MASS DISTRIBUTION OF FISSION PRODUCTS FROM THE IRRADIATION OF GOLD AND URANIUM BY NITROGEN IONS

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A study was made of the mass spectrum of fission fragments produced by irradiating thick gold and uranium targets with 115-Mev nitrogen ions. Fourteen different elements were separated from the irradiated targets. The mass distribution curve for fission fragments produced by irradiating gold has the form of a narrow peak with a half width of about 20 mass units. The maximum of the peak is at $A \sim 100$. The width of the mass distribution curve for fission fragments of irradiated uranium is much larger.

THE study of nuclear fission induced by heavy particles is of great interest because it enables us to obtain much additional information concerning the mechanism of fission at high excitation energies. Irradiation with heavy particles leads to the formation of a compound nucleus whose charge, mass number and excitation energy are determined quite unambiguously, because the capture of an energetic heavy particle, unlike that of a light particle, is not accompanied by the cascade ejection of nucleons. A more definite interpretation of the fission process is therefore possible.

The utilization of heavy particles also permits the investigation of the fission of a greater number of nuclei, including those with atomic numbers from 86 to 89 and from 95 to 100. Very little is known at present about the fission of these nuclei since experiments employing light particles encounter difficulties associated with the necessity for dealing with highly radioactive substances.

The present paper reports an investigation of the mass spectra of fission fragments from radon and einsteinium which were produced by irradiating gold and uranium with nitrogen ions.

EXPERIMENTAL METHOD

Gold and uranium plates 30μ thick and measuring 10×7 mm^2 were irradiated in the internal beam of a 150-cm cyclotron by quintuply charged nitrogen ions from a slit source. The energy of the nitrogen ions was 115 Mev, and the current at the target was $\sim 0.1\,\mu$a. The targets were fastened by means of a copper holder to a water-cooled probe. The current of bombarding particles was measured by using an electrometer to record the ions which passed through the target and entered the collector. In different experiments the time of irradiation varied from 30 min to 2 hrs.

The irradiated targets were dissolved and the different radioactive elements were separated with suitable carriers, which were inactive materials in amounts from 15 to 30 mg. The chemical yield of the carriers was determined by weighing after all purification operations had been performed. The separated radioactive isotopes were identified by their half-lives, energies and β-particle signs.[1] The intensity of β emission was measured by an end-window Geiger counter (type MST-17) with a mica window of 20 mm diameter and $5-6$ mg/cm^2 thickness. In order to avoid back-scattering of β particles the active materials were deposited on 4 mg/cm^2 tracing paper attached to a Plexiglas holder with a central opening. The thickness of the layer of deposited material did not exceed 10 mg/cm^2. The initial β activity of the specimens was $50-15000$ pulses/min from the irradiation of gold and $100-30000$ pulses/min from the irradiation of uranium. The counter background was 20 pulses/min. The β-particle energies were determined by absorption in aluminum, and their maximum energy was calculated by Feather's method. A magnetic analyzer was used to determine the signs of the β particles. The yields of identified nuclei were computed taking into account the time of target irradiation, the time from the termination of irradiation to the beginning of the count, the chemical yield of the element, β-particle absorption in the counter window and self-absorption.

FISSION PRODUCTS FORMED BY THE IRRADIATION OF GOLD WITH NITROGEN IONS

Table I contains a list of the relative yields of nuclei identified among the fission products from a thick gold target irradiated with 115-Mev nitro-

TABLE I

Nucleus	Relative yield	Type	Nucleus	Relative yield	Type
Ga^{72}	0.022±0.005	scr	Nb^{97}	0.29±0.04	scr
Ga^{73}	0.024±0.005	acc	Mo^{99}	1.00±0.25	acc
Rb^{86}	0.060±0.015	scr	Ru^{103}	1.05±0.35	,,
Sr^{89}	0.26±0.06	acc	Ru^{105}	0.62±0.12	,,
Sr^{91}	0.16±0.02	,,	Ag^{111}	0.120±0.025	,,
Sr^{92}	0.12±0.02	,,	Ag^{112}	0.062±0.012	scr
Y^{90}	0.19±0.04	scr	Ag^{113}	0.125±0.025	acc
Y^{91}	0.31±0.09	,,	Cd^{115}	0.045±0.009	,,
Y^{92}	0.26±0.05	,,	Cd^{115M}	0.085±0.025	scr
Y^{93}	0.35±0.05	acc	Sn^{121}	0.020±0.006	acc
Zr^{97}	0.16±0.02	,,	Sn^{123} (T=40min)	0.085±0.025	,,
Nb^{95}	0.37±0.11	scr	Sb^{122}	0.130±0.025	scr
Nb^{96}	0.37±0.08	,,	Ba^{139}	≤0.001	acc

gen ions. The yield of Mo^{99} is taken as unity. The errors indicated in the tables were obtained by averaging the deviations of several individual experimental values.

