(c) *Solutions of type C.* The solutions of this type have as non-vanishing components

$$J=\alpha P_j^m,\quad \mathbf{A}=\zeta\mathfrak{Y}_j^m,$$
$$\mathbf{G}=\gamma\mathfrak{X}_{j-1}^m+\Delta\mathfrak{Z}_{j+1},\quad \mathbf{U}=\epsilon\mathfrak{X}_{j-1}^m+\eta\mathfrak{Z}_{j+1}^m, \tag{33}$$

where α, ζ, γ, Δ, ϵ, and η are functions of r. This type of solution has a parity $(-1)^{j+1}$ under a reflection through the origin.

In the case $j=0$ the equations are fairly simple and one obtains the $^3P_0$ solution discussed in the preceding section. For larger values of j the equations, and also the boundary conditions giving the energy, are somewhat complicated and will therefore not be given here.[7]

For $j=1$ the solution is a mixture of $^3S_1$ and $^3D_1$ (with small amounts of $^3P_1$ and $^1P_1$, the proportions of these increasing as one goes to higher excited states). The lowest state of this type has an energy

$$\text{for } \sigma=\hbar/Mc,\quad W=0.165Mc^2,$$
$$\text{for } \sigma=a_0,\quad W=0.15486Mc^2,$$

where the value has been written with excessive precision to show its relation to the energy of the ground state. For $j=2$ the solution is largely a mixture of $^3P_2$ and $^3F_2$. The lowest state of this type has energy values $0.180Mc^2$ and $0.15494Mc^2$ for the above ranges, respectively. The preceding results are summarized in Table I.

In conclusion it should be emphasized that the numerical values for the energy levels are not significant because of the approximation introduced by the use of the square-well interaction. However, it is interesting that there are a number of different states lying close to the ground state with angular momenta 0, 1, and 2. These would be interpreted as particles with nearly equal masses and spins 0, 1, and 2. Further measurements and analysis of data on π-mesons should show whether variations in mass and spin actually occur.

[7] These will be found, in different notation, in reference 2. However, in Eq. (21b) of that paper there appears to be an error of sign in the third term of each of the two factors on the left-hand side.

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The Emission of Long-Range Charged Particles in the Slow Neutron Fission of Heavy Nuclei

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Light charged particles with ranges greater than 6 cm of air produced in the slow neutron fission of U^{233}, U^{235}, and Pu^{239} have been studied in detail by coincidence counting methods. In each case particles with a continuous range distribution extending to about 50 cm of air were observed, the distribution showing a broad maximum in the neighborhood of 20 cm. Direct measurement of the energies of the light particles from U^{235} showed a fairly symmetrical distribution about 15 Mev with a maximum energy of about 26 Mev. Comparison of the energy and range distributions shows that all the long-range particles are α-particles. The frequency of emission of these α-particles was found to be

1 in 405±30 fissions for U^{233},

1 in 505±50 fissions for U^{235}, 1 in 445±35 fissions for Pu^{239}.

No protons were observed, although the apparatus would have detected any with ranges lying between 10 and 100 cm of air. The energy distribution of fission fragments coincident with long-range α-particles was also measured. The usual two peaks were observed indicating asymmetric division of mass, but each peak was shifted to a lower energy than is observed in binary fission. Quantitative comparison of the energies involved showed that, on the average, the total kinetic energy carried away in fission accompanied by α-emission is about equal to that liberated in binary fission. Possible explanations for α-emission in fission are discussed.

I. INTRODUCTION

The occasional emission of light charged particles in the fission of uranium by slow neutrons seems to have been noticed first by Alvarez.[1] Subsequent investigations in several laboratories using coincidence counting techniques and uranium-loaded photographic emulsions have confirmed and extended the original observations. Farwell, Segrè, and Wiegand,[2] using a coincidence arrangement, reported that light particles with ranges up to 23 cm of air are produced in about 0.4 percent of fission events in U^{235} and in 0.2 percent of fissions in Pu^{239} by slow neutrons. By comparison of the ionization of the light particles with that of α-particles from polonium it was shown that they were probably α-particles, a conclusion in accord with the majority of measurements of grain density in photographic emulsions.[3-7] On the other hand, the work of Tsien and his associates[8] suggests that not all the light

[1] L. W. Alvarez, mentioned in reference 2. Earliest publications in the open literature are by Green and Livesey, Proc. Int. Conf., Cambridge, July, 1946, and Tsien, Chastel, Ho, and Vigneron, Comptes Rendus **223**, 986 (1946).
[2] Farwell, Segrè, and Wiegand, Phys. Rev. **71**, 327 (1947).
[3] P. Demers, Phys. Rev. **70**, 974 (1946).
[4] Wollan, Moak, and Sawyer, Phys. Rev. **72**, 447 (1947).
[5] L. L. Green and D. L. Livesey, Phil. Trans. A **241**, 323 (1948).
[6] L. Marshall, Phys. Rev. **75**, 1339 (1949).
[7] E. W. Titterton (unpublished). We are grateful to Dr. Titterton for communicating to us some of his results prior to publication.
[8] Tsien, Ho, Chastel, and Vigneron, J. de phys. et rad. **8**, 165, 200 (1947).

