ERNEST T. S. WALTON

The artificial production of fast particles

Nobel Lecture, December 11, 1951

The first successful experiments on the transmutation of atoms were carried out by Rutherford[1] in 1919 using swift naturally emitted α-particles. He found that when nitrogen was thus bombarded, fast protons were ejected. In the decade following, many similar experiments were made and these showed that certain other light elements could be disintegrated in like manner. Further progress was made difficult by the limited strengths of the available radioactive sources and because the energies of the α-particles emitted were too low. It became increasingly obvious that attempts should be made to produce by artificial means suitable streams of fast particles. The energy required would be small - a few microamperes of helium ions accelerated by means of a potential of a few million volts corresponds to the α-particle emission of some hundreds of grams of radium. Further, other particles which are not emitted by any radioactive substance should be accelerated and used in experiments. But the practical difficulties appeared to be immense. The potential barriers surrounding nuclei were known to be of the order of millions of volts in height and such potentials were far beyond anything which had been applied successfully to X-ray or cathode ray tubes. Their use seemed impracticable.

The recognition of these difficulties gave an impetus to the search for methods of producing fast particles without the use of correspondingly high voltages. Two main types may be noticed: *(i)* acceleration by a circular electric field in which the particles circulate many times, and *(ii)* acceleration by a series of impulses given to the particles at suitable regular intervals. These methods will now be described briefly.

(i) The betatron. This was formerly commonly called an induction accelerator because the circular electric field mentioned in *(i)* above is induced by the variation with time of a magnetic field with axial symmetry (Slepian[2], Wideröe[3]). A charged particle, if constrained to move on the circle, would be accelerated continuously as it travelled round it. If the electric field can be maintained for a sufficiently long time, a light particle could go round the circle many times and thus gain considerable energy. The method is un-

suitable for heavy particles because they do not travel sufficiently fast to traverse the orbit many times while the circular electric field exists. If the particles start from rest when the magnetic field is zero, it so happens that the field varies with time in the correct way to maintain them on the circular orbit. A uniform magnetic field is not suitable, since it is always just twice as strong as is required to constrain the particles to move on a circle, and they would spiral in towards the centre. Early attempts to use the method were not successful because very little consideration was given to the question of the stability of this orbit. This is of the utmost importance of the particle has to traverse the orbit many times. In 1929[4] it was shown that a field which decreased inversely with the distance from the axis of symmetry would constrain the particle to move on a particular circular orbit and, in addition, would give radial stability if certain small time varying electric fields were also present. Later, in their pioneer work on the cyclotron Lawrence and Livingston[5] showed that a magnetic field decreasing with the radial distance would produce axial stability owing to the curvature of the lines of force. The problem was discussed fully by Kerst and Serber[6] in 1941. They showed that both radial and axial stability could be ensured by a field which fell off as $1/r^n$, where n lies between 0 and 1. Kerst's experiments[7] were very successful and his apparatus has developed into the modern betatron which will give electrons of several hundred million electron-volts energy. This seems to be near the useful limit of this method.

(ii) The linear accelerator. In this method a stream of charged particles is sent down the common axis of a line of cylinders, and accelerated successively by electric fields between adjacent cylinders. If a high-frequency alternating potential is applied between the odd-and-even sets of cylinders, by a suitable choice of the lengths of these cylinders it can be arranged that the field is always an accelerating one when the particle is traversing the gap between a cylinder and the next one.

The potentials on the cylinders are changed while the particles are travelling through them and thus they are shielded from any adverse fields. The method is most suitable for heavy particles because then shorter cylinders and potentials at lower frequency may be used. For the acceleration of particles to high energies, the electrical capacity of the system requires large charging currents. In practice this requires considerable high-frequency power. As the path of a particle is long, only small output currents will be obtained unless good focusing is present. The principle of the method was suggested first by Ising[8] in 1925, but some years had to elapse before technique was sufficiently advanced for results of practical importance to be obtained. In 1928 Wideröe[3] obtained a doubling of the energy of particles, while in 1931 Sloan and Lawrence[9] were able to obtain a 30-fold multiplication of voltage and produced 10^{-7} amperes of 1,260,000 volt singly charged mercury ions.

