In the above considerations, free use was made of classical mechanics in making estimates regarding the nature of the collisions. Among them there was the estimate of the period of the whole system with fixed positions of the heavy aggregates which enters a comparison with the collision time. In a quantum calculation there enters in place of this the time corresponding to the transition frequency between the initial and final states. In the case of $N^{14}+N^{14}\rightarrow N^{13}+N^{15}$, this time is especially long because of the approximate resonance in neutron energies, i.e., the near equality of binding of the last neutron in N^{14} and N^{15}. In mass units $N^{14}+N^{14}-(N^{13}+N^{15})=0.00028=0.261$ Mev. The value of $\hbar/0.261$ Mev is 240×10^{-23} sec which is longer than the collision time of 169×10^{-23} sec but of the same order. The qualitative situation is not changed by the quantum estimate. It suggests, however, that characteristic differences may be found in reactions with different energy evolutions.

It appears from the above discussion that the measurements of the differential cross sections suggest the way in which virtual state formation enters the collision process. The suggested picture is either excitation to the lower part of the continuum strongly influenced by the degree to which a given orbit performs an adiabatic rather than shock-type collision; or else excitation to higher energies with a smaller influence of the degree of adiabaticity appears at present to be equally acceptable.

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Energy Distribution of Mass-97 Fission Fragments from Thermal-Neutron Fission of Uranium-235

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The energy distribution of mass-97 fragments from thermal neutron induced fission of U^{235} was measured with a high-resolution magnetic spectrograph. The fragments originate in a thin plating of U^{235} near the center of the Oak Ridge National Laboratory graphite reactor and travel 16 feet to a wedge magnet which analyzes and focuses them at the focal plane 6 feet beyond. There they are caught in an aluminum foil which, after the irradiation, is cut into strips each of which is radiochemically analyzed for Zr^{97}. The $H\rho$ distribution is complicated by the large energy width which leads to overlapping of momentum distributions from successive charges. An analysis of the shapes of the $H\rho$ distributions obtained with different relative charge populations determines that the width of the energy distributions is $(11.4\pm0.8)\%$ corrected for broadening due to prompt neutron emission. This result is in agreement with measurements of the distributions of the number of neutrons per fission but is in sharp disagreement with the predictions of Fong's theory of the fission process. The most probable energy is 174.7 ± 2 Mev for the mass-97 fission mode, and about 164.5 ± 3 Mev for the mass-91 mode.

INTRODUCTION

THE energy spectrum of fission fragments of a given mass has been investigated by several groups[1] using ionization chamber techniques; they have obtained roughly Gaussian distributions with the most probable total kinetic energy release, $\bar{E}$, about 155 Mev, and full width at half-maximum, $\Delta E/\bar{E}$, about 15%. Recent investigations of ionization defects for fission fragments[2] have indicated that the former result is much too small, and experiments using both time-of-flight[3] and calorimeter[4] techniques have measured $\bar{E}$ to be about 167 Mev. The situation regarding the width of the distributions is considerably less certain. By comparing the results of time of flight and ionization chamber experiments, Leachman[3] concluded that the experimental dispersion in the latter experiments was about 9%, which would reduce $\Delta E/\bar{E}$ to about 12%. However, Fong,[5] analyzing the same data, found $\Delta E/\bar{E}$ to be only 8%. From measurements of range distributions in various gases, Good and Wollan[6] found $\Delta E/\bar{E}=6\%$; however, their corrections for foil thickness were quite large and appear to be inconsistent with other data. The general consensus has been that, due to the large dispersion and many other inaccuracies inherent in ionization chamber and absorption techniques, these experiments do not establish a lower limit to the widths of the energy distributions. It was decided, therefore, to measure these widths by magnetic analysis. In the process, new measurements of $\bar{E}$ were obtained.

[1] D. C. Brunton and G. C. Hanna, Can. J. Research **28A**, 190 (1950); W. Jentschke, Z. Physik **120**, 165 (1943); A. Flammersfeld, Jensen, and Gentner, Z. Physik **120**, 450 (1943); M. Deutsch and M. Ramsey, U. S. Atomic Energy Commission Report MDDC-945, 1945 (unpublished).
[2] H. W. Schmitt and R. B. Leachman (private communication).
[3] R. B. Leachman, Phys. Rev. **87**, 444 (1952); R. B. Leachman and R. W. Schmitt, Phys. Rev. **96**, 1366 (1954); W. E. Stein (private communication).
[4] R. B. Leachman and W. D. Schafer, Can. J. Phys. **33**, 357 (1955).
[5] P. Fong, Phys. Rev. **102**, 434 (1956).
[6] W. M. Good and E. O. Wollan, Phys. Rev. **101**, 249 (1956).