Figure 1 presents the yields of the nuclei in the table as a function of the mass number A. It can be seen that most of the yield of fission products is concentrated in a narrow range of mass numbers. The yield of fission products rises quite sharply as the mass number increases from 70 to 100 and then drops off just as sharply for larger masses. This suggests that the yield of fission products of gold irradiated by nitrogen ions describes a curve with a sharp maximum. However such a conclusion requires additional analysis, because the yield curve can only be plotted from knowledge of the total yields of individual mass chains connecting all fission products of the same mass number. In our experiments the individual mass chains were represented by one, or in some instances two, nuclei, including both screened nuclei (scr), i.e., nuclei produced only through fission, and accumulating nuclei (acc), which were produced both directly through fission and by β decay of other nuclei of the same mass chain.

In order to determine how accurately the distribution obtained for the yields of individual nuclei corresponds to the true distribution of fission fragments, an additional calculation was needed to determine the total yields of separate mass chains from the experimental yields of the nuclei which were represented. The yields of the mass chains were calculated on the basis of two different hypotheses concerning the distribution of the charge of a fissioning nucleus between two fragments, that of equal charge displacement for the two fragments[2] and that of proportional distribution of the charge of the fissioning nucleus.[3] In this calculation it was assumed that the average number of neutrons emitted by fission fragments is 1.5 – 2 per fragment. The number of neutrons emitted by a compound nu-

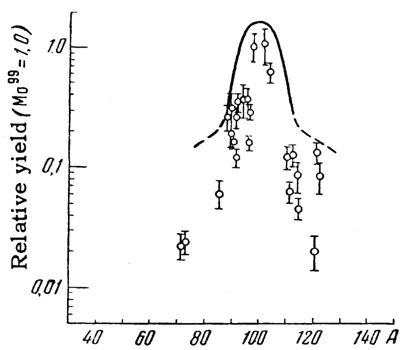

FIG. 1. Mass distribution of fission products produced by irradiating gold with nitrogen ions. o – experimental yields; solid line – curve calculated taking into account the yields of unidentified nuclei.

cleus before fission was estimated from the results of Refs. 4 and 5. A comparison of the cross sections for the reactions (N, 4n), (N, 5n) and (N, 6n) in gold and different nitrogen ion energies[4] with the cross section for gold fission,[5] similar to the comparison made in Ref. 6, showed that when a thick gold target is irradiated with 115-Mev nitrogen ions the average number of neutrons emitted by a compound nucleus before fission is 5 to 6 per fission. The total number ν of neutrons emitted in a single fission was taken as nine.

The expression used for the distribution function of the charges of fragments in a single mass chain was in satisfactory agreement with the experimental yields of the isobars Sr^{91} and Y^{91}, Sr^{92} and Y^{92}, Zr^{97} and Nb^{97}:

$$P(Z) = (1/\sqrt{1.7\pi}) \exp[-(Z-Z_p)^2/1.7]$$

$$\text{for } |Z-Z_p| \leqslant 2,$$

where Z_p is the charge of the fission fragment with the greatest yield among the fragments in a single mass chain.

From the experimental yields of individual nuclei we calculated the total yields of the corresponding mass chains. In addition to the experimentally determined yields of identified nuclei we included the yields of short- and long-lived stable fission products which could not be identified in the experiments. The symmetry and smoothness of the calculated curve served as criteria to determine which hypothesis concerning the charge distribution actually applies to gold fission by 115-Mev nitrogen ions. The requirements were satisfied better by the postulate of equal charge displacement.

Fig. 1 shows the yield of gold fission fragments produced by nitrogen ions as a function of mass number, calculated using the postulate of equal charge displacement. It is difficult to estimate the possible error for the calculated values of the yields, but it can be stated that the general character of the curve does not change essentially as ν is varied from 7 to 11. The most reliable data were obtained for the range $A = 85 - 115$, where the results of the calculation are practically independent of the choice of charge distribution hypothesis. The calculation for $A = 121$ and 123 gives a lower limit for the yields of these mass chains because the values used for the yields of Sn^{121} and Sn^{123} ($T = 40$ min) did not take into account the yields of the isomers Sn^{121m} and Sn^{123} ($T = 136$ days). The calculation for this range of values of A is less unambiguous.

