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Experiments on the interaction of high-speed nucleons with atomic nuclei

Nobel Lecture, December 11, 1951

The experimental researches in nuclear physics with which I have been associated have been concerned with the transmutation of atomic nuclei, the study of their level structure and of the forces which hold nuclei together. I began this work in the Cavendish Laboratory under the direction of Lord Rutherford in 1928. At this time experimental work on the energies of α-particles ejected from the radioactive elements had shown that these particles could have a substantially lower energy than the calculated height of the potential barrier around the nucleus. For a time this was somewhat of a puzzle, but in 1928 Gamow, who was then working in Copenhagen, and also Gurney and Condon, showed that this could be readily explained by attributing wave properties to the escaping α-particle so that the particle could escape from the nucleus without having a high enough energy to surmount the potential barrier. Gamow visited the Cavendish Laboratory in 1928 and I discussed with him the converse problem - the energy which would be required for a proton accelerated by high voltages to penetrate the nuclei of the light elements. As a result of these talks I prepared a memorandum which I sent to Rutherford showing that there was a quite high probability for the boron nucleus to be penetrated by a proton of only 300 kilovolts energy whilst conditions for lithium were even more favourable. Rutherford then agreed to my beginning work on this problem and I was soon joined by Dr. Walton who had previously been working on the development of an early linear accelerator and also on an equally early betatron.

Dr. Walton will describe the work on the development of our equipment. With our first apparatus we produced beams of protons from a canal ray tube and accelerated them by voltages of up to 280 kilovolts, and in 1930 bombarded a lithium target and other targets and looked for γ-rays with a gold-leaf electroscope. We found then only soft continuous radiation; we did not find gamma rays - as we now know, our proton energy was too far below the first resonance which gives rise to gamma ray emission. We were

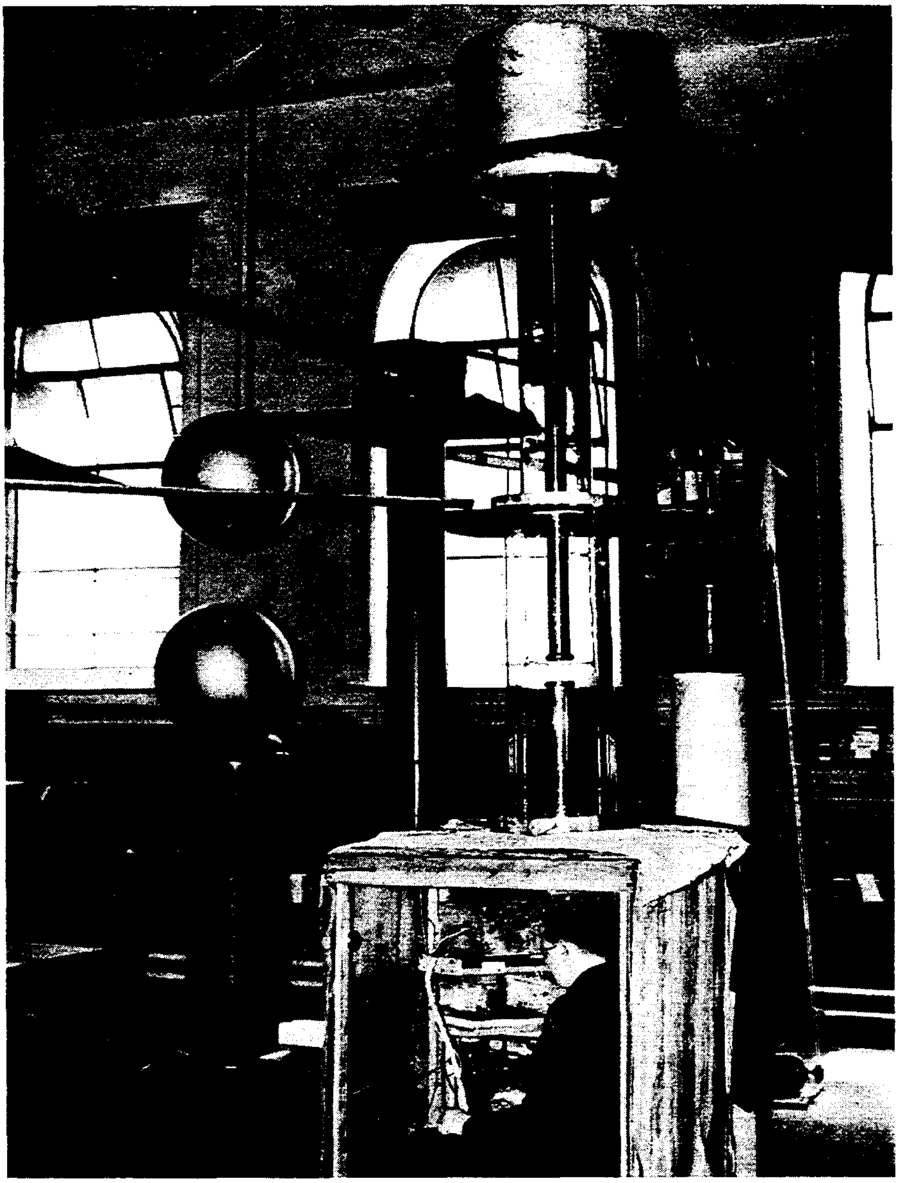

Fig. 1a.

then interrupted by the necessity to move our laboratory and in doing so we decided to increase the energy of our protons.

