A_I \approx 40-50$ with a heavy nucleus leads to the formation of a compound nucleus with a fairly high probability. At the same time, the experimental cross sections for compound nucleus formation and for the emission of x neutrons by it do not exhibit a considerable increase in the interaction barrier, which has been predicted in some papers. The fusion barriers appear to be close to those that might be expected from an analysis of interactions with ions of smaller mass.

As a result, the minimum excitation energy of the compound nucleus formed by fusing ions with mass $A_I \approx 40-50$ with heavy nuclei turns out to be about 20-30 MeV. This leads to the formation of weakly excited compound nuclei which emit only two or three neutrons. Since the 2n and 3n reactions proceed at energies that are close to the interaction barrier, their cross sections are strongly dependent on both the barrier height and the reaction Q value. This factor makes the choice of target-projectile combinations very delicate.

The experimental data obtained indicate that the conclusion about a decrease in the cross section for the formation of an element with increasing ion mass, which has been drawn on the basis of the use of the conventional method of synthesizing elements with $Z > 100$ in reactions with $A_I \leq 22$, is valid only for $A_I < 30$. As the ion mass A_I increases, the method of producing heavy elements with $Z \geq 104$ in reactions leading to the formation of weakly excited nuclei appers to be more efficient than that used previously. It should be noted that in this method one can use Pb and Bi isotopes as a target material rather than the rare and very radioactive isotopes of Pu, Cm and Cf. In this case the spontaneous fission background due to both the adjacent and spontaneous fission isomers is completely eliminated.

Although in the experiments described a narrow range of masses A_I and A_T has been investigated, the number of possible target-projectile combinations is large in this region. This fact opens up the possibility of producing a large number of neutron-deficient nuclei with $100 \leq Z \leq 104$ and $140 \leq N \leq 153$ and investigating their properties.

On the basis of the experimental data, the above method of calculating the xn-reaction cross sections can be used to estimate the possibilities of synthesizing elements with $Z = 106$-108 and $N = 152$-156, which may be formed in the bombardment of Pb and Bi targets with Cr, Mn and Fe ions. The estimates show that the expected cross sections for the formation of these nuclides may reach values of 10^{-32}-10^{-33} cm^2. Such experiments are presently accessible and may develop with the advent of new heavy ion accelerators. One can hope that this method may also prove efficient in the synthesis of superheavy elements with $Z \geq 110$.

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