particles are α-particles, but that some have masses as great as 9. In addition to the long-range particles, Cassels, Dainty, Feather, and Green[9] discovered the existence of a more abundant group of particles with ranges of about one cm of air accompanying the fission of uranium by slow neutrons. The observed frequency of emission of the short-range particles was about 1 in 25 fissions, assuming that they were emitted isotropically with respect to the direction of fission fragments. Subsequent angular distribution data indicate that this figure should be reduced to about 1 in 90 fission events.[5] Evidence for the emission of long-range particles in the photo-fission of uranium and thorium has recently been obtained by Titterton and Goward[10] and Titterton and Brinkley.[11]

A detailed investigation of light charged particles of all ranges emitted in the fission of U^{235} by slow neutrons has been made by Green and Livesey[5] and by Tsien, Ho, Chastel, and Vigneron.[8] These investigators observed fission events produced by slow neutrons in uranium-loaded photographic emulsions. It was found that both long-range and short-range particles are emitted preferentially at angles near 90° to the fission tracks, being slightly inclined towards the lighter fragment. The spread in angle of emission relative to the fission fragments is greater for the short-range particles than for the long-range particles,[12] although long-range particles are occasionally emitted at quite acute angles.[7] Only short-range particles have been observed in the fission of uranium and thorium by fast neutrons.[8,13]

The coincidence experiments of Farwell *et al.* and Cassels *et al.* show that the light particles are emitted within a time interval less than about 10^{-5} second of the instant of fission. Using a modified photographic plate in which the fissionable material was contained in a very thin film between two layers of emulsion, Demers[3] was able to show that the light particles are emitted within an interval less than 2×10^{-14} second after the fission has occurred. This result is consistent with the angular distribution observed, which suggests that the light particle is accelerated in the Coulomb field of the major fragments and must therefore be emitted within an interval not greater than about 10^{-21} second.

The relatively infrequent emission of light charged particles in fission makes the study of the process by the photographic plate method rather tedious if good statistical accuracy is to be obtained. Furthermore, owing to the desensitizing action on the emulsion of the uranyl ion, any energetic singly charged particles which may be produced in fission are unlikely to be observed. The use of the photographic plate method in the study of light charged particle emission in U^{233} or Pu^{239} is not practicable owing to fogging produced by the intense natural α-particle activity. For these reasons, coincidence counting methods were chosen for the experiments to be described. These experiments fall into four groups.

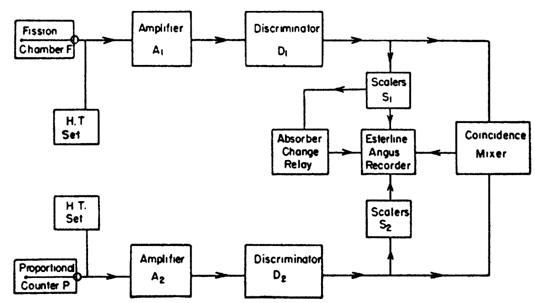

FIG. 2. Block diagram of electronic equipment for range measurements.

(1) Measurement of the range distributions of the long-range particles emitted in the fission of U^{233}, U^{235}, and Pu^{239} by pile neutrons.
(2) Search for singly charged particles and determination of the frequency of emission of the light particles in the fission of U^{233}, U^{235}, and Pu^{239} by pile neutrons.
(3) Measurement of the energy distribution of the light particles emitted in the fission of U^{235} by thermal neutrons.
(4) Measurement of the energy distribution of the major fragments coincident with long-range particle emission.

A brief account of part of this work has already been given.[14] A subsequent paper, now in preparation, will discuss in detail the short-range particles emitted in fission.[15]

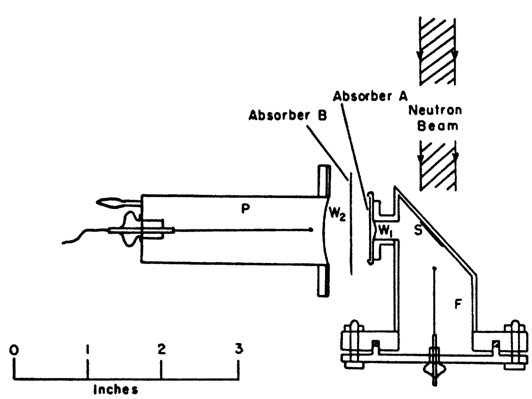

FIG. 1. Fission chamber and proportional counter used to study range distribution of long-range particles.