Fig. 1 a and 1 b show the new apparatus which was completed in early 1932. We were soon able to bring a narrow beam of 500 kilovolts protons

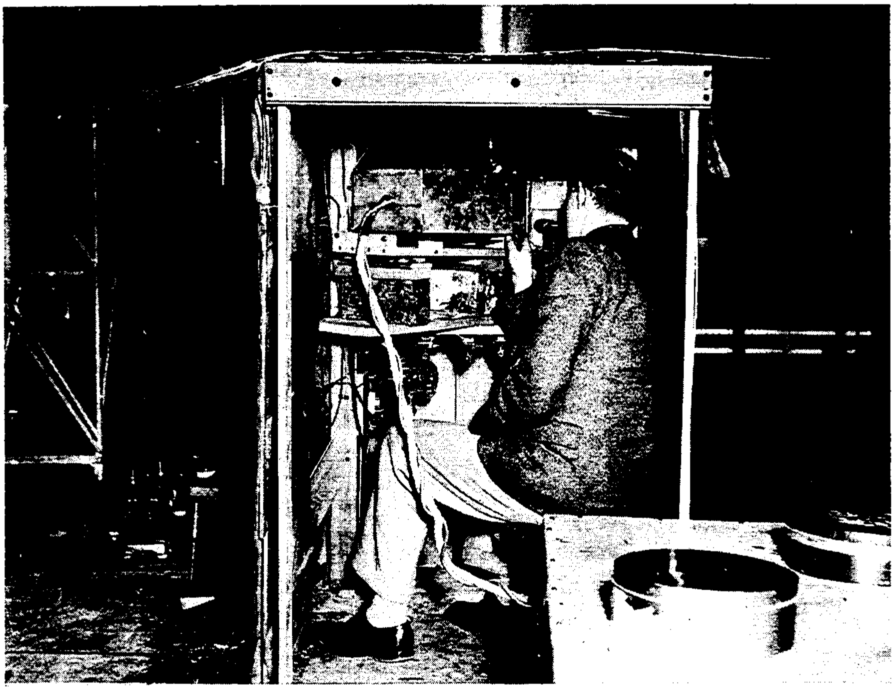

Fig. 1 b.

out through a thin mica window in the base of the experimental tube, and to measure their range as a function of energy.

Soon after this, we resumed our experiments on lithium, but this time, instead of looking for gamma rays, we set out to look for α-particles from the disintegration of lithium. A mica window was provided to allow the α–particles to escape, and opposite the mica window we placed the well-tried tool of Rutherford - the zinc sulphide screen (Fig. 2). Almost at once, at an energy of 125 kilovolts, Dr. Walton saw the bright scintillations characteristic of α-particles, and a first primitive absorption experiment showed that they had a range of about 8.4 cm. We then confirmed by a primitive coincidence experiment, carried out with two zinc sulphide screens and two observers tapping keys (Fig. 3), that the α-particles were emitted in pairs. Our resolving time was a second or so - somewhat longer than the resolving time of modern coincidence circuits which operate in units of millimicroseconds. More refined experiments showed that the energy of the α-particles was 8.6 million volts (Fig. 4). It was obvious then that lithium was being disintegrated into two α-particles with a total energy release of 17.2 million volts.

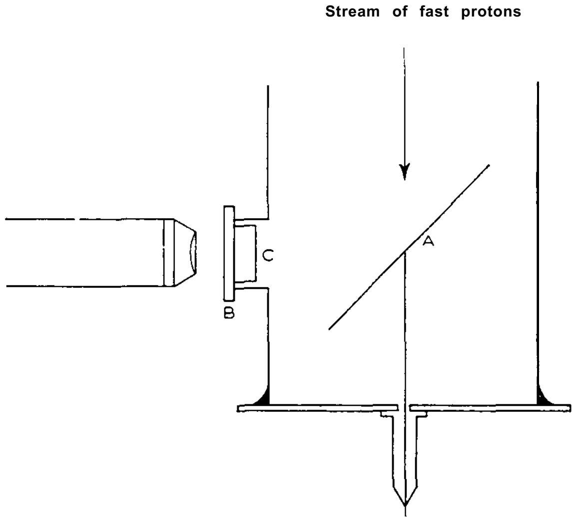

Fig. 2.

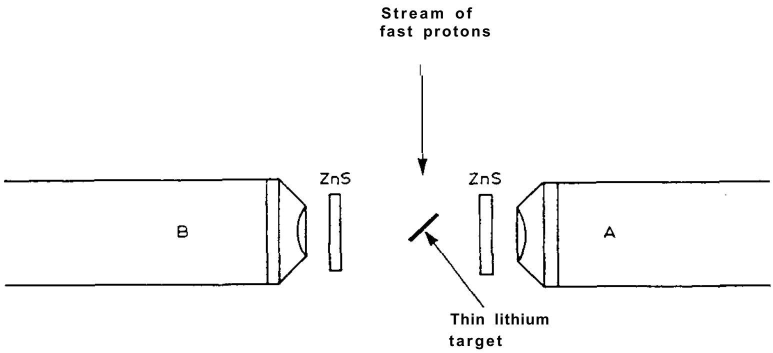

Fig. 3.

This energy could be provided by a diminution of mass of 0.0184 mass units.

The mass balance of the reaction at that time was

^{7}Li	7.0104	(Costa)
^{1}H	1.0072	
	8.0176	
$2\,^{4}He$	8.0022	
Mass decrease	0.0154	

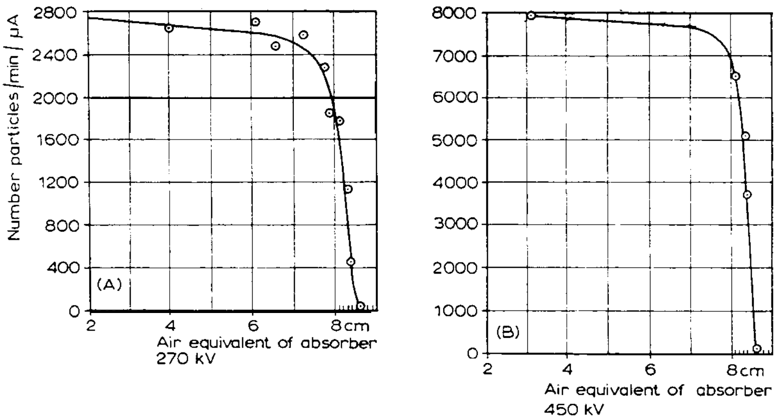

Fig. 4.

