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FISSION OF HEAVY NUCLEI WITH EMISSION OF LONG-RANGE α PARTICLES

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THE study of complex fission events of heavy nuclei with the emission of three charged particles has recently become of considerable interest. This phenomenon became known in 1946-1947 as a result of the work of several groups of investigators, who used thick-layer photoplates (Perfilov[1], Tsien San-Tsiang et al.,[2] Wollan et al.,[3] Demers,[4] Green and Livesey[5]) as well as specially constructed ionization chambers (Farwell et al.[6]).

Events of complex fission are conveniently observed in emulsion through a microscope. For that purpose a salt of uranium is introduced into the photoplate, which is then irradiated by thermal neutrons. Against a background of binary fissions one observes rare fission events, which have associated with the fission point a third track of a much lighter particle with a range greatly in excess of the range of fission fragments (Fig. 1).

These third particles were named long-range particles.

Later a whole series of papers appeared devoted to a study of this phenomenon, and it is interesting to discuss these.

In some papers[1,2] along with the long-range particles also short-range particles, connected with the fission process, were studied but these were later shown to be recoil nuclei resulting from the collison of fragments with nuclei in matter in the vicinity of the point where fission occurred.[7,8]

1. NATURE OF THE LONG-RANGE COMPONENT

Already in the first experiments attempts were made at establishing the identity of the long-range particles. Judging from grain density they could be classified as α particles.[3] One reaches the same conclusion from estimates based on the ionization produced by them.[6]

Tsien San-Tsiang et al.[2] performed calculations on the three-pronged forks observed in the emulsion, aimed at estimating the mass of the third particle. The angle between the heavy fission fragments differs from 180° by several degrees and this makes it possible to estimate the mass of the third particle, which turned out to be near the mass of an α particle. However the measurements were not accurate enough to rule out the possibility of such nuclei as He^3, Li^6, etc.

Starting from an assumed mechanism for ternary fission, Tsien San-Tsiang[2] calculated the maximum range for particles with various values for Z/A. The experimentally observed maximum range of the third particle approximately coincided with the range calculated for α particles.

Additional evidence indicating that the third particles are α particles was obtained in experiments by Allen and Dewan,[9] in which the energy distribution of the long-range particle was measured (see below).

In 1957 Fulmer and Cohen[10] once more and most accurately verified that the particles accompanying the fission of uranium nuclei were α particles. These authors made use of the method of magnetic deflection together with a pulse-height analyzer. A target with a sample of U^{235} and a layer of Po^{210} was placed near the center of the reactor. At the output of the reactor was placed a sectional magnetic spectrometer in back of which was a scintillation counter with the pulse-height analyzer. The presence in the setup of air at low pressure insured the complete stopping of all fission fragments. The radius ρ of the particle trajectory was constant. The experiment consisted of determining the relation between the pulse height A and the quantity $(H\rho)^2$. All points, including the point corresponding to the α particle from polonium, were found to fit well a single straight line. The slope of the line clearly determines Z^2/m since the pulse height A is proportional to the energy of the particle E, while the

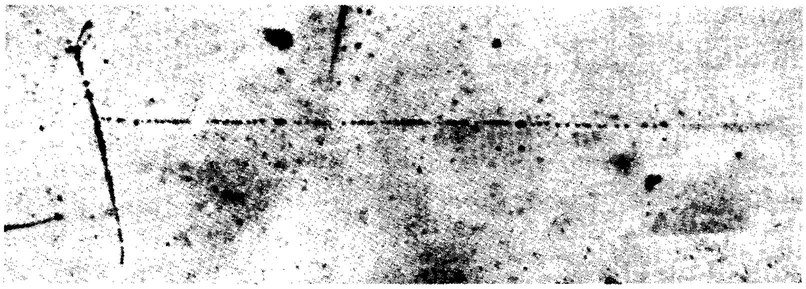

FIG. 1. Fission with a third long-range α particle.

relation between E and Hρ is given by $E = (Z^2/m) \times (H\rho)^2/(2c^2)$. This proved that the long-range particles have the same value of Z^2/m as do α particles. The second part of the experiment consisted of a measurment of the energy loss of the particles in an aluminum foil of known thickness placed directly at the detector. The energy loss of the particles was determined from the quantity Hρ and from the already known dependence A(E). The experimental results were in good agreement with calculations obtained on the basis of the known range-energy relation for α particles in aluminum. This led to the conclusion that the quantity mZ^2 of the particles being investigated was the same as mZ^2 for α particles. But if the compared particles have the same values of Z^2/m and mZ^2 then they must have the same values for both their charge and their mass.