II. RANGE MEASUREMENTS

The range distribution of the light charged particles was studied by means of the apparatus shown in Fig. 1. A source of fissionable material S (U^{233}, U^{235}, or Pu^{239}), deposited on a platinum foil, was mounted in the fission

[9] Cassels, Dainty, Feather, and Green, Proc. Roy. Soc. A **191**, 428 (1947).
[10] E. W. Titterton and F. K. Goward, Phys. Rev. **76**, 142 (1949).
[11] E. W. Titterton and T. A. Brinkley, Phil. Mag. **41**, 500 (1950).
[12] Tsien San-Tsiang, J. de phys. et rad. **9**, 6 (1948).
[13] Tsien San-Tsiang, and H. Faraggi, Comptes Rendus **225**, 294 (1947).
[14] K. W. Allen and J. T. Dewan, Phys. Rev. **75**, 337 (A) (1949).
[15] J. T. Dewan and K. W. Allen, Phys. Rev. **76**, 181 (A) (1949).

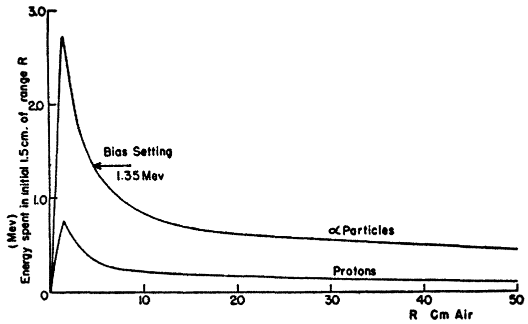

FIG. 3. *Calculated* energy spent in the proportional counter by protons and α-particles of initial range R.

chamber F and irradiated in a well-collimated beam of neutrons from an experimental hole of the Chalk River heavy water pile. A fraction of the long-range particles produced in the fission process was able to emerge through the mica window W_1 and pass into an end-window proportional counter P through a second mica window W_2. Aluminum absorbers A and B could be placed in the path of the light particles. Both the fission chamber and proportional counter were filled with a gas mixture consisting of 90 percent argon and 10 percent carbon dioxide to a pressure of 30 cm of mercury. This mixture resulted in very stable operation and in the production of pulses with rise times of 0.3 μsec. in both counters. In general, the proportional counter was operated with a gas multiplication of about 10.

The discriminator bias in the fission amplifier was set just above the level of the natural α-particles from the source; under these conditions all the fission fragments emerging from the source were counted, regardless of their directions of emission in the hemisphere. Thus there was, on the average, no angular correlation between fission fragments counted in F and long-range particles counted in P. Fission rates in excess of 10^6 counts per minute were generally employed.

A schematic diagram of the electronic equipment is shown in Fig. 2. Pulses from the fission chamber and proportional counter were amplified by similar systems each with a rise time of 0.2 μsec. The amplified pulses, after passing through pulse-height discriminators D_1 and D_2 were fed into a Rossi-type coincidence mixer with a resolving time of 0.56 μsec. Coincident pulses from the mixer were recorded on an Esterline-Angus pen recorder which also marked, after suitable scaling down, the numbers of fission pulses and proportional counter pulses. The final fission scaling unit contained a relay which controlled the position of a gravity-operated toothed wheel upon which were mounted fifteen aluminum absorbers B. In this way the absorber B could be changed automatically after a desired number of fissions, usually 256×10^6, the exact instant of change being indicated on the recording chart by a shift in the baseline. This method of recording had several advantages.

(a) All information was recorded on a single chart.

(b) A time scale was provided by the speed of the chart, which was quite constant, so that the time distribution of the pulses could be observed. Since the pile power was held steady to 0.1 percent, this served as a check on the stability of the counters as well as on the random distribution of the coincidences.

(c) The apparatus was self-recording, and could be operated without attention for long periods.

The fifteen absorbers B included four "infinitely thick" brass disks to stop all long-range particles and hence allow a direct determination of the background coincidence rate. The background obtained in this way agreed with that calculated from individual counting rates and the known resolving time of the coincidence mixer. It was generally less than 10 percent of the true coincidence rate. The aluminum absorbers B were spaced at intervals of about 3 mg/cm^2. Master aluminum absorbers, A, could also be inserted in the path of the particles thus enabling any desired portion of the range distribution to be studied in detail.

The effective length of the counter P, which was calibrated by a source of α-particles of known energy, was 1.5 cm of air. In Fig. 3, the *calculated* amount of energy spent in the counter by protons and α-particles of initial range R is plotted as ordinate against R as abscissa. Thus by suitable bias settings it was possible to distinguish between protons, α-particles, and heavier particles. Preliminary experiments with a source of uranium enriched in U^{235} showed that coincidences were observed only for absorber paths less than about 50 cm of air and for bias settings less than 2.7 Mev. This suggested that at least some of the long-range particles were α-particles with ranges up to 50 cm of air. No evidence was obtained for the existence of more heavily ionizing particles.