A little later Bainbridge redetermined the mass of ^{7}Li to be 7.0130. This changed the mass decrease to 0.0180 mass units, in very good agreement with the observed figure.

We also studied the variation of the number of disintegrations with energy and obtained the results shown in Fig. 5. The increase in disintegration with higher proton energy results from the increasing probability of penetration of the nuclei potential barriers predicted by the Gamow, Gurney and Condon theory.

We studied also the disintegration of boron and found a different type of absorption curve (Fig. 6) for the α-particles which were emitted with a continuous distribution in energy with a maximum range of 4.4 cm. The continuous distribution in energy was explained by boron breaking up into α-particles. We found also that α-particles were emitted from most elements but we found later that these were due largely to boron impurities in our targets, boron having a very high probability of disintegration.

These experiments were powerfully supported by Dee who was diverted by Rutherford from his cloud chamber work carried out with C. T. R. Wilson to join in this promising new field. Dee, with Walton, built himself another accelerating tube and arranged for protons to pass down a tube into a Wilson chamber. Thin mica windows were arranged for the α-particles to enter the cloud chamber. Figs. 7 and 8 show the transmutation of lithium into two α-particles and of boron into three α-particles.

Our next group of experiments were carried out with ions of heavy hydrogen which became available to the laboratory in 1933 through the kindness of Professor G. N. Lewis who sent a few cubic millimetres of heavy

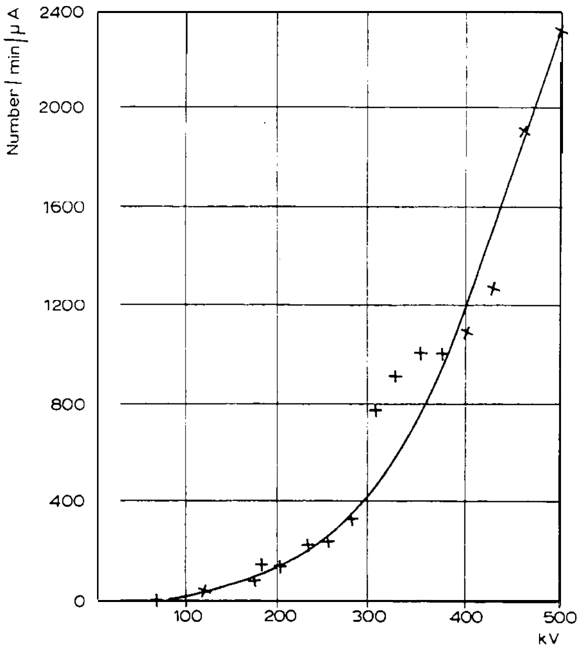

Fig. 5.

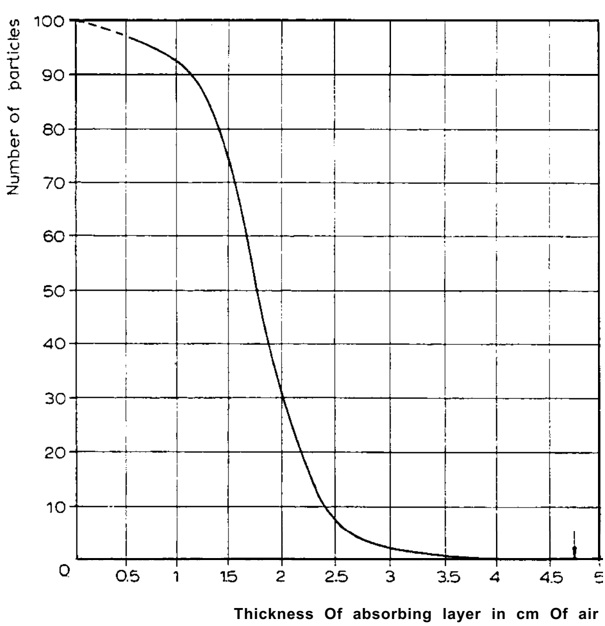

Fig. 6. Absorption curve of boron.

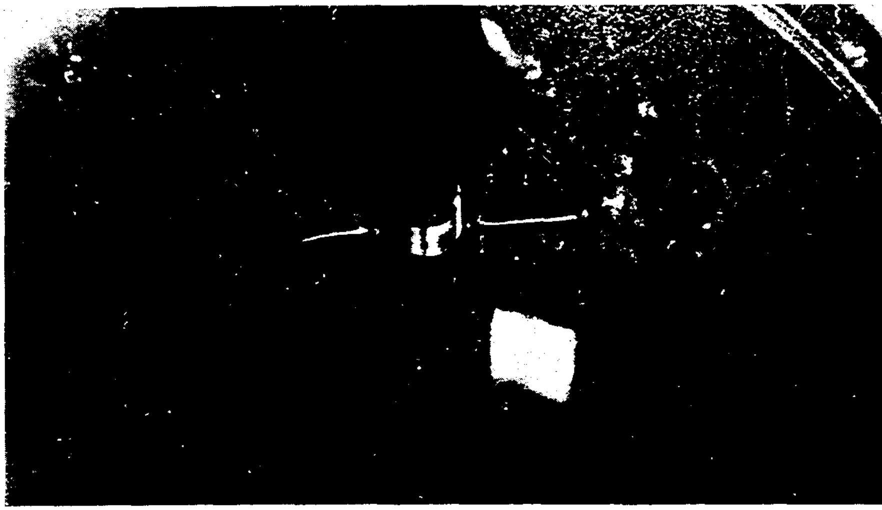

Fig. 7.

water over to Rutherford. Lawrence, Livingston, and Lewis, had carried out some pioneer experiments on disintegration produced by deuterons and had found that a group of protons of 18 cm range was emitted from most targets. By this time Oliphant had built a low-voltage accelerator to enable him to work with Rutherford in this exciting new field. Together they discovered the disintegration of deuterium by deuterons - or diplons as Rutherford wanted to call them. Figure 9 is a beautiful photograph by Dee showing the disintegration into a triton and a proton. The protons explained the observations of Lawrence, Livingston, and Lewis. In September, 1933, I brought back two cans of dilute heavy water from Berkeley and after this was concentrated by Harteck we obtained a little for our own use. We then studied the (d, p) type of reaction - the transmutation of ^{6}Li into ^{7}Li with the emission of a proton; the transmutation of ^{10}B into ^{11}B, ^{12}C into ^{13}C, again with the emission of one or more proton groups. The multiple proton groups showed the existence of excited levels of the residual nucleus.