In this way it was firmly established that the long-range particles produced in ternary fission of nuclei are in the overwhelming majority of cases α particles.

2. PROBABILITY OF COMPLEX FISSION

Fission with the production of long-range α particles is a rather rare event. To characterize the frequency of this process one normally makes use of the relative probability concept which determines in how many binary fission events a single ternary fission act will be observed. Many investigators measured the relative probability of double and triple fission. Various methods of nuclear physics were used. The fission of U^{235} by slow neutrons was studied in greatest detail. However the data of various authors are not in good agreement, due, apparently, to the low statistical accuracy of the measurements and to differences in the energy spectra of the neutrons used to irradiate the nuclei.

Let us discuss briefly the principal methods used to measure the relative probability of ternary fission.

Photoemulsions are used to determine the probability as follows. In the scanning the number of ternary fission events is registered and at the same time the total number of double fission events in the emulsion is counted. This method is tedious but comparatively simple and reliable. The majority of the measurements was carried out by this method. It turns out that for one complex fission event there are approximately 350 binary fissions. The disadvantage of this method of determination of the probability for complex fission lies in the fact that it can not be used in practice for the study of fission of strongly alpha-active isotopes (U^{233} and Pu^{239}). In this connection other methods were developed capable of providing a large amount of statistical material with data of great objectivity.

Farwell et al.[6] measured the relative probability of ternary fission by making use of a double ionization chamber. The target, with the isotope to be investigated on it, was placed on the central electrode of the chamber. In one half of the chamber the fission fragments were registered, this being accomplished by an appropriate setting of the bias, while in the other half the long-range α particles were registered. The back of the target was of sufficient thickness to absorb all fission fragments and natural α particles. In this manner the alpha chamber registered only α particles produced in the ternary fission of the nuclei. In order to eliminate background pulses coincidences between fission fragments and α particles were required at the output of the setup. If the fragments and the α particles are registered within the solid angle 2π, then the relative probability is equal to the number of registered fragments referred to twice the number of coincidences.

The latest data are given in the work of Fulmer and Cohen,[10] which was mentioned above. The number of ternary fission events was found by numerical integration of the distribution of the α particles in Hρ. With the help of the same setup the distribution in Hρ of the fission fragments was measured and their number per unit time was determined. It was found that for one fission event with the production of a long-range α particle there were 310 events of binary fission. Unfortunately the authors do not quote any errors for this result.

The probability of ternary fission of U^{235} was also measured by Allen and Dewan.[9] For the detection of long-range α particles a proportional counter of large dimensions was used. Above the counter was placed an ionization chamber which detected fission fragments (Fig. 2). The chamber was separated from the counter by a foil which served to slow down fission fragments and α particles due to natural radioactivity. Reactor neutrons were used for irradiation. In order to calculate the probability, the following quantities were determined: the number of double fission events, the number of coincidences between fission fragments and long-range α particles, and the effective solid angle in which events were detected. The obtained probability of 550 ± 50 is in disagreement with the data of other authors which indicate that the ternary fission is more frequent. The authors suppose that the discrepancy in the results is to be explained by a diffe-

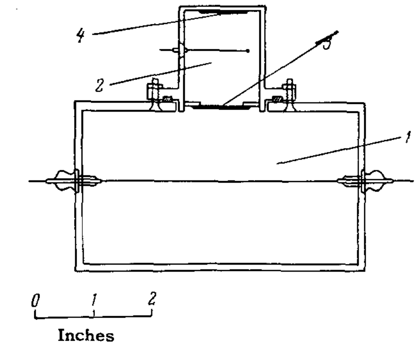

FIG. 2. Apparatus for the determination of ternary fission probability.[9] 1 – proportional counter, 2 – ionization chamber, 3 – foil for stopping fission fragments and α particles due to natural radioactivity, 4 – uranium target.

rence in the energy distribution of the fission-inducing neutrons.

Table I gives the data on the relative probability of complex fission of the U^{235} isotope by thermal neutrons, as obtained by various authors.