A detailed study of the range distribution of the particles was made with a bias setting equivalent to 1.35 Mev; at this setting, only α-particles with residual range on entering the counter lying between 0.75 cm and 4.75 cm were detected (Fig. 3). We may therefore say that the resolving power of the counter for α-particles was 4.0 cm. Furthermore, no singly charged particles could possibly be detected at this bias setting.

The range distribution obtained from a source of U^{235} is shown in Fig. 4. Corrections have been made for the

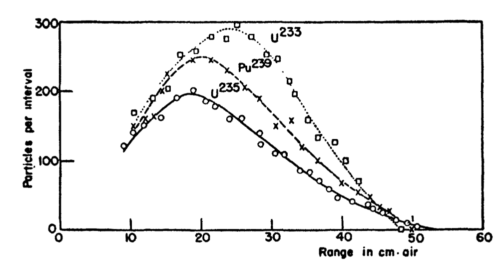

FIG. 4. Range distributions of long-range α-particles emitted in fission.

variation with α-particle energy of the stopping power of aluminum.[16] The total abundance of α-particles per fission was obtained by dividing the area under the curve by the resolving power of 4.0 cm and taking account of the solid angle of detection. This abundance, which was found to be approximately equal to that determined by setting the counter at low bias and detecting all particles passing through it in coincidence with fissions, was 1 in 600±80 fission events in U^{235}. Similar experiments were carried out with sources of U^{233} and Pu^{239}; the range distributions obtained are also shown in Fig. 4. In general, the curves for the three fissionable materials are similar in shape. Small differences are apparent in the positions of the peaks of the distributions and in the maximum ranges, which correspond to α-particles of about 25 Mev. The α-particle abundances were found to be 1 in 470±50 fissions of Pu^{239} and 1 in 370±50 fissions of U^{233} by pile neutrons. Since the abundances obtained by integration of the range distribution curves were equal to those obtained from the coincidence rates at very low bias settings, it seems unlikely that protons are produced in fission. However, protons, if produced in a manner analogous to the α-particles, might be expected to possess considerable energy and hence low specific ionization, so that they would have been difficult to detect in the experimental arrangement used. Further experiments were therefore undertaken to search for protons, and to obtain more accurate data on the frequency of emission of the α-particles.

III. ABUNDANCE MEASUREMENTS

The apparatus used for the abundance measurements is shown in Fig. 5. It consisted of a small fission chamber F placed over a large proportional counter P, the whole volume being filled with a 10:1 argon-carbon dioxide mixture to a pressure of one atmosphere. All fissions occurring in the thin source S were counted in the

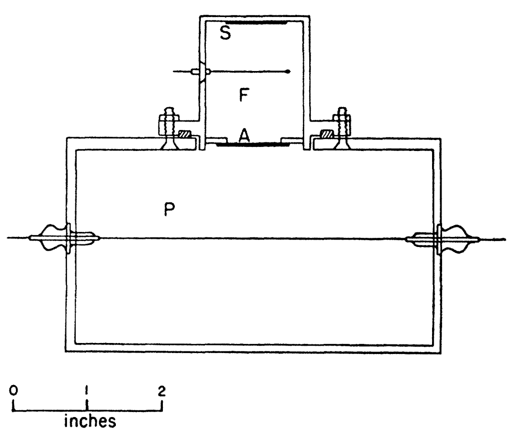

FIG. 5. Apparatus for measurement of frequency of α-emission in fission.

[16] M. S. Livingston and H. A. Bethe, Rev. Mod. Phys. 9, 276 (1937).

chamber F. Long-range particles in coincidence with fissions were counted in P after passage through a 0.001-inch aluminum foil, A, which prevented the entrance of fission fragments into P. The counter P was specifically designed to ensure a large minimum path length, equivalent to 3 cm of air, for particles from the source. The minimum amount of energy spent in P by an α-particle (50 cm initial range) was therefore 0.75 Mev. If only α-particles are emitted in fission the coincidence rate should then be independent of proportional counter bias for settings less than 0.75 Mev. The solid angle of detection in P, *viz.*, $4\pi/91$ steradians, was obtained by calculation and by counting α-particles from a U^{233} source of known strength placed at S, the two values agreeing within 1 percent. The standard source was also used to calibrate the discriminator bias in terms of energy released in the counter P. In order to ensure that no coincidences were lost because of too short a resolving time, a curve of coincidence rate *versus* resolving time was obtained (Fig. 6), and a conservative value of 1.25 μsec. chosen for subsequent measurements.

The integral abundance curves obtained for the three fissionable materials were very similar in nature, a typical one being shown in Fig. 7. There is no evidence for the emission of protons in fission as any significant number with ranges between 10 and 100 cm of air would have been indicated by a distinct rise in the curve below 0.75 Mev. Extrapolation of the bias curves leads to the following frequencies for α-emission in fission (after a correction has been made for those α-particles which are stopped in the aluminum foil):

U^{233}	1 in 405±30
U^{235}	1 in 505±50
Pu^{239}	1 in 445±35.

