1983 JULIAN MACK LECTURE

- 1300 STERLING HALL
- FRIDAY, APRIL 8, 4:00 P.M.

"FROM THE DISCOVERY OF THE NEUTRON TO NUCLEAR ENERGY"

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Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

On bombarding uranium with neutrons, Fermi and collaborators[1] found that at least four radioactive substances were produced, to two of which atomic numbers larger than 92 were ascribed. Further investigations[2] demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations.

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body for example, with similar properties to those of uranium was assumed to be eka-osmium ($Z = 94$) rather than uranium ($Z = 92$) or ruthenium ($Z = 44$).

Following up an observation of Curie and Savitch[3], Hahn and Strassmann[4] found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopes with radium. Further investigations, however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium ($Z = 56$) are formed as a consequence of the bombardment of uranium ($Z = 92$) with neutrons.*

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the 'Coulomb barrier', indicated by Gamow's theory of alpha-decay.

On the basis, however, of present ideas about the behaviour of heavy nuclei[5], an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops.

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension of nuclear matter has been used[6] and its value has been estimated from simple considerations regarding nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100.

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of mass depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should get a total kinetic energy of c. 200 MeV., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole 'fission' process can thus be described in an essentially classical way, without having to consider quantum-mechanical 'tunnel effects', which would actually be extremely small, on account of the large masses involved.

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of lanthanum[7], the other will be krypton ($Z = 92 - 56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed lanthanum-barium-cerium chains are then actually strontium-yttrium-zirconium chains.

It is possible[8], and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ^{239}U might be uranium isotopes ($Z = 92$) decaying through neptunium, rhodium, palladium and silver into cadmium.

In all these cases it might not be necessary to assume nuclear isomerism; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, some varying proportions of neutrons may be given to the two parts of the uranium nucleus.

By bombarding thorium with neutrons, substances are obtained which have been ascribed to radium and actinium isotopes[9]. Some of these periods are approximately equal to periods of lanthanum and lanthanum isotopes[9] resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a 'fission' of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of these products from a light element, for example, by means of neutron capture.

In might be mentioned that the body with half-life 24 min.,[9] which was chemically identified with actinium is probably really ^{239}U, and goes over into an eka-rhenium which appears mostly to be very decay slowly, probably with emission of alpha particles. (From magnetic deflection of these radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed changes has always puzzled us.) The formation of this body is typical resonance (or fission?); the compound state must have a lifetime a million times longer than the time it would take the nucleus to divide itself. Perhaps the state corresponds to some highly symmetrical type of motion of nuclear matter which does not favour 'fission' of the nucleus.

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[1] Fermi, E., Amaldi, O., D'Agostino, O., Rasetti, F., and Segrè, E., Proc. Roy. Soc., A, 146, 483 (1934).
[2] See Hahn, O., Meitner, L., and Strassmann, F., Z. Phys., 106, 249 (1937).
[3] Curie, I., and Savitch, P., C. R., 208, 1643 (1939).
[4] Hahn, O., and Strassmann, F., Naturwiss., 27, 89 (1939).
[5] Hahn, O., and Strassmann, F., Naturwiss., 27, 11 (1939).
[6] Bohr, N., Nature, 137, 344 (1936).
[7] Bohr, N., and Kalckar, F., Kgl. Danske Vid. Selskab, Math. Phys. Medd., 14, No. 10 (1937).
[8] See Meitner, L., Naturwiss., 7, and Hahn, O., Z. Phys., 106, 249 (1937).
[9] Hahn, O., and Meitner, L., Phys. Rev., 55, 511 (1939).

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The Existence of a Neutron.

By J. Chadwick, F.R.S.