EXPERIMENTAL

The measurements were made with a magnetic wedge spectrograph, the magnet of which is installed just outside the shield wall of the ORNL graphite reactor; the arm containing the source is a 16 feet long, $3\frac{1}{2}$-inch diameter tube lying in a reactor hole with the far end near the center of the reactor core. The source, a 40-microgram/cm^2 plating of U^{235}, $2\frac{1}{4}$ inches high by $\frac{3}{8}$ inch wide, is mounted just inside that end of the tube, in a flux of 5×10^{11} neutrons/cm^2-sec. Thus, fission fragments are produced at a rate of about 2.5×10^8 per second. Those emitted in the proper direction (about one in 10^5) travel down the tube and are analyzed in the magnet which focuses them to a line (for a given $H\rho$) on the focal plane six feet beyond; there they are stopped in a 0.001-in. aluminum foil. After a bombardment of some hours, the foil is removed and cut into strips, each strip corresponding to a given $H\rho$. These are then radiochemically processed for a given fission product, and the resulting activity is measured with end-window Geiger counters. The 17-hour activity of zirconium-97 was used for most of the measurements reported here.

The magnet is a 40-degree wedge with a uniform magnetic field; the strength of the field is set so that the radius of curvature for the fragments being received on the focal plane is between 38 and 41 inches. The path length through the magnetic field is about 27 inches. The fragments enter and leave at approximately normal incidence to the magnet edges; thus, there is no vertical focusing. The beam is defined by a 1-in. high slit at the entrance end of the magnet and a 1-in. high by 8-in. wide slit at the exit end; at the focal plane it is about $2\frac{1}{4}$ inches high. The dispersion of the system is about 0.71% in $H\rho$ per inch along the focal plane.

A 0.1-millicurie plating of Po^{210}, 1 in. high by $\frac{1}{8}$-in. wide, is installed beside the U^{235} source for calibration purposes. The alpha particles pass through a slit at the focal plane and out of the vacuum through a thin Mylar window. They are then detected by an end-window Geiger counter operated as a proportional counter. The line shape is determined by measuring the counting rate as a function of magnetic field. The alignment of the system was accomplished by finding the geometry which gives the narrowest line width (it was within $\frac{1}{2}$ inch of the calculated position). The resolution of the system can be determined from this line width. It is 0.25% as measured, or about 0.15% after corrections for the finite geometry. The polonium source is also used for routine energy calibrations, and is useful in several tests to be discussed below.

Since polonium alpha particles are focused at about half of the magnetic field used for fission fragments, there might be some question about the optics of the system at the higher fields. In order to check this, a 30-millicurie polonium source was put into the system prior to installation in the reactor. This allowed measurements to be made on the singly charged alpha particles from polonium, which are focused by about the same magnetic field as fission fragments. The resolution was found to be the same as for the doubly charged alpha particles.

To protect against multiple scattering in the 16-foot aluminum tube, four approximately equally spaced diaphrams with $2\frac{1}{4}$ in. inside diameter are installed in the tube. The diaphrams are of 0.001-inch aluminum foil which is opaque to fission fragments but thin enough to avoid edge scattering difficulties.

The catcher foil is usually covered during the bombardment with a 0.6-mg/cm^2 plastic film to assure that fragments moving with thermal velocity are not collected. Identical results were obtained, however, with and without this cover film.

Since the counting rates on the final samples are quite low, each was counted under a separate counter for a period of about 15 hours, with automatic recording. In addition, a 5-hour background was taken almost daily. The various counters were cross calibrated at frequent intervals with phosphorous-32 sources. A test showed that cross calibration with these gives the same relative efficiencies as a cross calibration with zirconium-97 samples. All data presented in this paper represent averages of a number of runs in each of which the sample for a given $H\rho$ was counted in a different counter.

The magnet contains $3\frac{1}{2}$ tons of steel and $\frac{3}{4}$ ton of copper. The yoke and poles were assembled from pieces cut from a four-inch steel plate with a cutting torch; with one slight exception, no machining was done except on the pole tips. The two-inch gap is maintained uniform with a brass spacer at each corner. Magnetic measurements indicated that the field is uniform to better than 0.01%, except near the edges. The field fall-off at the entering and exit edges was also carefully measured; the largest effect tending to reduce resolution was due to the difference in the fall-off pattern on the median plane and near the pole face, which, according to the measurements, should introduce a line width of about 0.1%. The magnetic field is measured with a Varian nuclear fluxmeter which utilizes the proton magnetic moment; the accuracy of measurement is about 0.05%. The drift of the field during a run is kept below 0.1% by maintaining careful temperature control at the regulator.

The vacuum system consists of a well-baffled, 300-liter/sec oil diffusion pump backed by a 110-liter/min mechanical pump. They maintain a vacuum of about 0.8×10^{-5} mm Hg, as measured with a triode-type ionization gauge at the pump header. Upon closing the diffusion pump valve, the ion gauge reading increases rapidly at first, and then continues to rise slowly and linearly with time. By extrapolating the linear rise back to the time when the valve was closed, a more accurate measurement of the average pressure in the system is obtained; it is about 1.1×10^{-5} mm Hg.