IV. ENERGY DISTRIBUTION OF LONG-RANGE PARTICLES

The experiments described above suggest that all of the energetic light particles emitted in fission are α-particles. This information is derived from specific ionization measurements which, however, are not sufficiently accurate to eliminate the possibility that at least some of the particles may be He^3, He^6, Li^6, etc. Furthermore, specific ionization measurements are particularly difficult to make and interpret in this case because of the wide spread in particle ranges.

If it is assumed that all of the particles are α-particles, then their energy distributions may be predicted uniquely from the range distributions shown in Fig. 4. We have therefore made a direct measurement of the energy distribution of the particles emitted in U^{235} fission for comparison with the predicted curve. This experiment utilized a back-to-back double ionization chamber, shown in Fig. 8, filled with argon at sufficiently high pressure to stop all the long-range particles in the sensitive region. The source S consisted of about 2.5 mg

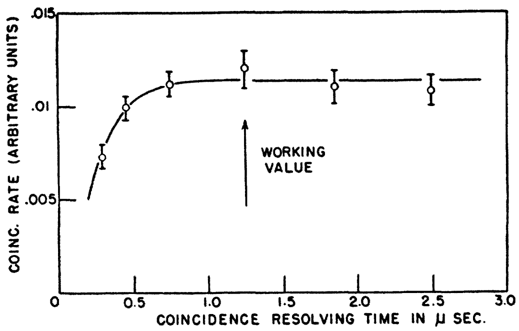

FIG. 6. Coincidence rate *versus* resolving time.

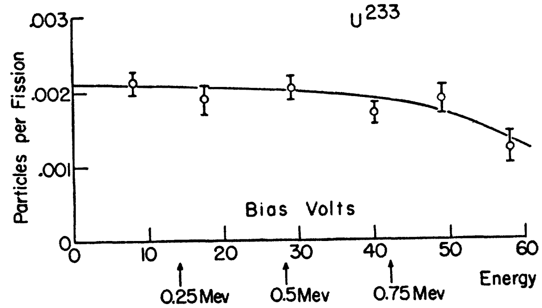

FIG. 7. Frequency of α-emission in fission of U^{233}.

of uranium oxide enriched in U^{235} deposited electrolytically on a 6 mg/cm^2 aluminum foil over a circular area 4 cm in diameter. It was mounted on the central electrode of the double chamber with the active material facing the fission chamber F. The aluminum foil was just thick enough to prevent fission fragments and natural α-particles from entering the chamber P. The long-range particles were collimated so that only those emitted at angles less than 45° to the axis of symmetry were able to enter the chamber. The product of collimator transmission and solid angle of detection was 1/92 of a sphere. The fission fragments were not collimated. The main body of the chamber was constructed from a 5-inch steel cylinder with $\frac{1}{4}$-inch walls, electrode assemblies being mounted on the two end plates for ease of access. A well-defined neutron beam passed axially through the chamber, entering and leaving through $\frac{1}{8}$-inch aluminum windows. Both fission chamber F and α-chamber P contained Frisch grids G_1 and G_2 designed to be about 96 percent efficient in shielding the electron collectors C_1 and C_2 from positive ion effects.[17] The plate-to-grid separation in chamber P was equivalent to 60 cm of air at a pressure of 10 atmos. of argon, so that all long-range particles were stopped in this region. For test purposes, a thin source of U^{233} was mounted in place of the source S, facing the chamber P. Studies of saturation and pulse rise time in the plate-grid region were carried out by connecting a fast amplifier to the grid G_2. With the chamber containing tank argon of 99.96 percent purity at a pressure of 10 atmos., saturation was achieved with a field of about 50 volts/cm. However the pulse rise time, which was about 25 μsec. even with a field strength as high as 500 volts/cm, was much too long for coincidence work. It was found that addition of 0.08 percent of CO_2 reduced this rise time to about 3 μsec., although saturation was then obtained only at fields greater than 250 volts/cm. The energy distribution of α-particles from the U^{233} source, obtained at a pressure of 0.6 atmos. and with electron collection at C_2, is shown in Fig. 9. At this pressure, the range of the α-particles is about the same as that of the most energetic long-range particles at a pressure of 10 atmos. The half-width of the α-particle distribution shows that the resolution of the chamber is about 5 percent. At higher pressures, the distribution was slightly broader, but the broadening could be accounted for by energy loss in the collimator.

The test source was removed and the fissile source S was inserted. In addition a very low activity Pu^{239} α-particle source was attached to the central electrode on the long-range particle side for energy calibration purposes. The source S was then irradiated in a beam of neutrons, and coincidences were sought between long-range particles and fission fragments. With the maximum neutron intensity, a large background of small pulses in the chamber P was encountered due to the effects of γ-rays and fast neutrons. This was an intrinsic difficulty of the experiment, since the extensive path length required to stop long-range particles in the chamber gas necessarily resulted in production of large pulses from the background ionization. Considerable reduction in the background was, however, effected by utilizing a neutron beam from the thermal column of the pile instead of one from an experimental hole. The effect was further minimized by working at low levels of intensity, and to this end a special circuit was developed for recording directly the sizes of individual α-particle pulses coincident with fission fragments. Thus good statistics were obtained with much lower counting rates than would otherwise have been possible. Only a brief account of the electronic arrangements (Fig. 10) will be given here as a detailed description is to be published elsewhere.