An important development occurred in 1932 when Lawrence and Livingston[5] suggested the use of a magnetic field to bend the particles round in a circle and thus use the same accelerating gap over and over again. It is possible to do this because with non-relativistic particles, the time taken to move round a semi-circle in a magnetic field is independent of their velocity. This is the arrangement used in the cyclotron which has been developed into such an important tool by Lawrence.

In 1929 it seemed that much development work would have to be done on the indirect methods of obtaining fast particles, while at the same time there were indications that, after all, nuclear disintegrations might be produced by particles of reasonably low energies. The application of the wave mechanics showed that there was a non-zero probability that particles might penetrate barriers which they could not surmount. If a sufficiently great number of low energy particles were directed against the barrier, some would go through. Using these ideas, Gamow[10] was able to explain the Geiger-Nuttall law for the emission of α-particles. In 1928 he visited the Cavendish Laboratory, and Cockcroft discussed with him the reverse problem of getting particles inside a nucleus. As a result of this, Cockcroft sent a memorandum to Rutherford in which he showed that protons of only 100,000 electron-volts energy had a small but not negligible chance of penetrating the nucleus of a light atom. As it was expected that very large numbers of protons could be accelerated by this voltage, an appreciable number of penetrations of the barrier should occur. This result had the effect of encouraging the transfer of attention from the indirect methods, which appeared to be a long-term project, to the production of fast particles by using high potentials of not unreasonable magnitude.

In the work carried out by J. D. Cockcroft[11] and the writer, the aim was to accelerate particles by the direct application of potentials of up to 300 kilovolts, these being about the highest potentials which it had been found possible to apply to a vacuum tube for the production of X-rays and cathode rays. The conventional tubes of the time were large glass bulbs with two stems and these were used both for the rectifiers and for the accelerating tube. They may be seen in the photograph (Fig. 1). The transformer voltage

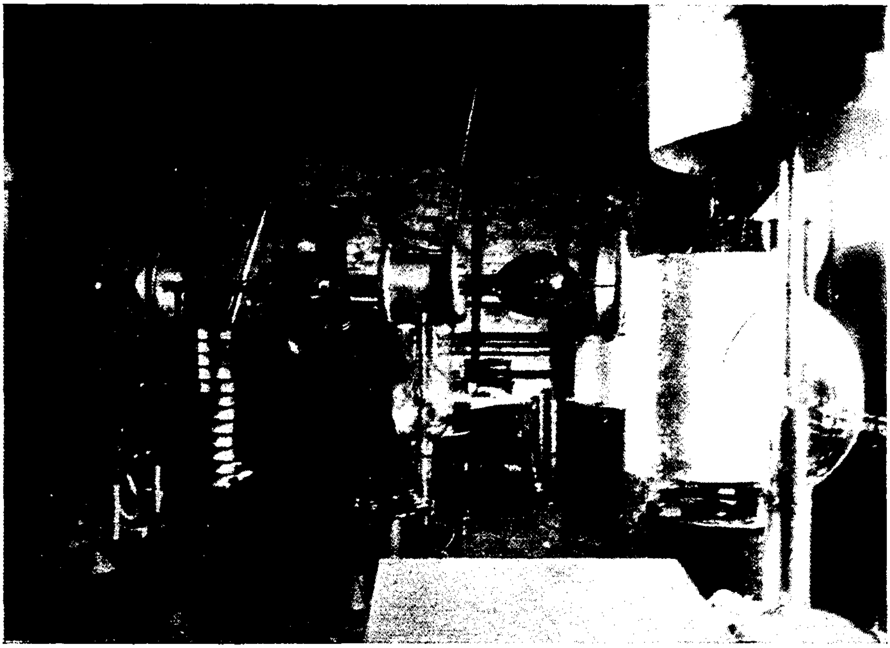


Fig. 1. *By courtesy of The Royal Society.*

was rectified by the two horizontal rectifiers placed in series, these being evacuated through a third bulb connecting them to the pumps. These are shown in the centre of the picture while the accelerating tube is on the right.