As installed at the reactor, the system requires a large amount of shielding. A one-ton beam catcher is placed just beyond the magnet in line with the reactor hole, and other shielding includes about 700 pounds of paraffin, 2000 pounds of lead bricks, 25 square feet of cadmium sheet, and a 30-gallon water tank.

RESULTS

In measuring energy distributions of fission fragments by magnetic analysis, a complication arises from the fact that these fragments do not occur in only a single charge state, but rather with a charge distribution centered at about 20 electronic charges. The $H\rho$ distribution thus consists of the momentum distribution repeated (with different weighting factors) at intervals of about 5% in $H\rho$. If the total width of the momentum distribution is much less than 5%, this produces little difficulty since the entire distribution may be studied at any given charge. However, if the momentum distribution is wider than 5%—i.e., if the width of the energy distribution is wider than 10%—considerable trouble will result from overlapping of the distributions from various charges. Although it was not expected when the experiment was first undertaken, this turned out to be the case encountered here.

The measured $H\rho$ distribution is shown in Fig. 1. Each set of points represents an average of about five separate runs. The errors shown are standard deviations as judged from reproducibility of the data. It should be noted that the ordinate scale is considerably expanded and does not go to zero. The errors are about 1.5 to 2%. The arrows show the position of the most probable energy, $\bar{E}$, for each charge; the method of obtaining these will be described below. It is quite clear that there is very considerable overlap between the distributions corresponding to different charges; this indicates that $\Delta E/\bar{E}$ is greater than 10%.

To make these considerations more quantitative, the expected $H\rho$ distributions were calculated for various ratios of width (i.e., full width at half-maximum) to separation of the momentum distributions from consecutive charges. Some of the results for Gaussian distributions are shown in Fig. 2, where relative populations of consecutive charges are assumed to be 0.8–1–1–0.8. From Fig. 2 it may be seen that the percentage dip between the peaks is determined almost exclusively by the ratio of width to separation, and is quite insensitive to the relative charge populations. This was checked and found to be valid for a large number of cases other than those shown. To test the sensitivity of these calculations to the assumption of Gaussian distributions, a similar study was made of all distributions of the form $N\propto\exp[-a|\rho-\bar{\rho}|^n]$. For n between 1 (the limiting case of sharp peakedness for this class of functions) and 3 (a relatively wide distribution), the width-to-separation ratio which produces a given percentage dip between the peaks differs from the Gaussian case ($n=2$) by less than 10%. For n greater than 3, the distributions become quite "square"; combinations of them could not fit the data. In the discussion below, Gaussian distributions are assumed; it should be understood that the results quoted may be slightly different if the distributions are markedly non-Gaussian.

In comparing the curves of Fig. 2 with the data of Fig. 1, the curve which fits the data best (solid line) is seen to correspond to a width-to-separation ratio of about 1.18. This corresponds to $\Delta E/\bar{E}=11.9\%$. The

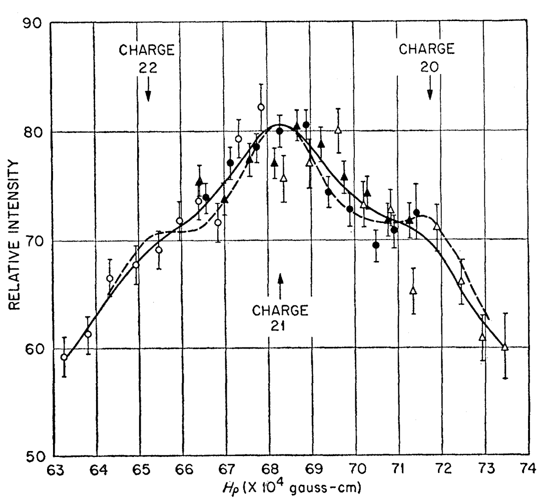

FIG. 1. $H\rho$ distribution for mass-97 fragments with 40-μg/cm^2 source. Note that ordinate does not go to zero. Each point represents an average from about five runs. Solid line represents best line through the data, and dashed "– – – line is distribution expected if width is minimum stated in text."

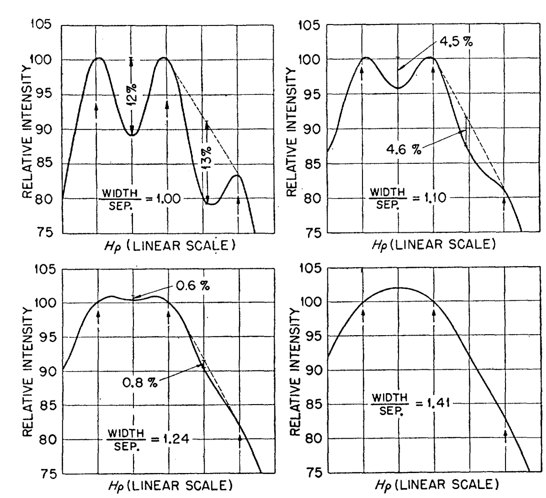

FIG. 2. Distributions expected for various values of the width to separation between successive distributions. It is assumed that the distributions are Gaussian and the ratio of populations of successive charge states is 0.8–1–1–0.8.