Amplified pulses from the chamber P were fed into a coincidence gating circuit. Those pulses coincident with a fission pulse passed through the gate unchanged; those not coincident with fissions were suppressed. Pulses passing through the gate were then lengthened in a two-stage peak voltmeter circuit and recorded on the chart of an Esterline-Angus recorder. The amplitude of the pulse finally written on the chart was proportional to the input pulse within 2 percent. The chart was calibrated in energy by means of α-pulses from the Pu source in the chamber P. Proper operation of the circuit required that there be no delay in the pulse triggering the gate; hence fission pulses were taken from the grid G_1 rather than from the collector C_1, the resulting loss

[17] Bunemann, Cranshaw, and Harvey, Can. J. Research A **27**, 191 (1949).

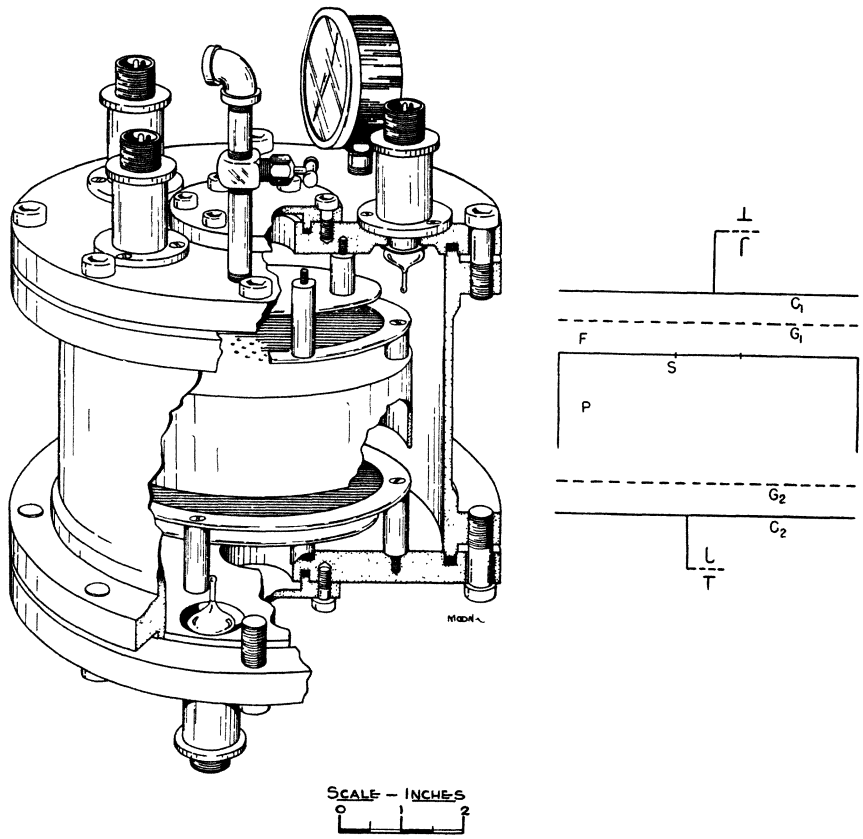

FIG. 8. High pressure double ionization chamber for energy measurements.

of amplitude due to positive ion effects being of no importance. Complete saturation of the fission pulses was also immaterial but care was taken to ensure that the α-pulses were saturated, the field in the region $S-G_2$ being about 400 volts/cm with a pressure of 10 atmos. The energy distribution of the long-range particles is plotted in Fig. 11. This curve was obtained from the analysis of 2000 pulses recorded in 87 hours. A very small correction for chance coincidences was made by substitution of artificial pulses for fission pulses and normalization to identical counting rates. This correction had the effect of reducing slightly the number of small coincident pulses recorded. The shape of the

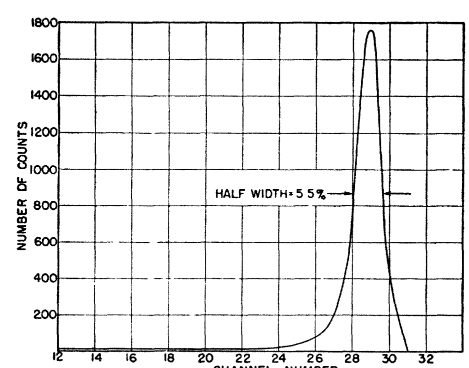

FIG. 9. Energy distribution of α-particles from thin U^{233} source.

distribution, after correcting for spread due to background ionization, is shown by the solid line in Fig. 11. This correction, of the order of 5 percent, was estimated by feeding artificial pulses of constant amplitude into the α-particle amplifier system along with the background pulses from the chamber P and observing the spread in size of the artificial output pulses. The dotted curve, obtained by correcting the solid curve to allow for the energy spent in the aluminum source backing, is the final energy distribution of the fission α-particles. The points associated with the dotted curve are those predicted from the range measurements (Fig. 4) on the assumption that all the particles are α-particles. Agreement is good, verifying that all the long-range particles are indeed α-particles. The abundance was found to be 1 in 550 ± 30 fissions of U^{235}, in good agreement with that obtained from range experiments.