During the course of these experiments we had looked for the emission of delayed α-particles from nuclei but had never found them. In early 1934 we heard of the production of artificial radioactivity by Curie and Joliot who observed a delayed emission of positrons from targets of boron, magnesium, and aluminium bombarded by α-particles. Walton and I were able to borrow a Geiger-counter equipment from Dr. Bainbridge - there was only one portable equipment in the Cavendish Laboratory at that time - and at

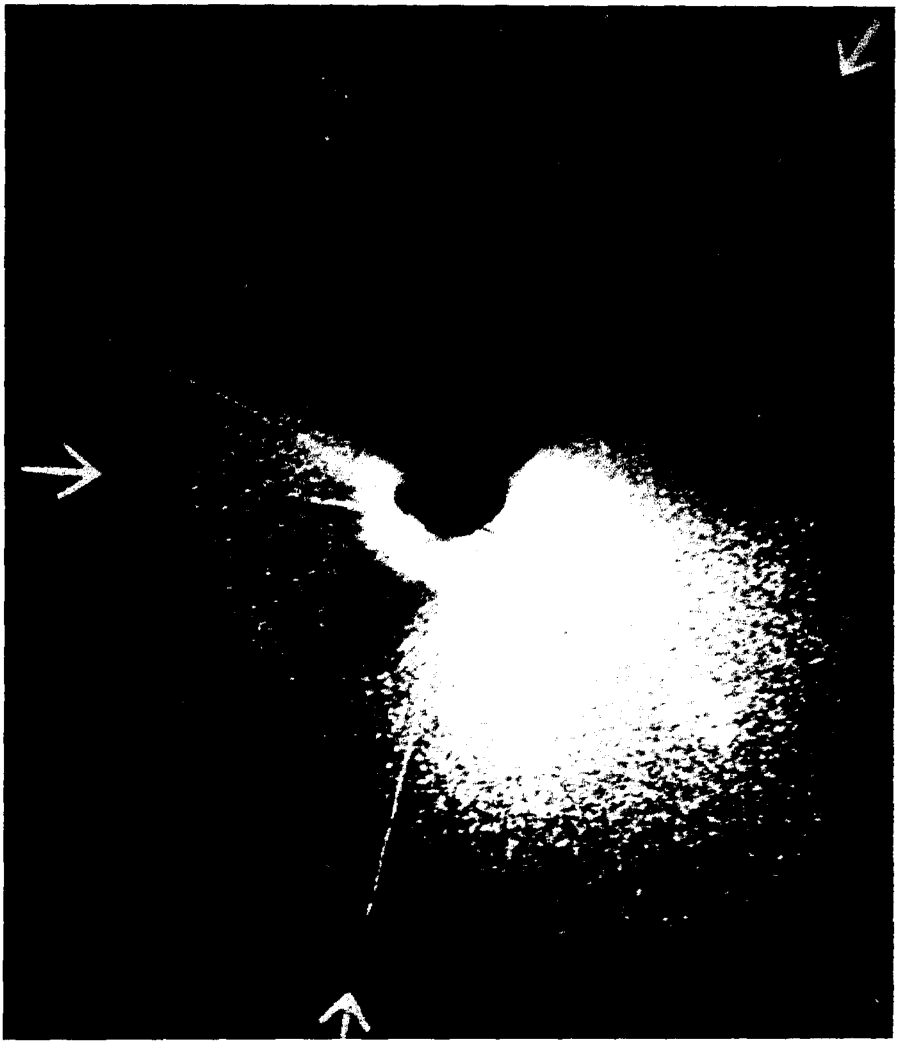

Fig. 8.

once found that when graphite was bombarded by a beam of 400-500 kilovolt protons, delayed positrons were emitted, and that the activity had a half-life of about 11 minutes. We found also that similar effects were produced by the deuteron bombardment of carbon, an effect which had also been found by Lauritsen and Crane. These two reactions were seen to be due to the formation of nitrogen 13, the first by proton capture and the second by a (d,p) reaction.