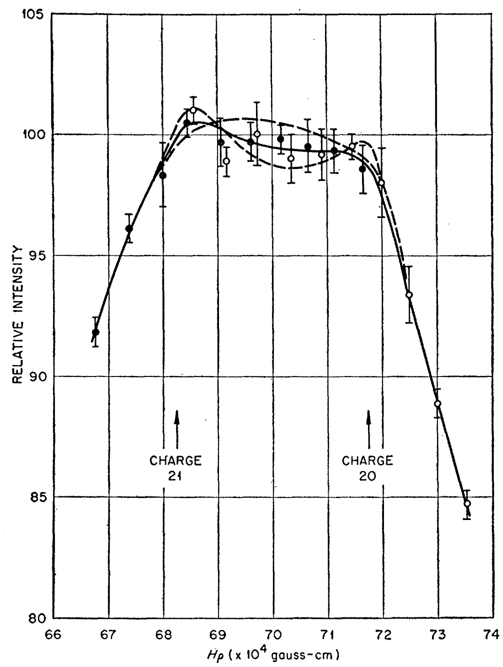

FIG. 3. $H\rho$ distribution for mass-97 fragments with 150-μg/cm^2 source.

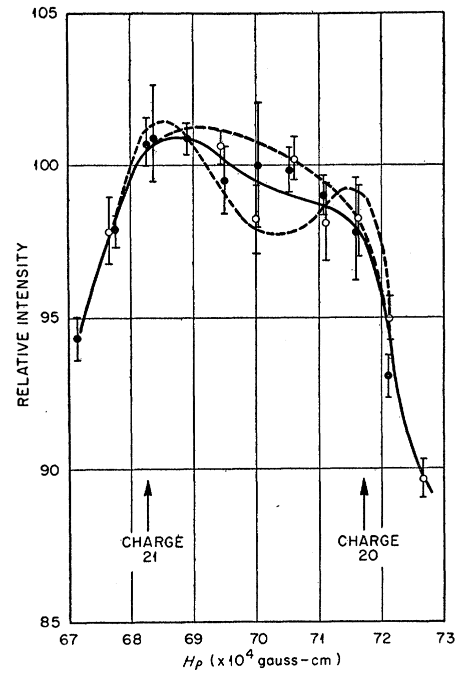

FIG. 4. $H\rho$ distribution for mass-97 fragments with 150-μg/cm^2 source. These data were taken about one month after the data in Fig. 3.

largest dips between the peaks (dashed curve) that are consistent with the data correspond to a width to separation ratio of 1.10, or $\Delta E/\bar{E}=10.9\%$. No upper limit on the width can be surmised from Fig. 1, as a very smooth curve could be drawn through the data within satistical accuracy.

To determine an upper limit, more accurate data are required. Therefore, the original U^{235} source was replaced with a 150-μg/cm^2 sample, 1 inch wide. This gives about ten times higher intensity. It introduces a 4% experimental width into the energy distribution, but since the intrinsic width is about 12%, this is a relatively minor correction. The increased intensity allows samples to be run in duplicate, thus doubling the rate of data accumulation; it also leads to improved counting accuracy because the counting errors inherent in counting close to background are eliminated.

The data obtained with this source are shown in Figs. 3 and 4. The values of $H\rho$ are corrected for the source thickness. The data in Fig. 4 were taken about one month later, and the slight shift in the relative population of the charge states may be explained as due to a very thin film of material accumulating on the surface. For example, a film thickness of 10^{-8} g/cm^2 (a fraction of one atom thick) could account for the shift. This would not affect the energy distribution, and, in fact, no shift was observed in the energy of the alpha particles from the polonium which would be covered with the same film. A similar explanation could account for the much larger difference between the relative charge populations in this data and the data in Fig. 1.

