LETTERS TO THE EDITORS

Ternary and Quaternary Fission of Uranium Nuclei

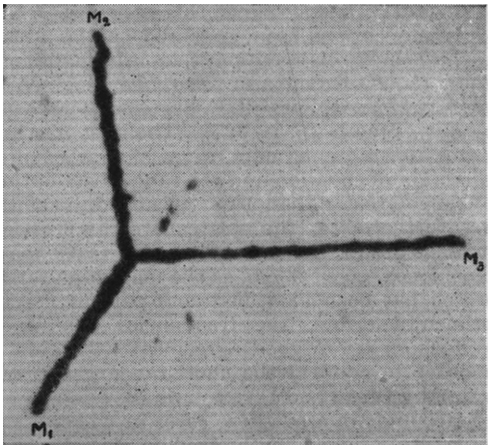
AFTER our experimental proof of the existence of tripartition and quadripartition (ternary and quaternary fission) of U^{235} by means of photographic emulsion[1,2], a systematic study of the mass and kinetic energy of fission fragments has been made with the Ilford Nuclear Research C_2 plate. The experimental conditions were similar to those of previous work. C_2 plates soaked with 10 per cent solution of uranyl nitrate were bombarded with slow neutrons produced near the beryllium target of the cyclotron of the Collège de France.

The results of the first series of experiments can be summarized in the following[3,4].

Tripartition. Usually two of the fragments are heavy (m_1, m_2) and the third one is light (m_3) (Fig. 1). The mean ranges of m_1 and m_2 are $1 \cdot 9$ and $2 \cdot 3$ cm. of air equivalent, while that of m_3 varies from 2 to 44 cm., the most frequent value being about 25 cm. The direction of emission of m_3 is nearly perpendicular to that of m_1 and m_2. The mass distribution of m_1 and m_2 has mean values of 99 and 131, whereas in the usual binary fission the most frequent masses are 96 and 138. The third fragment, m_3, seems to have two probable values, one about 5, the other about 9. Some cases, which could be interpreted as tripartitions, could be also interpreted by the mechanism of projection of atoms of carbon, nitrogen or oxygen ($m \sim 14$) or silver or bromine ($m \sim 90$) by a fission fragment; fission tracks of this kind were not counted in the statistics of tripartition. The total kinetic energy of the three fragments, about 155 MeV. [5], slightly higher than that of the usual binary fission fragments (150 MeV.), is in good agreement with the theoretical prediction[6]. The frequency of tripartition is about 1/300 of that of bipartition (usual fission process).

A parallel and independent investigation by Demers[7] shows that the third light fragment (considered as an α-particle) is emitted within 2×10^{-14} sec. after the act of division. This is in good agreement with our hypothesis of tripartition, namely, that three fragments are emitted in an interval of time comparable with the mean life-time of the compound nucleus ${}_{92}U^{236}$. The frequency observed by Demers is also in agreement with ours.

Recently, we have observed a particular case in which the third fragment is much heavier (Fig. 2). The calculated masses are about 127, 77 and 32 respectively. The three fragments are almost coplanar, their ionizations are much higher than that of α-particles and the total kinetic energy is about 142 MeV. This observation and the direction of emission of m_3 support the explanation in terms of tripartition[8,9] which is possible with a large positive amplitude of the deformation due to the fourth harmonic of the liquid drop (Bohr's liquid drop model of the nucleus). The relative sizes of the fragments (droplets) depend upon the amplitudes and the phases of deformations due to the second and fourth harmonics. Consequently, it is natural that the third fragment should have different values of mass such as we have observed. An analysis of fission fragments in the region of lower atomic weight by means of the mass spectrograph with a strong neutron source might give more information concerning the mass distribution of third fragment.