V. ENERGY DISTRIBUTION OF FISSION FRAGMENTS COINCIDENT WITH LONG-RANGE α-PARTICLES

In principle, the method used to obtain the energy distribution of the long-range α-particles can be used to determine the energy distribution of the major fission fragments coincident with these α-particles. In this case the triggering pulses are supplied by the long-range α-particles, the sizes of coincident fission pulses being recorded on the Esterline-Angus chart. In practice, however, some changes were necessary.

(a) Owing to the extremely high electric field, of the order of 450 volts per cm *per atmosphere*, required to saturate the fission pulses in the mixture of $A+0.08$ percent CO_2, it was found necessary to reduce the pressure to 5 atmos. to obtain saturation with the maximum field available. At this pressure only about the first 30 cm of range of a very energetic fission α-particles was contained in the sensitive region of chamber P so that these particles produced smaller pulses than they would have done at 10 atmos. pressure. These smaller pulses, however, were still well above the threshold of detection.

(b) It was not feasible to collimate the fission fragments in an attempt to get better resolution for two reasons. Firstly, at 5 atmos. pressure the fission fragment tracks were so short that energy losses in the collimator itself introduced considerable straggling. Secondly, due to Coulomb repulsion, the fission α-particle is emitted preferentially in the same hemisphere as the light fragment; thus when collimation is used the heavier fragment is observed much more frequently in coincidence with an α-particle than is the lighter. This effect was encountered in the initial measurements and necessitated the removal of the collimator.

(c) Because a long-range α-particle may traverse P very obliquely when one of the major fragments proceeds directly across F, the triggering pulse may be delayed by as much as 2.5 μsec. with respect to the corresponding fission pulse. As the fission pulses decayed with a time constant of about 10 μsec. (necessary to minimize background effects and chance coincidences) the delay could result in some loss of amplitude of the fission fragment pulse in passing through the coincidence gate. In order to eliminate this effect the fission pulses, before passing into the coincidence gate, were shaped into flat-topped pulses of the proper amplitude and 15 μsec. duration. A direct measurement then showed that the loss in amplitude for triggering delays of 3 μsec. was less than 0.5 percent.

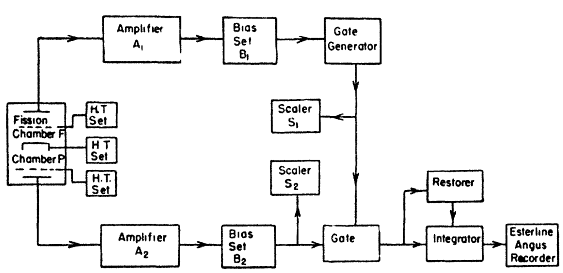

FIG. 10. Block diagram of electronic recording system used in energy measurements.

The method of the experiment was as follows. A very thin source of natural uranium, 0.02 mg/cm^2 in thickness, deposited uniformly on 0.001-inch aluminum foil, was placed over a hole in the common cathode facing the fission chamber F, and the energy distribution of fission fragments resulting from slow neutron bombardment was studied with a 30-channel pulse analyzer. When the electric field was high enough to saturate the pulses, the shape of the distribution was similar to that obtained by others under more nearly ideal conditions, although the resolution was not quite as good. By direct comparison with natural α-particles, the peak energies were found to be 58 and 92 Mev in good agreement with other work.[18] The normal fission fragment distribution was also obtained with fission pulses being recorded on the Esterline-Angus chart. This was done at a low neutron intensity giving about 15 fissions/min. The shape of the distribution was the same as that obtained with the pulse analyzer at the rate of 1000 fissions/min. The gating circuit was then brought into operation, and the sizes of fission pulses coincident with long-range α-particles were recorded. A series of runs was made over a period of five days, normal distributions being taken between triggered runs to check the constancy of the calibration. The final results are shown in Fig. 12, a total of about 1200 pulses being recorded for each distribution. The high energy peak is shifted by 10.5 Mev and the low energy peak by 8 Mev. The reduced amplitude of the high energy peak is due to the angular distribution effect mentioned above.

It is estimated that the triggering α-particles had a mean energy of about 15 Mev. Thus the average total energy released in fission accompanied by α-emission is $50+81.5+15=146.5$ Mev. This is to be compared with the average kinetic energy of the fragments in binary fission, *viz.*, $92+58=150$ Mev.