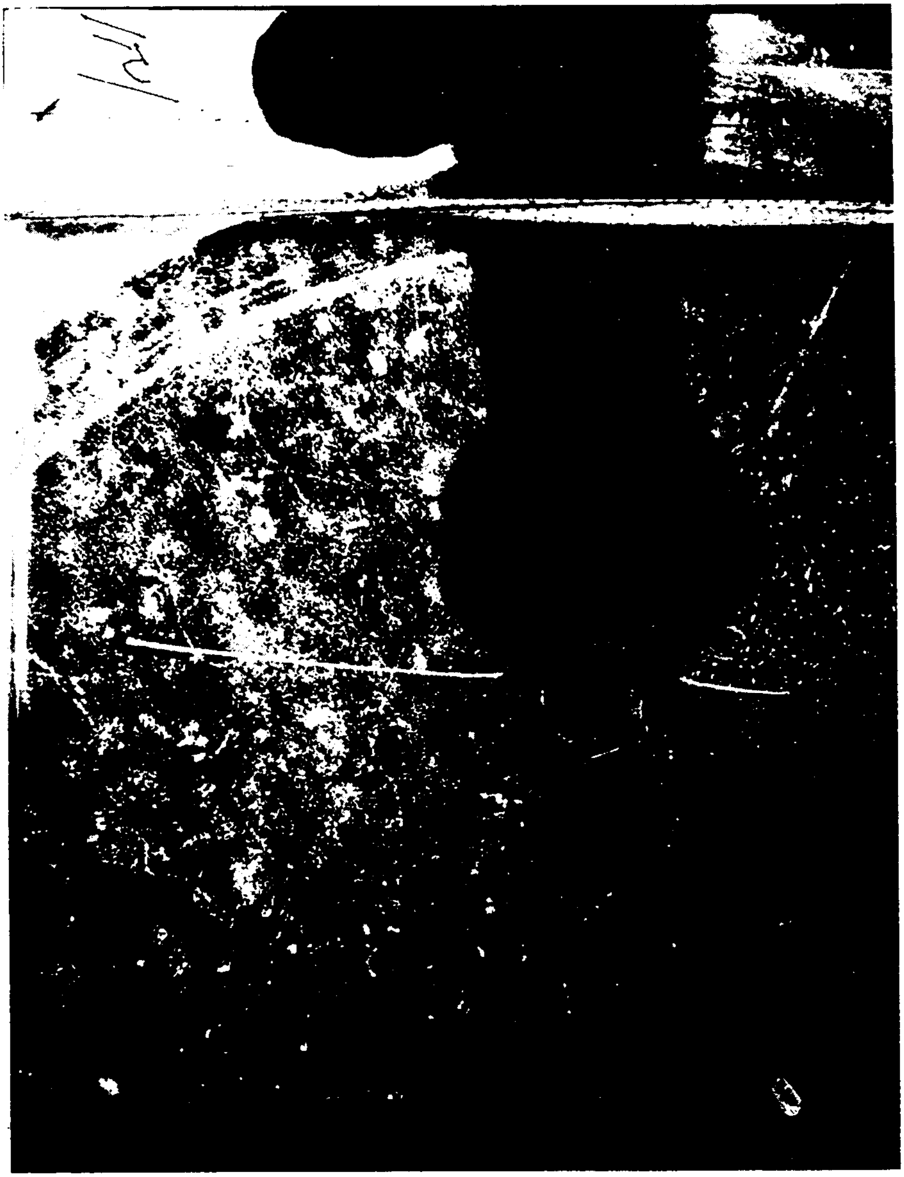

Fig. 9.

The next group of experiments were carried out in association with Dr. W. B. Lewis. Our apparatus was greatly improved in accuracy and we were able to study the disintegration of boron, carbon, nitrogen, and oxygen by deuterons with some precision.

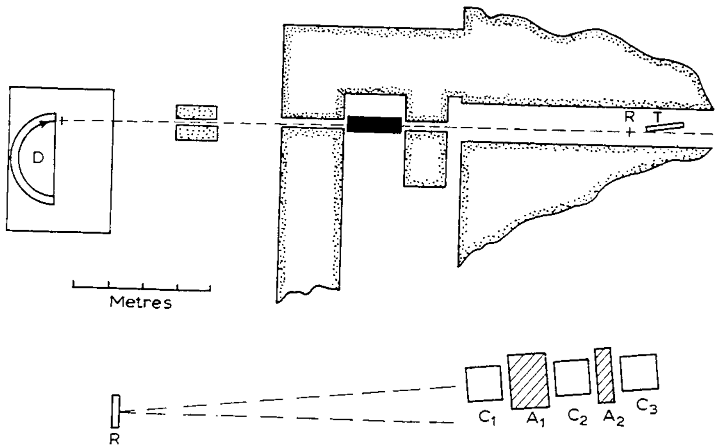

Fig. 10.

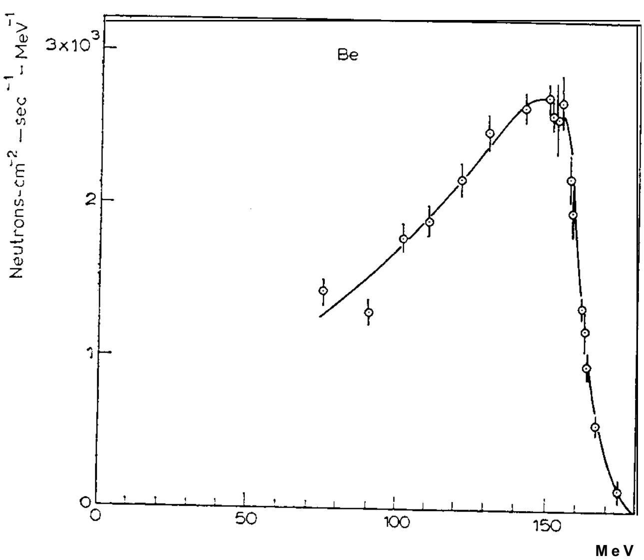

Fig. 11.

We studied for example the interesting (d,α) reactions in carbon and nitrogen

$$^{12}_{6}C + ^{2}_{1}D \rightarrow ^{10}_{5}B + ^{4}_{2}He$$

$$^{14}_{7}N + ^{2}_{1}D \rightarrow ^{12}_{6}C + ^{4}_{2}He \; [\text{or} \rightarrow 4\; ^{4}_{2}He]$$

These new reactions enabled a close check to be made on the new scale of nuclear masses which had recently been proposed by Bethe and Oliphant.

For some time after this I was diverted by Rutherford from nuclear physics to take charge of the Royal Society Mond Laboratory when Kapitza was retained in Russia. I was interested however to some extent in the building of the Cavendish Laboratory cyclotron, which I was at last able to persuade Rutherford to build, on my return from Berkeley in 1937; and in the High Voltage Laboratory, with its voltage multiplier accelerator for 1 million volts. Dee was however the effective leader of this laboratory.