Author	Method	Relative Probability
Green and Livesey[5]	Photomethod	1:(340 ± 40)
Farwell et al[6]	Ionization chamber	1:250
Marshall[11]	Photomethod	1:230
Tsien San-Tsiang et al.[2]	Photomethod	1:(330±110)
Titterton[12]	Photomethod	1:(422±50)
Allen and Dewan[9]	Ionization chamber	1:(505 ± 50)
Hill[13]	Ionization chamber	1:(220 ± 33)
Fulmer and Cohen[10]	Magnetic deflection	1:310

Auclair[13a] has measured the dependence of the probability for ternary fission with the emission of a long-range particle on the energy of the incident neutrons in the thermal region. Within the limits of the statistical errors (10%) the fission probability is independent of neutron energy.

Tsien San-Tsiang et al.[2] indicated that fission of uranium and thorium with the emission of long-range α particles is not observed with fast neutrons [from the reaction Be(d, n) for $E_d = 6.7$ Mev]. The authors concluded that this type of fission is characteristic only of the lower excited states of the nuclei undergoing fission. In the opinion of these authors the capture of a fast neutron leaves the nucleus in a state where its energy level is significantly above the fission threshold of the compound nucleus, and in such a case long-range particles are not produced. Supporting this statement was the fact that for the more "easily fissioning" Pu^{239} nucleus the probability for complex fission (measured by Tsien San-Tsiang et al.[2]) is half as big as that for U^{235}, i.e., the excited level of the Pu^{239} nucleus resulting from the capture of a zero-energy neutron is higher than that of U^{235}.

However, later it was found[7,14] that fast neutrons can induce fission of uranium with emission of long-range particles. Furthermore, according to the data of Allen and Dewan[9] the probability for complex fission of Pu^{239} and U^{233} by thermal neutrons is actually even somewhat higher than that for U^{235}, namely 1:(445 ± 35) for Pu^{239} and 1:(405 ± 30) for U^{233}.

New experimental data touching on this question were obtained by Perfilov and Solov'eva.[15,16] The neutrons were obtained from the reactions (D + T) and (D + D) and had respectively 14 and 2.5 Mev. The photoplates were screened from thermal and scattered neutrons by cadmium and boron, so that thermal and scattered neutrons could be responsible for no more than 2% of the total number of fission events. It was found that for one complex fission event of natural uranium by 2.5-Mev neutrons there are 600 binary fissions, and for 14-Mev neutrons there are between 1000 and 1300 binary fissions, i.e., the process is several times less probable than is the fission of U^{235} by thermal neutrons.

A group of French investigators[17] found, using the method of Allen and Dewan,[9] 1500 binary fissions for one ternary fission of Pu^{239} at $E_n = 300$ kev. Further, approximately the same probability occurs for U^{233}. At present these authors are studying the probability of ternary fission for the U^{233}, U^{235}, U^{238}, and Pu^{239} isotopes by neutrons of various energies. The neutron sources will be: thermal neutrons, of which definite groups up to 1.5 ev will be selected by a crystal monochromator, fast neutrons from the reactor, as well as from the reaction $T(p, n)He^3$ produced by a Van der Graaff generator (neutron energies of 300, 700, and 2000 kev). In this work the photoplate method will be used, with the fissioning substance placed outside the emulsion and the number of fission events in the sample determined from the number of tracks of recoil protons produced by fission neutrons.

The probability of complex fission of U^{238} and Th^{232} by gamma rays with maximum energy of 23 Mev has also been studied and found to be approximately the same as in the fission of U^{235} by thermal neutrons.[18,19]

In the fission of thorium by fast neutrons[20] and uranium by gamma rays[21] two events were found in which two long-range α particles were associated with the fission point. The energy of each particle in both cases is approximately 10 Mev and the angle between them is 7° and 9°. Energy considerations are not in contradiction with the assumption that these events correspond to the emission at the instant of fission of a Be^8 nucleus which decays into two α particles while still in the field of the fragments. No similar events have been observed in other experiments.

Of some interest is the question of complex spontaneous fission.

In 1955 it was reported at the first Geneva conference[22] that according to the data of Mostovaya the probability of ternary spontaneous fission of Pu^{240} is 1.60 ± 0.15 times larger than the probability of ternary fission of Pu^{239} by slow neutrons.