In comparing the data in Figs. 3 and 4 with the curves in Fig. 2, it may be observed that there are many qualitative differences between the data and the theoretical curves for very large widths. The latter show almost no slope change at the position of the most probable energy for each charge, whereas very definite slope changes are observable from the data. For the case where the charge population of two consecutive charges is equal, the theoretical curves have a maximum halfway between, whereas there is no evidence for this in the data. After a detailed comparison, an upper limit of width-to-separation ratio of about 1.32 is obtained from both Figs. 3 and 4. Corrected for source thickness, this corresponds to $\Delta E/\bar{E}=13.1\%$. The best line through the data gives a width-to-separation ratio $=1.24$ or $\Delta E/\bar{E}=12.0\%$, and the largest possible dip between the peaks consistent with the data gives $\Delta E/\bar{E}=10.8\%$. When these results are combined with those from Fig. 1, the most probable value for $\Delta E/\bar{E}$ is about 12.0%. Since the same lower limit, about 10.8%, was obtained in three independent measurements, it is very unlikely that the actual value is that low. A more realistic lower limit is perhaps 11.2%. The upper limit by the same reasoning, is about 12.8%. Thus, the final result is $\Delta E/\bar{E}=12.0\pm0.8\%$. The distribution observed here was widened by the emission of prompt neutrons. When this is taken into account, the width before emission of prompt neutrons becomes $\Delta E/\bar{E}=11.4\pm0.8\%$.

Because of the variation in the number of neutrons per fission, the fragments detected in this experiment correspond to a distribution of masses in the original fission which is perhaps three mass units wide. The amount by which this widens the observed distribution cannot be estimated without a theory. However, in view of the very strong evidence that the kinetic energy is due to Coulomb repulsion, it seems reasonable to assume that the energy variation between different mass splittings is roughly proportional to the product of the nuclear charges of the two fragments. For the case under consideration, this would cause the most probable energy for the various fragment masses to be spread by about 1–2%. In accordance with the properties of Gaussian distributions, this should produce no widening of the observed distribution.

According to Fig. 2, the maximum of the $H\rho$ distribution does not necessarily correspond to $\bar{E}$; the deviation may be considerable when populations of successive charge states are approximately equal. To determine $\bar{E}$, it is therefore desirable to make measurements with various relative charge populations.

This was accomplished by operating the system at a slightly increased pressure, so that fragments undergo electron pickup collisions with air molecules in the 16-foot path from the source to the magnet. The probability for a charge-changing collision in the magnetic field must be kept small as this removes particles from the beam and converts them into background. The pressure is therefore adjusted to give approximately one collision between the source and magnet; the probability for a collision in the magnet is only 14% since the path length is shorter by that factor. The $H\rho$ distributions for two different pressures is shown in Fig. 5, and the best lines through the data of Figs. 1, 3, and 4 are also reproduced there. Sharp changes of slope are seen at $H\rho=682\,500$ and 717 500 gauss-cm. The separation between these values is just the expected separation between consecutive charges. It seems safe, therefore, to conclude that these values correspond to $\bar{E}$ for two consecutive charges. If these charges are taken as 20 and 19, $\bar{E}=158.5$ Mev. If they are taken as 21 and 20, $\bar{E}=174.7$ Mev. The uncertainties in these energies is about ± 2 Mev. Charges other than those assumed here would give energies inconsistent with time of flight[3] and calorimeter[4] measurements of the total kinetic energy release in fission.

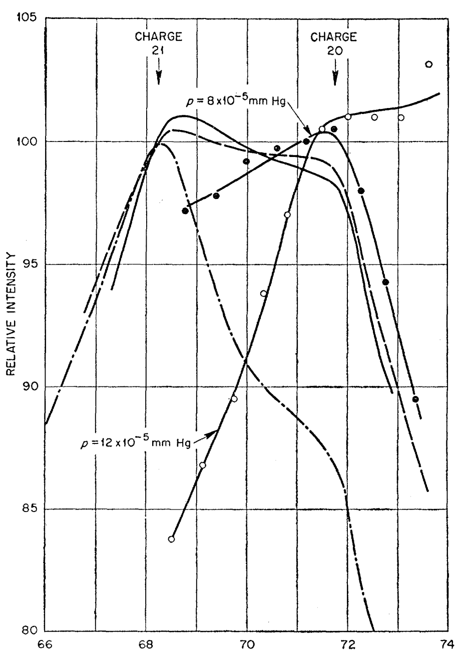

FIG. 5. $H\rho$ distributions for mass-97 fragments with the system operated at increased pressures. Curves without data points are from Figs. 1, 3, and 4.

In order to determine which of the two energies is correct, measurements were made of the $H\rho$ distribution of mass-91 fragments by doing the radiochemical analysis for Sr^{91}; the results are shown in Fig. 6. The maximum at $H\rho=688\,000$ corresponds to $\bar{E}=164.5\pm3$ Mev for mass 91. According to the ionization chamber[1] and time-of-flight[3] data, the total energy release in the mass-97 fission mode is about 5% higher than in the mass-91 mode, so that the larger of the two values of $\bar{E}$ for mass 97 is most probably the correct one.