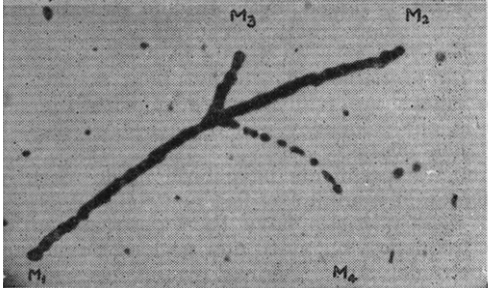


Fig. 2 (above); Fig. 3 (below)

Fig. 2. TRIPARTITION OF URANIUM NUCLEUS WITH THREE FRAGMENTS OF COMPARABLE MASSES: $m_1 = 127$; $m_2 = 77$; $m_3 = 32$

Fig. 3. QUADRIPARTITION OF URANIUM NUCLEUS

Quadripartition. The first case of quadripartition has already been published in detail[2,5]. Another one is shown in Fig. 3. The four fragments are not coplanar. The calculated masses are: $m_1 = 84$, $m_2 = 76$, $m_3 = 72$ and $m_4 = 4$, with a total kinetic energy about 90–95 MeV. If the internal excitation energies of the fragments are about the same both for binary and quaternary fissions, the observed total kinetic energy for the latter is in good agreement with that estimated by Bohr and Wheeler. The frequency of quadripartition is about 1/3,000 that of bipartition.

A detailed report of this work will be published shortly in the *Journal de Physique et Le Radium.*

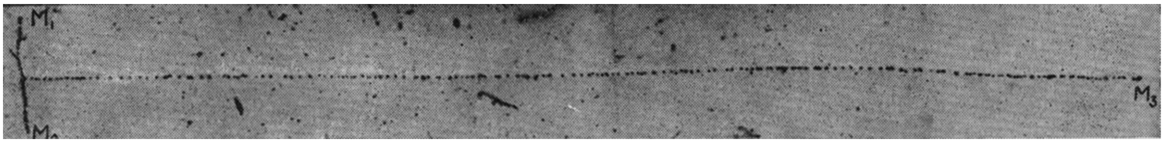


Fig. 1. TRIPARTITION OF URANIUM NUCLEUS WITH LIGHT THIRD FRAGMENT (ITS RANGE IN STANDARD AIR = 44 CM.). THE TWO BRANCHES ON M_1 TRACK ARE DUE TO NUCLEAR COLLISIONS OF M_1 WITH KNOWN NUCLEI CONTAINED IN PHOTOGRAPHIC EMULSION
$m_1 = 110, m_2 = 120, m_3 = 6 \pm 1$. Total kinetic energy $\sim$ 179 MeV.

Note added in proof.—Since this letter was written, two communications have appeared on the emission of a third light charged particle in the fission of uranium (L. L. Green and D. L. Livesey, *Nature*, March 8, p. 332; G. Farwell, E. Segrè and C. Wiegand, *Phys. Rev.*, March 15, p. 327). The first one, using the same technique as ours, gives similar results on the direction of emission and the range distribution of m_3 of range greater than 1 cm. of air equivalent. It shows, furthermore, the existence of an important short-range group. The second one, using the method of coincidence, gives 23 cm. as the maximum range of m_3 which has been identified as α-particle. Within experimental errors, the frequencies observed by these authors are in good agreement with ours.

In order to confirm the short-range group of m_3 indicated by Green and Livesey, we have re-examined our plates and counted those cases in which a short-range track is linked in the middle straight part of the main fission tracks. The statistics show that particles of range from 3 mm. to 3 cm. are present, the most probable range being about 8 mm. If all these tracks are really connected with the fission process, the frequency will be one short particle in 90 fission events.

Similar experiments have been made recently on the fission of uranium by fast neutrons. Short-range third light particles have been observed with the same frequency, but until now no long-range particle has been detected. Similar results have also been obtained in the case of fission of thorium by fast neutrons (observation made by the senior author in collaboration with Mrs. H. Faraggi).

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March 15.

[1] Tsien San-Tsiang, Chastel, R., Ho Zah-Wei and Vigneron, L., *C.R. Acad. Sci., Paris*, **223**, 986 (1946).

[2] Ho Zah-Wei, Tsien San-Tsiang, Vigneron, L., and Chastel, R., *C.R. Acad. Sci., Paris*, **223**, 1119 (1946).

[3] Tsien San-Tsiang, Ho Zah-Wei, Chastel R., and Vigneron, L., *C.R. Acad. Sci., Paris*, **224**, 272 (1947).

[4] Tsien San-Tsiang, Ho Zah-Wei, Chastel, R., and Vigneron, L., *Phys. Rev.*, **71**, 382 (1947).