After the War in the autumn of 1946 with many colleagues I started to transform the Royal Air Force Station at Harwell into a Research Establishment. Since then we have built a synchrocyclotron for producing 180 MeV protons, a Van de Graaff generator for experiments with 3 MeV protons

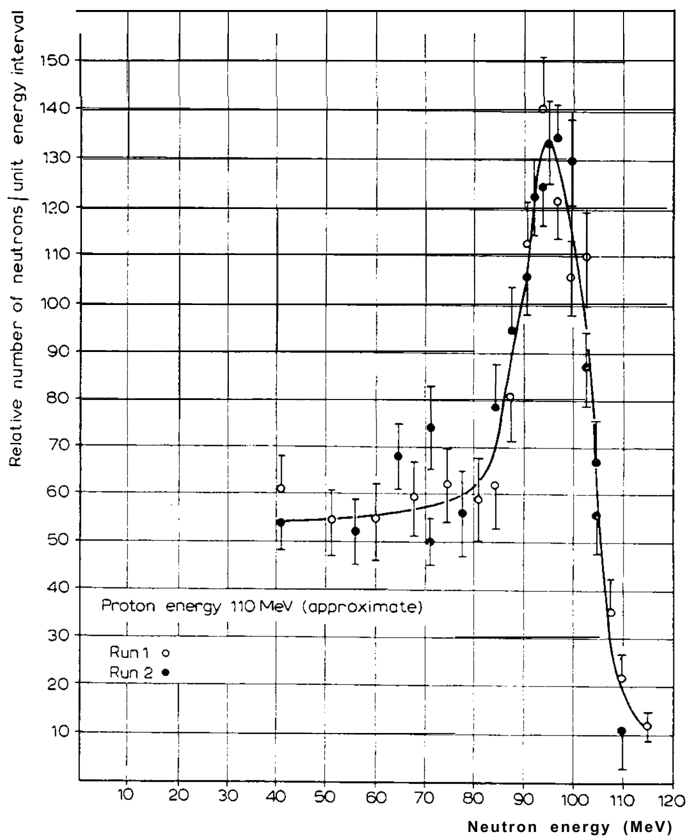

Fig. 12. Neutron energy distribution for beryllium.

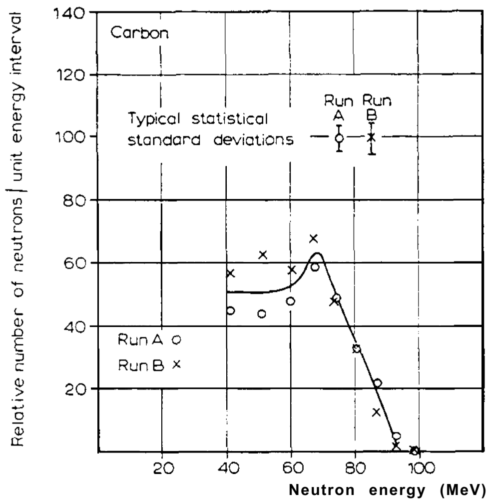

Fig. 13. Energy distribution of neutrons from carbon target bombarded by 100-MeV protons.

and deuterons, and a linear accelerator for electrons as our principle tools of nuclear physics. I will now describe some of the experiments which have been carried out by the cyclotron group working under the leadership of Dr. Pickavance.

Experiments on nuclear forces have been carried out with beams of neutrons and protons. High-energy neutrons are produced by allowing the proton beam to strike a target inside the vacuum tank. Neutrons which are projected forward pass through a thin window in the wall of the vacuum tank and then through collimating tubes in blocks of concrete having a total thickness of 4½ metres. (Fig. 10). The energy of the neutrons can be determined by allowing them to project protons from a polythene disc. The projected protons then pass through a coincidence « telescope »of two proportional counters and one gridded ionization chamber which records slow protons. Fig. 11 shows the energy spectrum of the neutrons from beryllium. A fairly high proportion of the neutrons are projected forward with almost the full energy of the protons. The tail of neutrons is due to multiple scattering inside the nucleus. I will also show the results of a similar experiment (Fig. 12) carried out by the Harvard workers using 110 MeV protons. You will see that the peak is more pronounced. It seems that nuclear matter is particularly transparent to neutrons of about 110 MeV energy, due to a peculiar interference effect. You will perhaps think that the Harvard peak is more clearly defined because of better geometry. So I will show you their results for carbon (Fig. 13). The peak has now almost vanished. This must be connected with the fact that about 20 MeV of energy are required to extract a neutron from carbon so that the neutrons will be of a lower energy for which the nuclear matter is not so transparent. Fig. 14 shows the Harwell results for aluminium. You will see that there is now a very pronounced tail. This must be due again to the neutrons losing energy making multiple small-angle collisions in the nuclear matter before emerging.

Experiments have also been carried out by Mrs. Skyrme to investigate the spectrum of lower energy neutrons. Fig. 15 shows that there is a strong group of «evaporation neutrons» which have a peak energy of about 1 MeV. It appears that about four neutrons are evaporated from a Tungsten target for each inelastic collision of a high-energy neutron with a target. Smaller numbers of neutrons are evaporated from light nuclei.

Experiments have also been carried out on neutron-proton scattering. The beam of neutrons was used to project protons, and the number projected at different angles was measured. The effective neutron energy could be defined by two limits - the first set by only recording protons through a given thickness of graphite - the second from the maximum energy of the internal proton beam in the cyclotron.

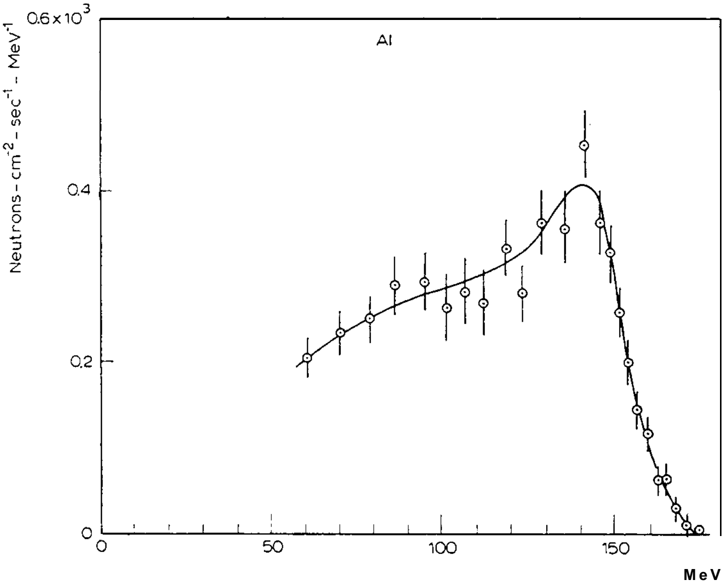

Fig. 14.