The data in Fig. 5 may be used to determine the difference between the electron pickup and loss cross sections for these fragments in air. The measurements were made between taking the data of Figs. 3 and 4; it thus appears that a pressure of 12×10^{-5} mm Hg results in an average of a little *more* than one net electron pickup, while a pressure of 8×10^{-5} mm Hg results in an average of a little *less* than one. Thus, the pressure required to give an average of one net electron pickup is about $(10\pm1)\times10^{-5}$ mm Hg. This corresponds to an electron-pickup minus electron-loss cross section of $(3.7\pm0.4)\times10^{-16}$ cm^2. This is in fair agreement with Bohr and Lindhard's theoretical value[7] of 2.7×10^{-16} cm^2 made up of 3.3×10^{-16} cm^2 capture cross section and 0.6×10^{-16} cm^2 loss cross section. The pickup cross section must be much larger than the loss cross section since the equilibrium charge for air is about 16 electronic charges.

CRITICAL ANALYSIS OF THE EXPERIMENT

It hardly need be pointed out that the relatively large energy widths found in this experiment bear a striking resemblance to the results of an experiment done improperly. It is therefore quite important to make a critical analysis of the various factors that could introduce line broadening. The most obvious difficulty would be in the optics of the system. This, however, is excluded by the extremely narrow distributions continually obtained for polonium alpha particles, both doubly charged and singly charged. Any

[7] N. Bohr and J. Lindhard, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. 28, 7 (1954).

possible difficulty must therefore be of a type which does not affect alpha particles in the same way.

The fission fragments differ from the alpha particles in that they originate in a different source foil, they have different scattering properties, their observed energy distribution would be affected by electron pickup or loss in the magnetic field, they are detected differently, and the measurements are integrated over much longer times.

(*a*) *Uranium Source*.—The uranium foils were scanned by alpha-particle counting and found to be macroscopically uniform in thickness to within 10%. To investigate the microscopic uniformity, a piece from the 40-μg/cm^2 plating was used to measure the alpha-particle energy spectrum from U^{234} with an ionization chamber spectrograph.[8] The width of the peak was equal to the resolution of the instrument, which would exclude the possibility that an appreciable fraction of the plating was thicker than 100 μg/cm^2. The low-energy tail on the measured spectrum was approximately what might be expected from a source 100 μg/cm^2 thick, but it could also be explained by the presence (with 3% intensity) of alpha particles of lower energy than those leading to the ground and first excited states of daughter nuclei. In any case, the effective thickness seems to be no more than 100 μg/cm^2, and even this would not cause significant broadening of the observed spectrum.

There is also a possibility of a thin layer of absorping material covering the uranium after installation in the reactor. However, two different sources were used, and there was no evidence of anything covering the polonium which was mounted beside it. Also, the position of the fission-fragment peaks did not change with time over several months. The source was also visually inspected and appeared clean.

(*b*) *Multiple Scattering*.—If the fragments were multiply scattered from various parts of the tube between the source and detector, the effective size of the source would be very large and would cause the observed distribution to be broadened. Actually, this should not be considered here since multiple scattering is considerably *worse* for polonium alpha particles than for fission fragments. The effects were carefully investigated, however, and four different slit systems were used without any observable difference in the results. According to the calculations, these systems ranged from barely adequate to completely adequate. Multiple scattering from air molecules is negligible by many orders of magnitude at these pressures.

(*c*) *Electron Pickup or Loss in the Magnetic Field*.—An electron pickup or loss collision in the magnetic field removes the fragment from the beam and adds it to background; if there were an appreciable probability for this, the distributions could be seriously broadened.

[8] The alpha-particle spectrograph measurements were made by C. J. Borkowski and E. Fairstein of this Laboratory.

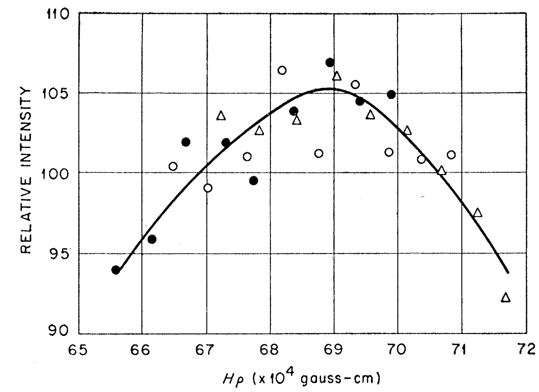

FIG. 6. $H\rho$ distribution for mass-91 fragments with 150-μg/cm^2 source.

According to the measurement of the electron pickup cross section discussed previously in connection with Fig. 5, the probability for such a collision with an air molecule is about 1.8%, which is quite negligible. To lessen the possibility of such collisions with the chamber walls in accompaniment with a slight multiple scattering which returns the fragment to the beam, slits of 0.001-in. aluminum foil were inserted at each end of the magnetic field. The geometry was such that fragments from all but the upper and lower 10% of the source could not touch the chamber walls without being scattered from the entrance slit, and the remaining 20% would require a very large multiple scattering to pass the exit slit. Only one fragment in 10^4 could be scattered from these slits. Measurements were also made with the slits removed, and although a rough calculation indicated that the effect might not be negligible if the alignment was poor, no difference in the results was observed. The relative intensities with and without slits also indicated that the alignment was satisfactory.