At the Mendeleev meeting in 1959 Thompson[23] reported on the complex spontaneous fission of Cf^{252}. Using a perfected method for producing the Cf^{252} isotope the Berkeley group separated approximately $1\mu g$ of Cf^{252}. This made possible the study of complex spontaneous fission events of Cf^{252}. As is known, the period for spontaneous fission for this isotope equals 66 years. Therefore approximately 5×10^7 fissions per minute were occurring in the prepared sample. Since Cf^{252} has a small alpha-decay period (2.2 years) the study of its fission by the photoplate method presents a complicated problem. As a result of the comparatively favorable relation between the periods of spontaneous fission and alpha decay the sample of Cf^{252}

could be introduced into the emulsion for several hours and after development a large number of tracks due to fission fragments could be observed against a background of α-particle tracks. (The Cf^{252} was removed by washing out the emulsion before development.) The authors found that along with fission into two fragments there occurs fission with production of long-range α particles. According to preliminary data there are 300 binary fission events for one act of ternary fission.

It is seen that the probability for fission accompanied by long-range α particles is far from being adequately investigated. Consequently at this time it is not possible to reach any conclusions or systematize the data on ternary fission of various isotopes.

3. ENERGY DISTRIBUTION OF LONG-RANGE α PARTICLES

The energy spectrum of α particles produced in complex fission of uranium were studied by the photoplate method,[2,5,7,12] by absorption in thin aluminum foils,[9,13] by ionization chambers with a grid,[9] and by deflecting the α particles in a magnetic field.[10]

The energy of α particles in individual complex fission events was determined in the standard manner, namely by measuring their range in a photoemulsion with known range-energy relation for α particles. The dependence on the energy E of the number of events for which the α-particle energy lies in the interval between E and E + dE yields the desired distribution. It was established that the α-particle spectrum is continuous and that it contains a broad maximum near 15-17 Mev. The energies of the particles were contained in the interval between 7 and 28 Mev and the half-width of the maximum in the distribution was approximately 12 Mev.

Allen and Dewan[9] used to study the spectrum of the α particles the method of absorption in aluminum foils of varying thickness. A target made out of the fissionable material was mounted on the central electrode of the ionization chamber which was inlined at 45° with respect to the axis of the chamber. The long-range α particles produced in the chamber passed through mica windows into a proportional counter. The fragments and the particles were recorded in coincidence. Between the chamber and the counter the long-range particles passed through thin aluminum foils. Only those particles were recorded which produced maximal ionization in the volume of the counter, i.e. particles with definite residual range were selected.

From the known thickness of the mica windows and aluminum foils it was possible to determine the energy of the recorded particles (their range in air). From the dependence of the number of coincidences on the thickness of the foil the full energy distribution of the long-range α particles was calculated. According to these authors the maximum in the distribution corresponds to a range of 25 cm in air, that is to an energy of 15 Mev.

An analogous method was used by Hill[15] to study the energy of α particles. He obtained for the energy distribution of the long-range α particles a formula in agreement with the results of Allen and Dewan and represented approximately by the Gaussian:

$$W(E) \sim \exp\left[-\left(\frac{E-15.15}{6.05}\right)^2\right].$$

It was taken into account here that the maximum in the distribution as obtained in that work fell at 15.15 Mev.

In that same work of Allen and Dewan the energy distribution of α particles produced in the fission of U^{235} by slow neutrons was studied by means of an ionization chamber with a grid. This experiment was performed with a double ionization chamber filled with gas to a pressure of about 10 atm; fission fragments were registered in one half of the chamber, the long-range particles associated with the fission in the other. The target was mounted on the central high-voltage electrode of the chamber. The backing of the target fully absorbed fission fragments and α particles due to the natural radioactivity of uranium. Since the alpha chamber was equipped with a grid shielding the collecting electrode from positive ions, the amplitude of the pulse on the collecting electrode was proportional to the energy of the α particle. Whenever coincidences from the two chambers were obtained the amplitude of the pulse due to the long-range particle was measured with the help of a pulse height analyzer. A Pu^{239} source was attached to the target on the large chamber side for energy calibration purposes.

The measured energy distribution of the long-range particles was in good agreement with the distribution obtained by the absorption method. This circumstance indicates that all of the long-range particles associated with the fission of uranium are α particles, and not He^3, Li^6, and the like. Indeed the energy distribution of the particles was calculated from the results of the absorption experiment on the assumption that they were all α particles. The agreement between that distribution and the one obtained by direct measurements of the ionization produced by the particles proves that in ternary fission no long-range nuclei are produced what so ever, except for nuclei of He^4.