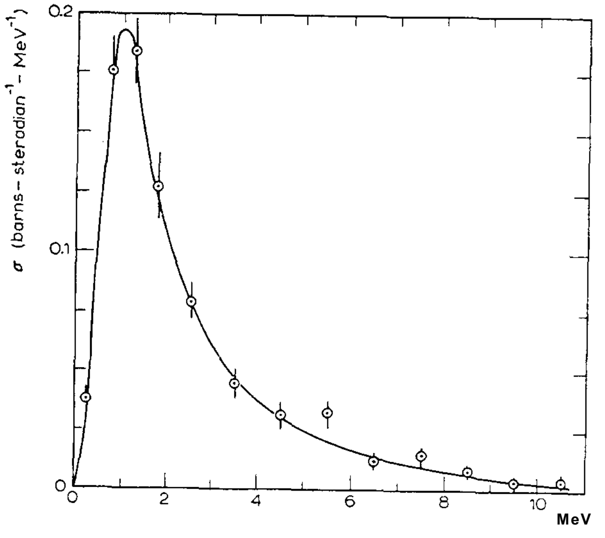

Fig. 15.

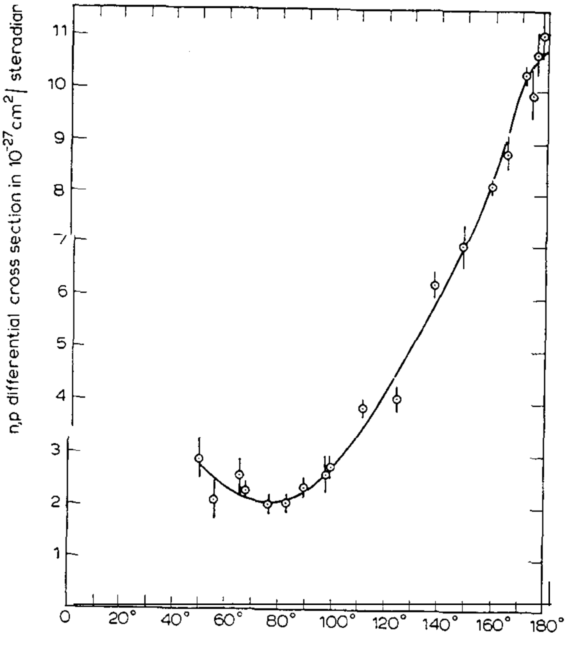

Fig. 16. *Abscissa:* Neutron scattering angle.

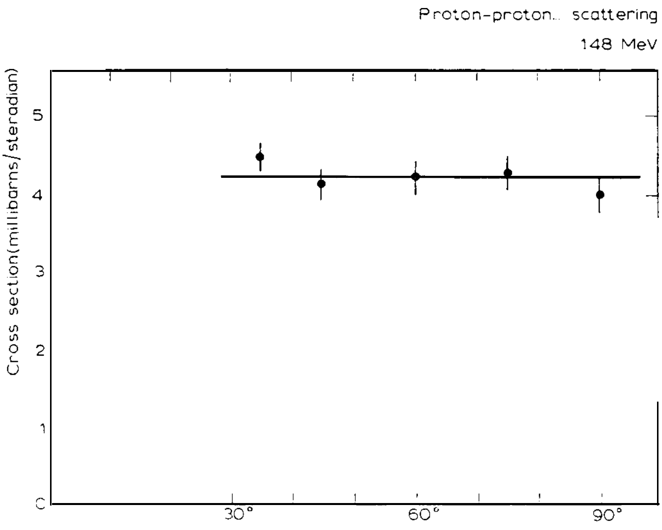

Fig. 17. *Abscissa:* Centre of mass scattering angle.

The results of the (n,p) scattering experiment, plotted in centre of gravity co-ordinates are shown in Fig. 16. You will see that there is a pronounced minimum and that the general character of the scattering is far removed from elastic sphere scattering.

Experiments were then carried out on (p,p) scattering. The protons are scattered out of their final orbit by a uranium foil and then enter a magnetically screened channel so that they can escape from the cyclotron into a long pipe. We obtain about 10^{15} protons /cm^2 per second at a distance of 40 feet. The protons, which have an energy of about 145 MeV are then scattered by polythene and the projected protons are received by a telescope of counters. Background effects can also be reduced by recording the scattered proton at 90°. The results are shown in Fig. 17. You will see that the (p,p) cross section is almost independent of angle in centre of gravity co-ordinates down to 30°. The characteristics of (p,p) scattering are therefore quite different from (p,n) scattering. Some differences would be expected owing to the effect of the Pauli exclusion principle on (p,p) scattering. It is therefore not certain that the (p,p) and (p,n) forces are basically different.

The results for the (p,p) differential scattering cross section at 90° can be compared with the values obtained at other energies of other cyclotron groups. The cross section tends to become constant at energies above about 200 MeV.

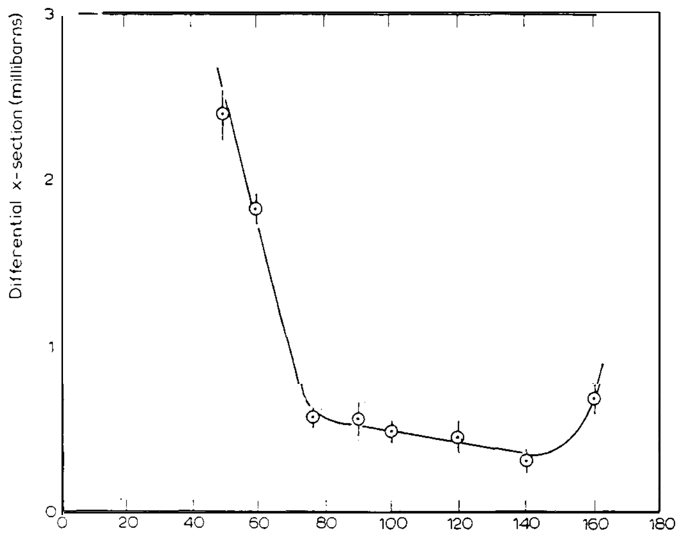

Fig. 18. *Abscissa* : Centre of mass angle.