VI. DISCUSSION

The experimental results presented above show that the long-range particles emitted in the fission of U^{235} by slow neutrons are α-particles. The frequency of the process *viz.* 1 in 505 ± 50 fissions by pile neutrons and in 550 ± 30 fissions by thermal neutrons is rather less than that obtained by most other workers (about 1 in 300 fissions). The reason for the disagreement with earlier work is not understood, but may possibly be connected

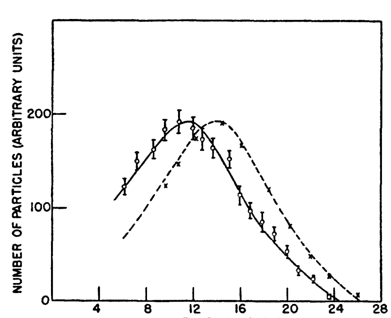

FIG. 11. Energy distribution of long-range α-particles emitted in fission of U^{235}. The broken line shows the distribution after correction for energy loss in the aluminum foil. Crosses indicate the curve predicted by the range measurements.

[18] D. C. Brunton and G. C. Hanna, Can. J. Research A **28**, 190 (1950).

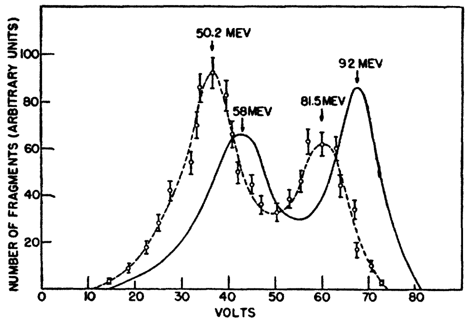

FIG. 12. Energy distribution of fission fragments. Solid curve is the normal distribution. Broken curve is the distribution in energy of fragments in coincidence with long-range α-particles.

with the energy spectrum of the neutrons producing fission. Tsien[12] has suggested that the greater the excitation of the compound nucleus, the less favored is the emission of long-range α-particles. The absence of such emission in the fast neutron fission of uranium and thorium substantiates this argument. Further experiments to determine the dependence on neutron energy of α-emission in fission are desirable.

From the similarity of the range distributions and specific ionizations, we conclude that the long-range particles emitted in the fission of U^{233} and Pu^{239} are also α-particles. In the case of U^{235} fission, the energy released in binary and ternary processes is about the same. No significant change in the mass ratio of the two main fragments is evident in the rarer mode of fission. This is in agreement with Marshall's conclusions.[6]

Tsien[12] has given a rather detailed discussion of the two main modes of ternary fission, *viz.*, fission accompanied by long-range α-particles, and fission accompanied by short-range charged particles. Using dynamical arguments based upon a simplified three-sphere model he has shown that it is possible to account for the energy and angular distributions of the light particles, independently of their precise nature and mass. As it has now been shown that all the *long-range* particles are α-particles, a rather more specific explanation of the process seems desirable, at the same time retaining the general features of Tsien's arguments.

Feather[19] has suggested that an α-particle may be evaporated from a highly excited fragment produced in a binary division if it lies in the particular range of nuclei which are unstable, or almost unstable, against α-emission in the ground state. The very considerable excitation of the fragment would account for the emission of α-particles within a time $\sim 10^{-21}$ sec. which is necessary to explain their angular distribution and energy. Because the region of maximum α-instability lies in the neighborhood of $Z\sim 40$ and $Z\sim 60$, this explanation predicts more asymmetry in the division of mass between the major fragments than in the average binary fission process. This does not appear to be supported experimentally, although it cannot be ruled out by our measurements.

Alternatively, it may be argued that the α-particle is emitted before the main division of the compound nucleus take place. For according to the Bohr-Wheeler nuclear model, excitations of the compound nucleus lasting for $\sim 10^{-14}$ sec. after a slow neutron is captured occur before the actual division takes place. If during this interval, the electrostatic α-particle barrier at some point of the nuclear surface is reduced to less than about 9 Mev (neutron binding energy ~ 4 Mev$+\alpha$-disintegration energy ~ 5 Mev) an α-particle may be emitted. If fission occurs immediately after the α-emission, the α-particle will be accelerated in the Coulomb field of the two major fragments. Thus the process may be visualized as a special type of α-decay. A long-lived compound nucleus would favor this picture of the process, hence more α-particles are to be expected in slow neutron fission than in fast neutron fission, as is required by experiment. It would however seem to be very difficult to distinguish experimentally between this process and that proposed by Feather.

It is a pleasure to acknowledge the continued interest of Dr. B. W. Sargent during the experiments. The cooperation of the pile operating staff, under the direction of Mr. D. D. Stewart and Mr. G. M. James, is greatly appreciated, and thanks are also due Dr. J. G. MacHutchin for preparation of the sources of fissionable materials.

[19] N. Feather, Nature **159**, 607 (1947).