Lastly, the energy spectrum of α particles produced in the fission of U^{235} by thermal neutrons was studied by means of a magnetic spectrograph by Fulmer and Cohen,[10] whose work was mentioned above. The high resolving power of the setup made it possible to obtain high-precision data. Results of these measurements show that there is no fine structure in the energy distribution of the particles. It is interesting to note the good agreement between data obtained by the various methods (Fig. 3). The differences in the results of the measurements at low energies are apparently to be

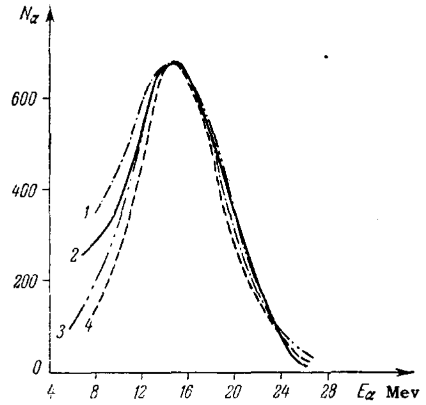

FIG. 3. Energy distribution of long-range α particles: 1 – ref. 9, 2 – ref. 10, 3 – ref. 13, 4 – ref. 14.

explained by the impreciseness of the absorption and photoplate methods .

According to Allen and Dewan the energy spectra of α particles produced in the fission of U^{233} and Pu^{239} are of the same character as in the fission of U^{235}. A certain shift of the maximum towards higher energies was observed.

These are the principal results on the study of the energy spectra of α particles in the fission of nuclei by slow neutrons.

It follows from the work of Perfilov and Solov'eva[15,16] that the energy distributions of long-range α particles produced in the fission of natural uranium by 2.5 and 14 Mev neutrons are not very different from the spectra observed in the fission of U^{235} by thermal neutrons.

4. ANGULAR DISTRIBUTION OF LONG-RANGE α PARTICLES

A simple and reliable method for measuring the angular distribution of α particles with respect to the fission fragments is the photoplate method. At this time other methods are not yet developed. The angle ψ between the line of flight of the α particle and of one of the fission fragments is found by measuring the horizontal and vertical projections of their tracks and the angle between the horizontal projections. The angle is calculated from the formula.

$$\cos\psi = \frac{x_\alpha x_f \cos\varphi + z_\alpha z_f}{\sqrt{x_\alpha^2 + z_\alpha^2}\sqrt{x_f^2 + z_f^2}},$$

in which x_α, x_f and z_α, z_f are the horizontal and vertical projections of the α particles and fragments respectively, and φ is the projection of the angle between them.

It follows from the results of a number of authors,[2,12,24] who studied the angular distribution of long-range α particles with respect to fission fragments, that the α particles are emitted mainly into a region of angles near 80° with respect to the line of flight of the light fragment (the fragment with longest range). Thus the long-range α particles are mainly to be found in the hemisphere corresponding to the light fission fragment. Figure 4 shows a characteristic angular distribution of α particles relative to the light fission fragment.[24]

It is seen from Fig. 4 that there is a significant number of events for which the deviation from the most probable value is large.

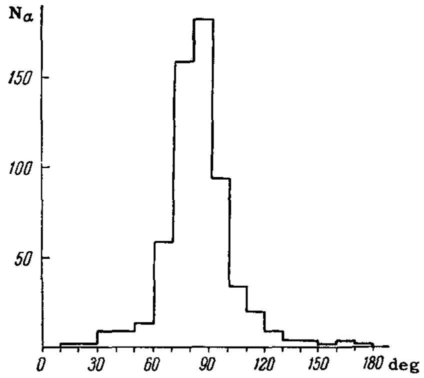

FIG. 4. Angular distribution of long-range α particles relative to the light fission fragment.[7]

According to Perfilov and Solov'eva,[24] the angular distribution of the α particles becomes broader with increasing range and for α particles with ranges bigger than $200\,\mu$ ($E > 21$ Mev) it approaches an isotropic distribution. Further, the angle of emission of the α particles is independent of the asymmetry in the ranges of the fission fragments. From this relation between the angular and energetic distributions of the α particles one may conclude that the α particle exists as a temporary substructure with definite energy distribution inside the nucleus, is released in the fission process with an initial velocity determined by this distribution, and only then becomes subject to the Coulomb forces of the fission fragments.

In the complex fission of natural uranium by 2.5- and 14-Mev neutrons[15,16] it was found that the characteristics of the angular distribution are preserved and the maximum occurs at approximately 80°.