A further experiment was carried out on the inelastic scattering of protons by deuterons. To achieve this, the protons were scattered from heavy water. The results of this experiment are shown in Fig. 18. It is hoped next to carry out a similar experiment on the scattering of neutrons by deuterons.

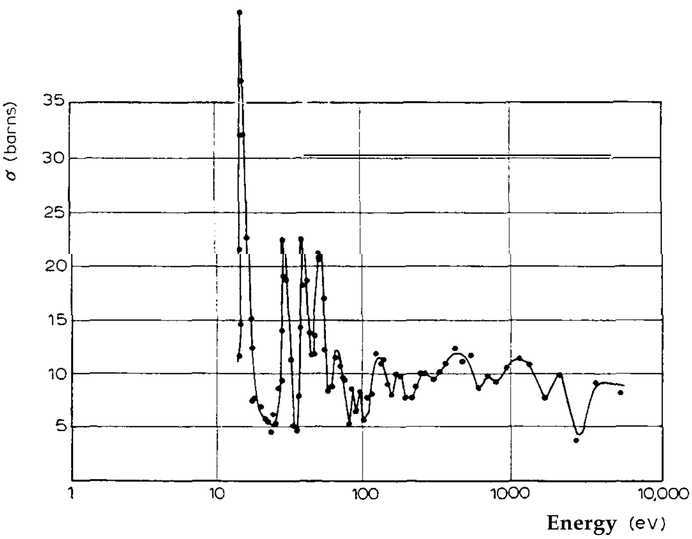

Fig. 20. Total cross section of silver.

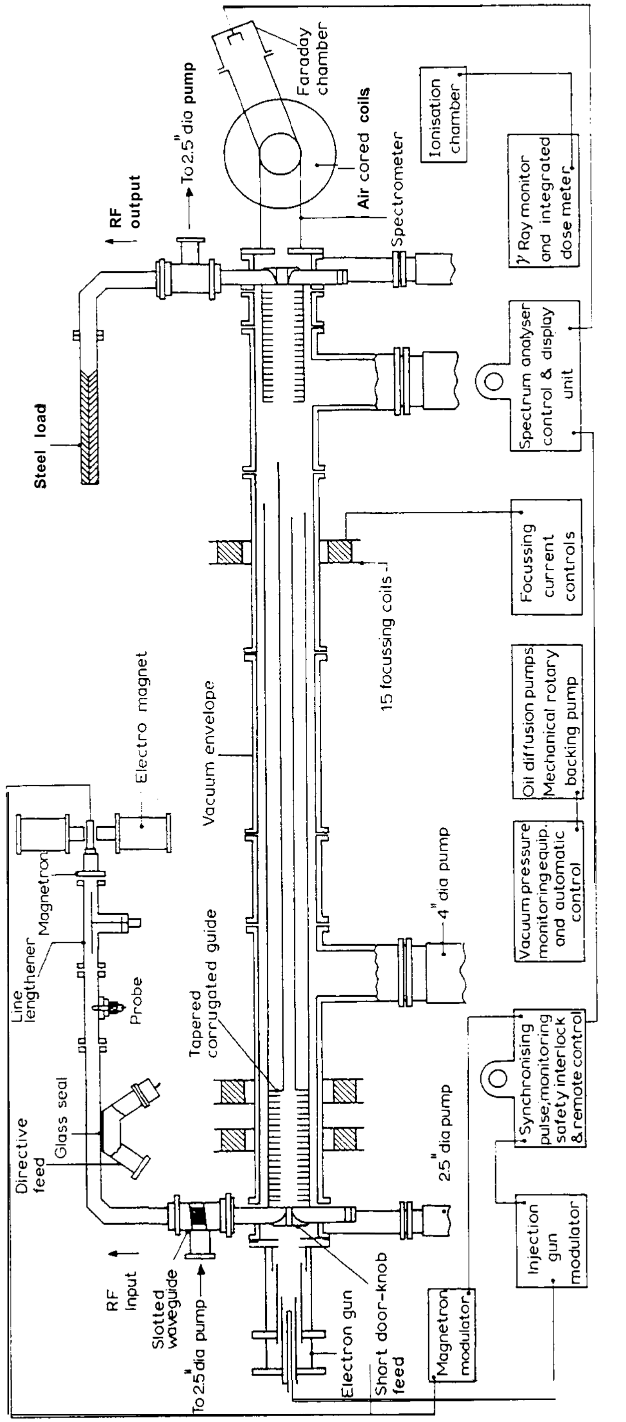

Fig. 19. Schematic diagram of 4.0 MeV linear accelerator.

The linear accelerator. During the post-war years another group at Harwell has developed the electron travelling wave linear accelerator. Fig. 19 shows a diagram of the 3.5 MeV accelerator. This accelerator has been used at Harwell to produce an intense pulsed source of neutrons. The electrons are produced in pulses having a duration of about two microseconds and produce high energy X-rays in a heavy target which in turn splits up heavy water and produces neutrons. About 2.10^{12} neutrons/second are produced in the pulse when the beam current in the accelerator is 120 milliamperes, when the electron energy is 3.2 MeV. The neutrons are partially slowed down in the heavy water. We then use the time of flight method to carry out experiments on neutrons of a given energy. Fig. 20 shows results for the total cross section of silver.

The energy of this linear accelerator is now being extended to 13 MeV and perhaps to 15 MeV. We then hope to increase the neutron intensity by a factor of 100. We may also reduce the pulse width to a fraction of a microsecond. After this we hope to have good resolution up to 10,000 volts.

Work is also proceeding on linear accelerators to produce much higher energy particles.