Some consideration was also given to the possibility that electrons might be lost from the fragment because of electromagnetic interaction with the magnetic field. The effect was calculated by the method of Oppenheimer[9] and was found to be much too small. In addition, the effect, if present, should be extremely sensitive to the magnetic field strength. The same $H\rho$ can be observed at different parts of the focal plane with magnetic fields differing by as much as 6%, and no intensity differences can be detected.

(*d*) *Detection*.—The observed energy distribution could be spread if the chemical decontamination from other fission products were not complete. To test this, a sample containing all fission products from which difficulties in chemical separation might be expected was processed, and no activity was found in the zirconium fraction. The procedure is a much used and well established one; and the decay of the final precipitate, including the complexity introduced by the grow-in of the 72-min daughter activity is exactly as expected.

[9] J. R. Oppenheimer, Phys. Rev. 31, 66 (1928).

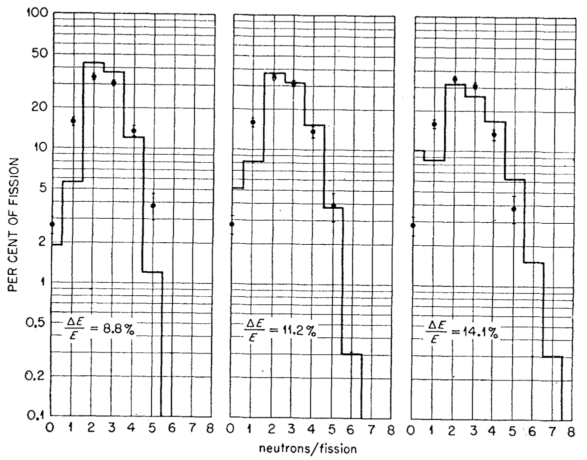

FIG. 7. Distribution of number of neutrons per fission. Solid lines are results calculated for various assumed widths of the energy distribution. Data points are from reference 11.

In addition, the highly quantitative reproducibility of the data between various runs would seem to exclude the possibility of appreciable contamination.

Difficulty could also result if the activity observed were produced by neutron activation in the aluminum or some other such process. The aluminum was analyzed for impurities and the effect was calculated and found to be completely negligible. Also, an aluminum foil stored nearby for several weeks was processed and no activity was observed. There is every evidence that the activity being observed originates in the source, as it was found to be proportional to the mass of uranium in three separate sources. It is also quite certain that it is sensitive to the magnetic field; in one group of experiments, the relative intensity was followed continuously through three orders of magnitude by varying the magnetic field.

(*e*) *Instrumental Time Variations.*—Since the results of fission-fragment runs are integrated over many hours, whereas the polonium alpha-particle measurements take only a few minutes, the observed fission-fragment distributions would be broadened if the magnetic field or the alignment of the system varies with time. The magnetic field was measured at frequent intervals in many runs, and was always measured at the beginning and end of each run. No variations larger than 0.1% were ever observed. The positioning of the plate on which the catcher foil is mounted was set and routinely checked with a plumb bob attached to a building column. Movement of the magnet or the source would appear to be impossible; in addition, the position of the polonium alpha line did not vary in a number of checks made over a period of several months.

Some additional confidence in the validity of this experiment was obtained from experiments in which the system was filled with gases to relatively high pressures. In these experiments the charge changes in the magnetic field so frequently that the magnetic deflection is determined by the average charge, and only a single peak is obtained. By operating at 5.7 mm Hg of helium, a distribution 3.6% wide was obtained; this width is completely explained by the statistics of the charge changing process. Unfortunately, this method cannot be used for measuring the width of the energy distribution since the equilibrium charge changes with energy in such a way as to almost completely compensate the effect of the inhomogeneous energy distribution.