[5] In the previous publications, the calculation of energy was based upon the *V—R* relation given by Bøggild, Bostrøm and Lauritsen (*Kgl. Danske Videnskab. Selskab. Math.-Fys. Medd.*, **28**; 1940), assuming the total kinetic energy of binary fission fragments to be 162 MeV., instead of the more recent value, 151 MeV., from Flammersfeld, Jensen and Gentner (*Z. Phys.*, **120**, 450; 1943). Therefore, our formerly published total kinetic energy should be diminished by about 10 MeV.

[6] Bohr, N., and Wheeler, J. A., *Phys. Rev.*, **56**, 426 (1939).

[7] Demers, P., *Phys. Rev.*, **70**, 974 (1946).

[8] Present, R. D., *Phys. Rev.*, **59**, 466 (1941).

[9] Tsien San-Tsiang, *C.R. Acad. Sci., Paris*, **224**, 1056 (1947).

An Electron Accelerator with an Air-cored Field

ARISING primarily from the fact that iron becomes saturated in the region of 10,000–20,000 gauss, high-energy ions and electrons have been obtained from cyclotrons and betatrons only by the use of magnetic fields of large orbital radii. The question has, therefore, often been raised as to the possibility of using iron-free fields of short duration, especially as fields of the highest magnitude have been obtained in this way. The following note describes an experimental resonance accelerator for electrons which uses such an air-cored field.

The principle of the accelerator has already been described[1]. Electrons are accelerated by a 1,200 Mc./s. electric field across a pair of dees situated in a magnetic field of 425 gauss. Owing to the relativity mass increase, the electrons tend to lag behind the accelerating potential, and, in order to keep them in resonance, an increasing magnetic field is superimposed on the static field. The phasing condition requires that the rate of increase of magnetic field, dH/dt, be less than $2\,Ve\,.\,n\,.\,H_0/m_0\,c^2$, where Ve is the energy added to the electrons per transit of the dee gaps, n is the frequency of the accelerating field, and H_0 is the magnitude of the static field.

A focusing static field is produced by a Helmholtz pair of coils, each of 120 turns of mean radius 11·5 cm., excited by a direct current of 48 amp. The dynamic field is also produced by a Helmholtz pair, each coil of four turns and 7 cm. radius. A condenser bank of 0·0108 μf., charged to 20,000 V., is shorted across the dynamic coils and produces a field of approximately 300 gauss at the peak of a sinusoidal oscillation of 250 kc./s. frequency. The growth of the dynamic field is synchronized with the start of the electric field pulse by using the same rotary spark modulator to control both circuits.

The dees are 2 cm. deep and 5 cm. in radius, and are constructed from wire hoops mounted perpendicularly from frames forming the dee gaps. They are situated in an evacuated glass vessel in the mid-plane of the Helmholtz coil system. The ultra-high-frequency is fed to the dees by a Lecher wire system which fans out to the width of the dee frames at the gaps. The oscillations are produced by a 25-cm. magnetron operating at 100 pulses per second, each pulse being of 1 μsec. duration, and of peak power up to 200 kW. The dee voltage is estimated to be of the order 1,000 V.

A tungsten filament, partly enclosed in a split cylindrical shield, is situated along the axis of the dees, and a small tungsten target is located at the periphery of one of the dees.

X-rays have been detected by a Geiger counter set up in the vicinity of the accelerator and are emitted at the value of the static field calculated for resonance with the electric field. The form of the resonance curve is shown in Fig. 1. Tests have been made on the X-rays produced both with and without the dynamic field operating. Absorption curves in lead are shown in Fig. 2. With the dynamic field operating it is clear that the X-ray yield is considerably increased, and there is an indication in the foot of the absorption curves that the radiation is also harder. The mean energy of the X-rays determined from the absorption coefficient in lead is approximately 60 kV.

For a constant magnetic field of 425 gauss, electrons should be able to reach energies of the order 0·5 MeV. before lagging 90° in phase behind the accelerating electric field[2]. In the present experiment, however, electrons will not attain energies greater than 100 kV. before they collide with the target at a radius of 4 cm. An experimental mean energy of 60 kV. is therefore not inconsistent with the upper limit, as it is improbable that many electrons will reach this maximum in the 1 μsec. acceleration time, and also as the radiation is from a thick target.

For a magnetic field which grows from 425 gauss to approximately 725 gauss in the micro-second acceleration-time, there should be a group of electrons which attain an energy as high as 300 kV., but an analysis of the energy spectrum to be expected of