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§ 1. It was shown by Bothe and Becker* that some light elements when bombarded by α-particles of polonium emit radiations which appear to be of the γ-ray type. The element beryllium gave a particularly marked effect of this kind, and later observations by Bothe, by Alma. Curie-Joliot† and by Webster‡ showed that the radiation excited in beryllium possessed a penetrating power distinctly greater than that of any γ-radiation yet found from the radioactive elements. In Webster's experiments the intensity of the radiation was measured both by means of the Geiger-Müller tube counter and in a high pressure ionisation chamber. He found that the beryllium radiation had an absorption coefficient in lead of about 0·23 cm.$^{-1}$ as measured under his experimental conditions. Making the necessary corrections for these conditions and using the results of Gray and Tarrant to estimate the relative contributions of scattering, photoelectric absorption, and nuclear absorption in the absorption of such penetrating radiation, Webster concluded that the radiation had a quantum energy of about 7×10^6 electron volts. Similarly he found that the radiation from boron bombarded by α-particles of polonium consisted in part of a radiation rather more penetrating than that from beryllium, and he estimated the quantum energy of this component as about 10×10^6 electron volts. These conclusions agree quite well with the supposition that the radiations arise by the capture of the α-particle into the beryllium (or boron) nucleus and the emission of the surplus energy as a quantum of radiation.

The radiations showed, however, certain peculiarities, and at my request the beryllium radiation was passed into an expansion chamber and several photographs were taken. No unexpected phenomena were observed though, as will be seen later, similar experiments have now revealed some rather striking events. The failure of these early experiments was partly due to the weakness of the available source of polonium, and partly to the experimental arrangement, which, as it now appears, was not very suitable.

* 'Z. Physik,' vol. 66, p. 289 (1930).
† I. Curie, 'C. R. Acad. Sci. Paris,' vol. 195, p. 1412 (1932).
‡ 'Proc. Roy. Soc.,' A, vol. 136, p. 428 (1932).

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Artificial Radioactivity produced by Neutron Bombardment

By E. Fermi, E. Amaldi, O. D'Agostino, F. Rasetti, and E. Segrè

(Communicated by Lord Rutherford, O.M., F.R.S.—Received July 25, 1934)

I—*Introduction*

This paper aims at giving a fuller account of experiments made in the Physical Laboratory of the University of Rome, on new radio-elements produced by neutron bombardment. Preliminary results have already been announced in short communications.*

Curie and Joliot† first discovered that the product atom of an artificial disintegration need not always correspond to a stable isotope, but could also disintegrate with a relatively long mean life with emission of light particles. As bombarding particles they used α-particles from polonium, and found that the light particle emitted was generally a positron. Similar results were obtained on several elements by other experimenters using α-particles, and artificially accelerated protons and deutons.‡

The use of charged particles for the bombardment, limits the possibility of an activation only to light elements. Indeed, only about ten elements up to the atomic number 16 could be activated by these methods.

It seemed therefore convenient to try the effect of a neutron bombardment, as these particles can reach the nucleus even of the heaviest elements. Available neutron sources are, of course, much less intense than α-particles or proton or deuton sources. But it was reasonable to assume that this factor would be partly compensated by the higher efficiency of neutrons in producing disintegrations. Indeed, experiment showed that more than forty elements out of about sixty investigated could be activated by this method.

* Fermi, 'Ric. Scient.,' vol. 1, pp. 283, 330 (1934); Amaldi, D'Agostino, Fermi, Rasetti and Segrè, 'Ric. Scient.,' vol. 1, pp. 452, 652, 21 (1934); Fermi, Rasetti and D'Agostino, 'Ric. Scient.,' vol. 1, pp. 533 (1934); Fermi, 'Nature,' vol. 133, pp. 757, 898 (1934). See also Fermi, 'Nuovo Cim.,' vol. 11, p. 429 (1934); Amaldi, Fermi, Rasetti and Segrè, 'Nuovo Cim.,' vol. 11, p. 442 (1934); Amaldi and Segrè, 'Nuovo Cim.,' vol. 11, p. 452 (1934); D'Agostino 'Gazz. Chim. Ital.,' in press (1934).
† 'C.R. Acad. Sci. Paris,' vol 198, pp. 256, 361 (1934).
‡ Frisch, 'Nature,' vol. 133, p. 721 (1934); Wertenstein, 'Nature,' vol. 133, p. 864 (1934); Cockcroft, Gilbert and Walton, 'Nature,' vol. 133, p. 328 (1934); Neddermeyer and Anderson, 'Phys. Rev.,' vol. 45, p. 498 (1934); Lauritsen, Crane and Harper, 'Science,' vol. 79, p. 234 (1934).

RADIOATTIVITÀ « BETA » PROVOCATA DA BOMBARDAMENTO DI NEUTRONI. — III.

E. Amaldi, O. D'Agostino, E. Fermi, F. Rasetti, E. Segrè

* Ric. Scientifica e, 5 (1), 452-453 (1934).