In photofission,[20] as well as in the fission of U^{238} and Th^{232} by fast neutrons,[14] the α particles are emitted at an angle which also is close to 90°.

5. THE ENERGY SPECTRUM OF THE FRAGMENTS IN TERNARY FISSION

It is of interest to discuss the energy distribution of the fission fragments accompanying the emission of long-range α particles. In the study of ternary fission of uranium by the photoplate method it was noted[2,7] that in a majority of the events the fragments have different ranges. The ratio of the ranges is approximately 1.3. The photoplate method is not suitable for a precise measurement of the energy distribution of the fragments.

Allen and Dewan[9] were the first to attempt to measure the energy spectrum of the fragments in the ternary fission of U^{235}. The fragments and the α particles were detected with the help of the double ionization chamber discussed above. Coincidences between the fragments and the α particles were recorded. The pulse heights due to the fragments were measured with a multichannel analyzer. It was found that the fragment spectrum has two maxima and is shifted relative to the spectrum in binary fission in the direction of lower energies. The maximum corresponding to the light fission fragment (higher energies) is shifted by 10 Mev and the "hump" corresponding to heavy fragments - by 7 Mev. The results of the measurements by Allen and Dewan were affected by the angular correlation between the fragments and the α particles. Since a larger number of long-range α particles falls into the light fragment hemisphere than in the heavy fragment hemisphere, and since the fragments and the α particles are detected on opposite sides of the target of fissioning material, the "heavy hump" as obtained in this experiment was considerably higher than the light one and had a larger area.

A more accurate fragment distribution was obtained by Dmitriev, Drapchinskiĭ, Petrzhak, and Romanov.[25] The fragments were detected by a chamber with a grid and the α particles were fixed by a ring chamber surrounding the central electrode and symmetric relative to its plane (Fig. 5). A source of fissioning material in the form of a thin metallized collodion film with a deposit of a uranium salt was mounted on the central electrode. Under the conditions of this experiment the angular correlation between the fragments and the α particles had no effect on the results of the measurements since the α particles entered the alpha chamber on both sides of the target. Coincidences between fragments and α particles produced a pulse at the input of a 63-channel pulse-height analyzer with electronic memory, connected to the fragment channel, permitting the registration of the amplitude. After correcting the results of the measurements for the ionization produced by the long-range α particles within the volume of the fission chamber it was found that the humps were shifted as in the work of Allen and Dewan. However the height of the light hump was approximately 10% bigger than the height of the heavy hump. The humps were found to be narrower than in binary fission which is partially explained by the geometrical collimation of the fragments due to the angular correlation between the fragments and the α particles and due to the detection conditions. Figure 6 shows the results of the measurements of the energy distribution of fragments of ternary fission of U^{235} by slow neutrons. It should be noted that the spectrum of fragments from the ternary fission of U^{235} and U^{233} are analogous in form and are equally shifted relative to the fragment spectra obtained in binary fission.

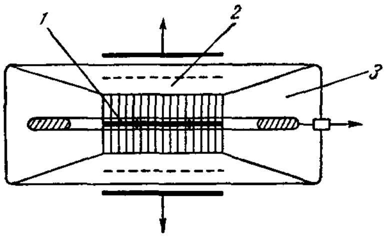

FIG. 5. Ionization chamber for energy measurements of the fission fragments.[25] 1 – central electrode and target of fissioning material, 2 – fragment chamber, 3 – long-range α particle detecting chamber.

Mostovoĭ, Mostovaya, Sovinskiĭ, and Saltykov[26] found the energy distribution of U^{235} fragments by the same method as used in the work of Allen and Dewan. However, the authors made use of the data on the angular correlation between the fragments and α particles to correct the results of their measurements, the correction involving an extrapolation of the "humps" corresponding to light and heavy fragments. The resultant distribution agrees well in shape with the distribution shown in Fig. 6. The only discrepancy is in the energy shift of the humps which, according to these authors,[26] amounts to 13.8 Mev. One can, apparently, consider the results of all authors as being approximately in agreement within the limits of experimental errors. Consequently it follows that the sum of kinetic energies of the most probable fragments in binary fission is approximately the same as the sum of kinetic energies of the most probable fragments and of the α particles in ternary fission. From the data it is possible to estimate the difference in the internal excitation energies of the most probable fragments in binary and ternary fission. It is equal to a few Mev. According to the statistical theory of fission developed by Fong,[27] such a difference in the internal excitation energies should result in a considerable decrease in the probability of ternary fission as compared with binary fission. This fact is confirmed by experiment (probability 1:300). Further, the smaller internal excitation of the fragments should lead to a smaller average number of neutrons, emitted by the fragments. According to the estimates of Mostovoĭ et al. this