CORRELATION WITH THEORY AND OTHER EXPERIMENTS

The kinetic energy distribution of fission fragments is closely correlated with the distribution of the number of neutrons per fission. This arises from the fact that the latter quantity is determined, at least statistically, by the excitation energy of the fragments, and the sum of the excitation and kinetic energies is a constant. Calculations were therefore made of the distributions of the number of neutrons per fission to be expected for various widths of the energy distribution. The binding energies of the various neutrons were taken from the calculations of Metropolis and Reitwiesner[10] and the energy distribution with which the neutrons are emitted (except the last neutron) was replaced with a delta-function at 1.5 Mev. The most probable excitation energy was obtained from the condition that the total number of neutrons is 2.5; it was 22 Mev. Various distributions of this energy between the two fragments were assumed and the results averaged over with arbitrarily assigned weights. The final results are shown by the solid lines in Fig. 7 for three different assumed widths of the fission fragment energy distribution. The data points are from the measurements of Diven *et al.*[11] The fit is not very satisfactory as regards the ratio of probabilities for zero and one neutron. This is very difficult to understand, as this part of the calculation is quite independent of the simplifying assumptions.* However, the general fit is quite satisfactory for $\Delta E/\bar{E}=11.2\%$. For $\Delta E/\bar{E}=8.8\%$, the calculated distribution is much too narrow to fit the data, and for $\Delta E/\bar{E}=14.1\%$, it is much too wide. These results can be expressed roughly as $\Delta E/\bar{E}=11.2\pm1.5\%$. This is in good agreement with the result from the present experiment, $\Delta E/\bar{E}=11.4\pm0.8\%$. A calculation of the distribution of the number of neutrons per fission has recently been reported by Leachman.[12] He used the energy distributions from ionization chamber data[1] as

[10] N. Metropolis and G. Reitwiesner, Atomic Energy Commission Report NP-1980 (unpublished).

[11] Diven, Martin, Taschek, and Terrell, Phys. Rev. **101**, 2011 (1956).

* *Note added in proof.*—It has been found that this discrepancy is removed if it is assumed that there is no correlation between the excitation energies of the two fragments, see reference 12. This seems very strange since much of the excitation arises from deformation energy, and it would seem quite certain that the deformation energies of the two fragments are strongly correlated.

[12] R. B. Leachman, Phys. Rev. **101**, 1005 (1956)

corrected for experimental resolution, and made different simplifying assumptions, so that it is difficult to compare his calculation with the above.

The results of this experiment may also be compared with the predictions of Fong's[5] theory of the fission process. Figure 8 shows the Coulomb energy and the Coulomb-plus-deformation energy plotted against α_{31}, the coefficient of the third Legendre polynomial in an expansion of the shape of the light fragment. These curves were calculated by the methods of reference 5. From Fig. 8, the minimum of the Coulomb-plus-excitation energy, and hence the maximum excitation energy, occurs at $\alpha_{31}=0.024$; this is therefore the most probable deformation.

Fong's expression for the probability, Ω, of a given fission mode is

$$\Omega(\epsilon)=C\epsilon^{\frac{3}{4}}\exp[2(a\epsilon)^{\frac{1}{2}}]. \qquad (1)$$

In (1), ϵ is the total excitation energy eventually available for emission of neutrons minus the distortion energy. From data on the average number of neutrons per fission, the former is about 22 Mev for the most probable mode, and from Fig. 8 the latter is about 13 Mev for the most probable mode; thus $\epsilon \simeq 9$ Mev. The quantity a in (1) is the sum of the Weisskopf energy level density parameters for the two fragments, which, was taken by Fong to be 11.5 Mev^{-1}. By using these values in (1), Ω drops to half its maximum value when E decreases by 0.58 Mev. From Fig. 8, this corresponds to half-maximum probabilities for the Coulomb energy at 177.2 Mev and 167.7 Mev. The Coulomb energy at this point eventually becomes the kinetic energy, so that this calculation gives $\Delta E/\bar{E}=5.5\%$. This is in violent disagreement with the experimental value given here, $\Delta E/\bar{E}=(11.4\pm0.8)\%$. In going over the above calculation, it appears that it is very insensitive to all parameters used except a. The value of a required to reproduce the experimental value of $\Delta E/\bar{E}$ is about 3.5 Mev^{-1}, which is about the value of a expected for nuclei of mass 60. One possible interpretation of this result is that the excitation is shared among only 60 nucleons in each fragment. In any case, however, the modification of a completely destroys Fong's very impressive fit to the experimental mass distribution. Since this fit to the mass distribution has been by far the most convincing argument for the validity of Fong's theory, the experimental result obtained here would seem to reduce considerably one's confidence in that theory.

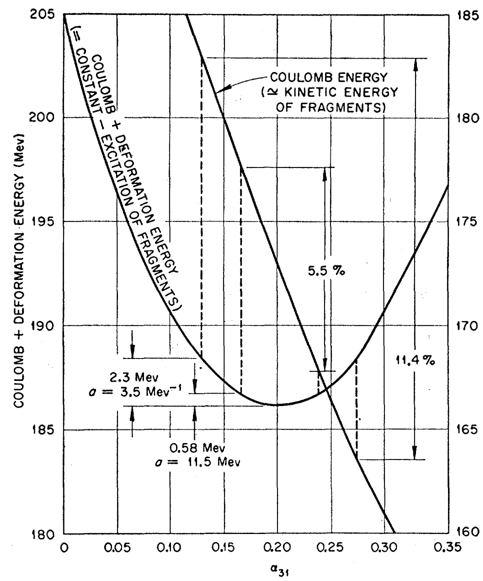

FIG. 8. Calculation of energy distribution from Fong's theory. See discussion in text.

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