As can be seen from the figure, when the yields of experimentally unidentified nuclides are also taken into account there is no essential change in the character of the experimental distribution. The mass distribution curve of fission fragments in the range $A = 85 - 115$ has the shape of a narrow peak with a half width of about 20 mass units; the maximum is at $A \sim 100$. The yields of $Ga^{72,73}$, Se^{123} and Sb^{122}, as well as the yields of the mass chains that correspond to these nuclides, lie off the smooth curve and appear to be somewhat high.

The general character of the mass distribution curve of gold fission fragments produced by nitrogen ions is approximately the same as for the fission of bismuth by 22-Mev deuterons.[7]

FISSION PRODUCTS FORMED BY THE IRRADIATION OF URANIUM WITH NITROGEN IONS

About 20 different isotopes were identified among the fission products of uranium irradiated with nitrogen ions. The yields of accumulating nuclides as a fraction of the yield of Ag^{113} are given in Table II.

If it is assumed that not more than 10 neutrons are emitted by the compound nucleus and fission fragments in one fission of a uranium nucleus by a 115-Mev nitrogen ion, the yield of each of the tabulated nuclides, with the exception of $Sr^{91,92}$, Zr^{97} and $Ba^{139,140}$, is not less than 70% of the total yield of the corresponding mass chain, according to either of the two hypotheses mentioned for the distribution of the charge of the fissioning nucleus between two fission fragments. Therefore the yields in the table must be regarded as lower limits that are quite close to the total yields of the corresponding mass chains. This conclusion is supported by the fact that the yields of screened nuclides Ga^{72} and Ag^{112} are considerably lower than the yields of neighboring accumulating nuclides.

Figure 2 shows the yields of accumulating nuclides as a function of the mass number. The combined yield of Cd^{115} and Cd^{115m} is given for $A = 115$. It is seen from the figure that the experimental results quite unambiguously determine a curve with a broad maximum. The somewhat reduced yields of $Sr^{91,92}$ and Ba^{140} can be attributed to the fact that these nuclides are more distant than the others from the β-stable range, so that their yields represent only a small part of the total yield of the corresponding mass chains. The yields of the other fission fragments are almost constant for mass numbers from 90 to 145. The half width of the curve is not less than 50 mass units.

An investigation of the fission products from the

TABLE II

Nuclide	Relative yield	Nuclide	Relative yield
Ga^{73}	0.03 ± 0.015	Cd^{115}	0.80 ± 0.15
Sr^{89}	0.65 ± 0.15	Cd^{115M}	0.70 ± 0.25
Sr^{91}	0.40 ± 0.05	Sn^{121}	1.10 ± 0.30
Sr^{92}	0.30 ± 0.05	Ba^{139}	0.65 ± 0.15
Zr^{97}	0.55 ± 0.10	Ba^{140}	0.25 ± 0.06
Mo^{99}	0.80 ± 0.20	Ce^{141}	0.90 ± 0.25
Ag^{111}	0.80 ± 0.15	Ce^{143}	0.70 ± 0.15
Ag^{113}	1.00 ± 0.15		

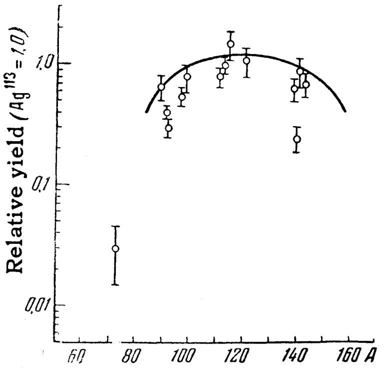

FIG. 2. Mass distribution of fission products from the irradiation of uranium with nitrogen ions.

irradiation of uranium with C^{13} ions[8] also shows the presence of a broad mass spectrum.

DISCUSSION

When elements at the end of the periodic table are bombarded with heavy particles, there is, in most cases, complete fusion of the nuclei that participate in the reactions. The cross sections for reactions which result in the capture of only a part of an incoming particle comprise a small fraction of the total cross section.[9] Therefore fission by heavy particles can be represented by the following scheme: formation of a compound nucleus, neutron emission, and fission. The number of neutrons ejected before fission is determined by the excitation energy of the compound nucleus and by the fissility of the intermediate nucleus.

When Au^{197} is bombarded with 115-Mev ions of N^{14}, excited Rn^{211} compound nuclei are formed which, as already mentioned, fission after the emission of a few, usually 5 or 6, neutrons that carry away a considerable portion of the excitation energy of the compound nucleus. The mass distribution curve of the fission products of gold bombarded with nitrogen ions therefore reflects the character of the fission of $Rn^{206-205}$ at relatively low excitation energies (not above 15 — 20 Mev). In this case, fission yields two fragments of approximately equal masses.