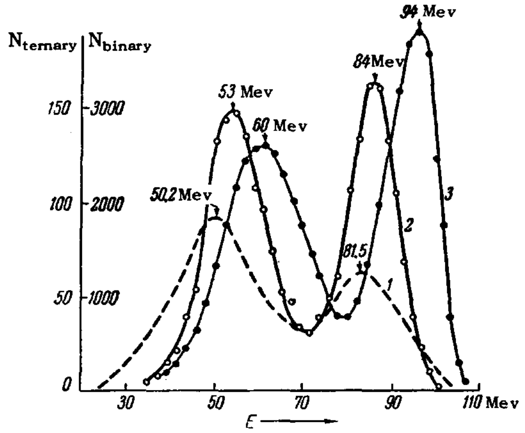

FIG. 6. Energy distribution of U^{235} fragments in ternary fission. 1 – ternary fission,[9] 2 – ternary fission,[25] 3 – binary fission.[25] Correction for the ionization effect not included.

number should be $\bar{\nu}_{\text{ternary}} = 1.6$, which is in agreement with the experimental data obtained by Apalin, Dobrynin, Zakharova, Kutikov, and Mikaélyan.[28] In this experiment a double ionization chamber was used to detect the fission fragments and the long-range α particles. The chamber was placed in the center of a tank, filled with liquid scintillator which served as the detector for the fission neutrons. By comparing the number of coincidences between fragments and neutrons in binary fission with the number of coincidences between fragments, neutrons and α particles in ternary fission, these authors found that $\bar{\nu}_{\text{ternary}} = 1.77 \pm 0.09$ for $E_\alpha > 9$ Mev, and $\bar{\nu}_{\text{ternary}} = 1.79 \pm 0.13$ for $E_\alpha > 22$ Mev. This shows that the excitation energy of the fragments is independent of the energy of the long-range α particles.

We have discussed the main features of the experimental data on nuclear fission with the production of long-range α particles. What can be the mechanism responsible for complex fission? Various authors have advanced several hypotheses.

6. TERNARY FISSION MECHANISM HYPOTHESES

To explain the experimental data on the angular and energy distributions of long-range α particles Tsien et al.[2] proposed the following mechanism for ternary fission. In the process of neutron capture the nucleus is excited and this excitation energy is transformed into the energy of vibrational motion of the nuclear liquid (drop). As was shown by Present[29] and Present and Knipp,[30] for large deformations corresponding to fourth harmonics two "necks" can be formed, which become breaking points as the drop is elongated. According to the hypothesis of Tsien et al. the central drop is an α particle. As a consequence of asymmetry of the fragments and intense vibrations of the system, leading to the elongation of the necks between the fragments, all three parts of the nucleus touch up to the instant of fission. At the instant of fission they break apart under the influence of Coulomb forces. The velocity and direction of motion of the α particle depend on its initial position relative to the two other fragments. Its motion will be in the direction of the resultant of the Coulomb forces of the heavy fragments. For this reason the α particle is predominantly deflected in the direction of the lighter fragment. This hypothesis makes possible an estimate of the most probable energy of the α particle; the value obtained is in agreement with experiment.

Such a description of the mechanism of nuclear fission with the production of long-range α particles is but qualitative. The question remains unanswered why in the majority of cases α particles, and not some other nuclei, are produced. Further, this hypothesis cannot explain the observed probability for ternary fission and its dependence on neutron energy, as well as the connection between the angular and energy correlations between the α particles and the fission fragments.

In the opinion of Fraser,[27] the α particle is emitted after fission, predominantly from the fragment which is alpha-unstable in its ground state. Since regions of alpha-unstable nuclei fall approximately near $Z = 40$ and $Z = 60$, the energy distribution of ternary fission fragments should be more asymmetric than in binary fission.

This hypothesis meets immediately with a number of objections. The last conclusion is in contradiction with experimental data on the angular and energy distributions of ternary fission fragments.

It is difficult to expect the experimentally observed angular distribution of the α particles if they are evaporated from the fragments. As was shown by Wollan et al.,[3] the maximum in the angular distribution of α particles emitted isotropically by the moving fragment should, due to the motion of the fragment, occur in the laboratory system at an angle of 45 degrees with respect to the direction of motion of the fragment.

Demers[4] attempted to estimate an upper limit on the time of emission of the α particle. To this end a photoplate with a thin insensitive layer of gelatin, containing a uranium salt, was used. In the scanning of the neutron irradiated photoplate not a single track of a long-range α particle could be found, originating outside the gelatin layer of 0.2μ thickness. Since the velocities of the fission fragments are of the order of 10^9 cm/sec, the long-range α particles must have been emitted from the fragments in no case later than 2×10^{-14} sec after fission. The probability of fragment disintegration in the time $t \approx 10^{-14}$ sec is extremely small.

Could the α particle be emitted before the instant of fission? Allen and Dewan[9] suppose that when the surface of the excited nucleus is deformed, the α particle is emitted from the point with a strongly lowered potential barrier and fission occurs afterwards. The magnitude of the barrier is lowest near the "neck" of the deformed nucleus and for this reason definite angular and energy distributions of α particles are observed experimentally. The longer the lifetime of the compound nucleus, the more probable the emission of α particles. Therefore the probability for ternary fission induced by slow neutrons is higher than for fission induced by fast neutrons. It would seem that with this hypothesis it is possible to qualitatively explain all the experimental data on ternary fission. In fact the Allen and Dewan hypothesis is untenable for the following reason.

Fulmer and Cohen[10] give convincing proof that the long-range α particles are produced neither before nor after fission. Whether the α particles are evaporated from the compound nucleus or from the fragments, their energy distribution is determined by two factors: the temperature distribution inside the nucleus (Maxwellian) and the penetrability of the Coulomb barrier. It turns out that the "tail" of the experimental energy distribution of the α particles agrees well with the "tail" of a Maxwellian distribution corresponding to a temperature of 1.4 Mev. Therefore the penetrability of the Coulomb barrier for particles with energy in excess of 17 Mev is equal to unity. Making use of this circumstance one can construct the dependence of barrier penetrability on the energy of the α particle in the low-energy region. This dependence is shown in Fig. 7 by the solid curve; the dashed curves give the dependence of barrier penetrability on α-particle energy for $Z = 30$, $Z = 50$ and $Z = 90$. It is seen from the figure that an effective charge of about 20 must be ascribed to the nucleus emitting the α particle.

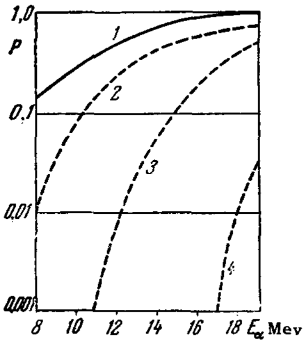

FIG. 7. Coulomb barrier penetrability P as a function of α particle energy for various Z.[10] 1 – for long-range α particles from U^{235} fission, 2 – Z = 30, 3 – Z = 50, 4 – Z = 90.

Experimentally no fission fragments with that small a charge was observed. At first sight the large barrier penetrability might be caused by a lowering of the Coulomb barrier near the neck of the fissioning nucleus. However estimates show that for this to happen an improbably large nuclear deformation would be necessary, since the Coulomb barrier in the neck is a slowly decreasing function of the distance between the two fragments that are being formed.

Thus, in spite of the large experimental material available on the subject of nuclear fission with the production of long-range α particles, particularly for the U^{235} isotope fission by slow neutrons, it has not been possible so far to formulate an acceptable hypothesis explaining the mechanism of this type of fission.

In conclusion it should be mentioned that there exist data[1,2] indicating that complex fission with comparable in mass fragments occurs with very small probability. These results found no confirmation in the experiments of Rosen and Hudson,[31] and no new information on this type of fission appeared in the following years. In 1959 Thompson reported at the Mendeleyev Conference on spontaneous fission of Cf^{252} into three fragments of comparable mass with a probability of approximately 1:300 relative to binary fission.

It is clear that the existing experimental material is not sufficient to make serious scientific generalizations on the subject of nuclear fission with either the emission of long-range α particles or the production of comparable in mass fragments. One can hope that the intensive investigations under way now in many laboratories of the world will lead to an understanding of the mechanism responsible for this interesting nuclear process.

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