When a thick U^{238} target is bombarded with N^{14} ions compound nuclei of E^{252} are formed, with an excitation energy of 60 — 85 Mev. An investigation of the products of uranium bombardment with energetic heavy particles[9,10] shows that the probability of fission is considerably greater than the probability for the formation of nuclides by neutron evaporation from the compound nucleus. This suggests that the compound nuclei E^{252} fission predominantly without previous emission of neutrons or after emitting only 1 or 2 neutrons, which carry away only a small fraction of the excitation energy of the compound nucleus. Therefore the mass spectrum of fission fragments from uranium bombardment with nitrogen ions is characteristic of the fission of $E^{252-250}$ at high excitation energies (40 — 85 Mev). In this case both symmetric and asymmetric fission occur.

The magnitude of possible fission of uranium by neutrons produced in the bombardment of the target with nitrogen ions was estimated through a control experiment in which the uranium target was covered with 14 mg/cm^2 aluminum foil; in this case fission could be caused only by neutrons. This experiment showed that uranium fission by neutrons does not exceed 5% of fission by nitrogen ions and does not provide an explanation of the broad mass distribution of fragments from uranium fission by nitrogen ions.

Thus the half width of the fragment mass distribution curve is considerably smaller for radon fission than for the fission of einsteinium. It is difficult to determine whether the excitation energy, Z, A or Z^2/A of the fissioned nucleus results in the considerably narrower mass spectrum for the case of radon. However, it is noteworthy that an experiment in which two gold foils placed together were bombarded (with 115-Mev and 85-Mev nitrogen ions striking the first and second foil, respectively) showed that the mass distribution of radon fission fragments is narrower for the lower bombarding energy. The ratio of the yields of fragments at the edges of the peak ($Sr^{89,91,92}$ and $Ag^{111,112,113}$) to the yield of fragments at the center (Mo^{99}) is smaller for the second foil by a factor of 1.5 — 2.5.

The somewhat high yields of Sn^{123} and Sb^{122} from a thick gold target (Fig. 1) are probably associated with the effect of the closed shells of Z = 50 and N = 50. However, the possibility remains that the high yield of these nuclides, as well as of $Ga^{72,73}$, results from asymmetric fission of the lightest radon isotopes produced in the reaction at low excitation energies.

The different ratios of the isotopes Cd^{115} and $Cd^{115}m$ in the fission of radon and einsteinium ($Cd^{115}/Cd^{115}m = 0.5$ for Rn and $Cd^{115}/Cd^{115}m = 1$ for E), are evidently associated with different ratios between the yield of cadmium formed directly through fission and the yield of cadmium which results from the β decay of other fragments.

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THE SCATTERING OF MU MESONS IN BERYLLIUM

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We investigated the scattering of μ mesons in beryllium plates. The momenta of the μ mesons were in the range (130 ± 16) Mev/c. The observed angular distribution agrees within statistical error with the distribution to be expected from a Coulomb interaction between the μ mesons and the atoms of the material.

1. INTRODUCTION

THERE is reliable evidence for the absence of a non-Coulomb interaction between μ mesons and nucleons. It is to be expected, then, that the scattering of μ mesons in matter should be explicable in terms of electromagnetic interactions between the μ mesons and atoms. This question has been investigated experimentally for various momenta of of the μ mesons, and most of the results indicate there are more scattering events than would be expected on the basis of a nuclear model in which the nuclear charge is uniformly distributed in a sphere of finite radius $(R = 1.2 \times 10^{-13} A^{1/3}\,\text{cm.})$.

According to the latest data from the Manchester group,[1] in the momentum range 600 Mev/c to 100 Bev/c, the experimental distribution of μ mesons scattered from lead differs significantly from what would be expected from a nucleus of finite size, and agrees better with what would be expected from a point nucleus. One might try to explain the increase in the anomalous scattering at high energies by the absorption, in the nucleus, of virtual photons accompanying the moving μ meson. Such calculations have been carried out by Fowler.[2] According to Fowler's data, the anomalous scattering is small or entirely absent at momenta less than 270 Mev/c. The scattering cross section is proportional to A^2 and at large angles is such that the probability of a single scattering with a large momentum transfer is comparable with the corresponding quantity for a point nucleus. It is not yet possible to make a quantitative comparison between Fowler's calculations and the experimental data.

At small momenta, about 100 Mev/c, Alikhanov and Eliseev obtained evidence for anomalous scattering in graphite.[3] The anomalous cross section was about $5 \times 10^{-27}\,\text{cm}^2/\text{nucleon}$ and decreased with increasing energy. Alikhanian and Kirillov-Ugriumov studied the scattering of μ mesons with sharply defined momenta from copper and found an