With this apparatus several microamperes of protons accelerated by about 280 kilovolts could be obtained.

At this stage the laboratory used had to be vacated and a much larger room became available. Taking advantage of this, the production of much higher energy particles was attempted[12]. For this purpose the voltage multiplier circuit shown in Fig. 2 was used. It is a modification of one due to Schenkel[13]. It gives a fourfold multiplication of voltage and is capable of extension to any even multiple of the transformer voltage. Essentially, it consists of condensers C_1 and C_2 in series, the voltages across them being maintained equal by means of the transfer condenser C_3. This condenser is connected, in effect, alternately in parallel in rapid succession across C_1 and C_2. C_1 becomes charged to twice the peak voltage *(V)* of the transformer because during one half-cycle, C_4 is charged to *V* through the rectifier D_1 while during the next half-cycle the voltage across C_4 is added to the transformer voltage and thus C_1 gets charged through the rectifier D_2 to twice the transformer voltage.

In addition to giving a steady voltage which may be any desired even multiple of the transformer voltage, the circuit has other advantages. It gives steady voltage tappings at intermediate points, these being useful when using a multi-section accelerating tube. The rectifiers are all connected in series and so may be erected as a single column and evacuated by one diffusion pump at earth potential. They, as well as the accelerating tube, were made out of straight glass cylinders, these being found to withstand high voltages much better than the largest glass bulbs obtainable.

Fig. 3 is a photograph of the high-voltage equipment at the Cavendish Laboratory as it appeared towards the end of 1931. The tower of four rectifiers is on the left and the 2-section accelerating tube is on the right of the centre of the picture. They were evacuated by separate oil diffusion pumps of the type which had recently been developed by C. R. Burch[14] at Metropolitan Vickers. Their use simplified greatly the problem of maintaining a sufficiently low pressure in the apparatus. High-vacuum technique was also made much simpler by the use of «plasticene» and later by the use of Apieson Sealing Compound Q. The pieces to be joined had merely to be placed

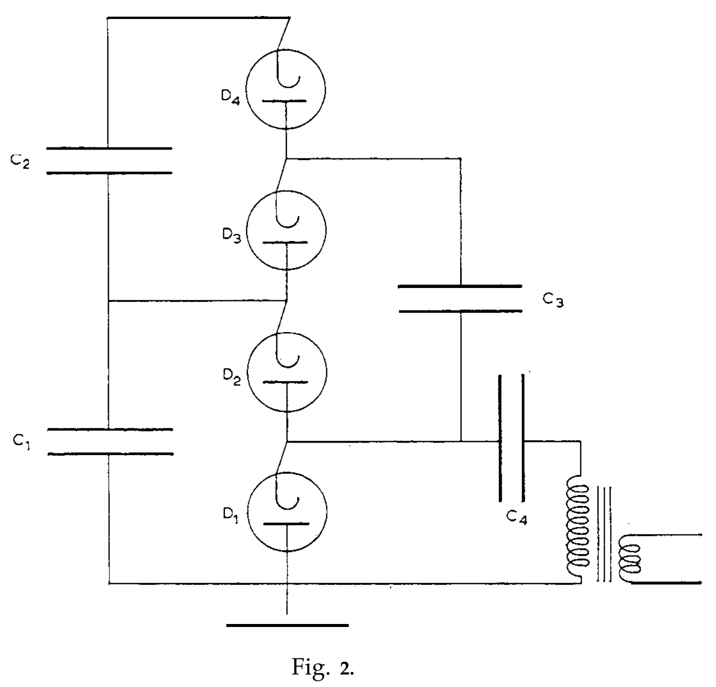
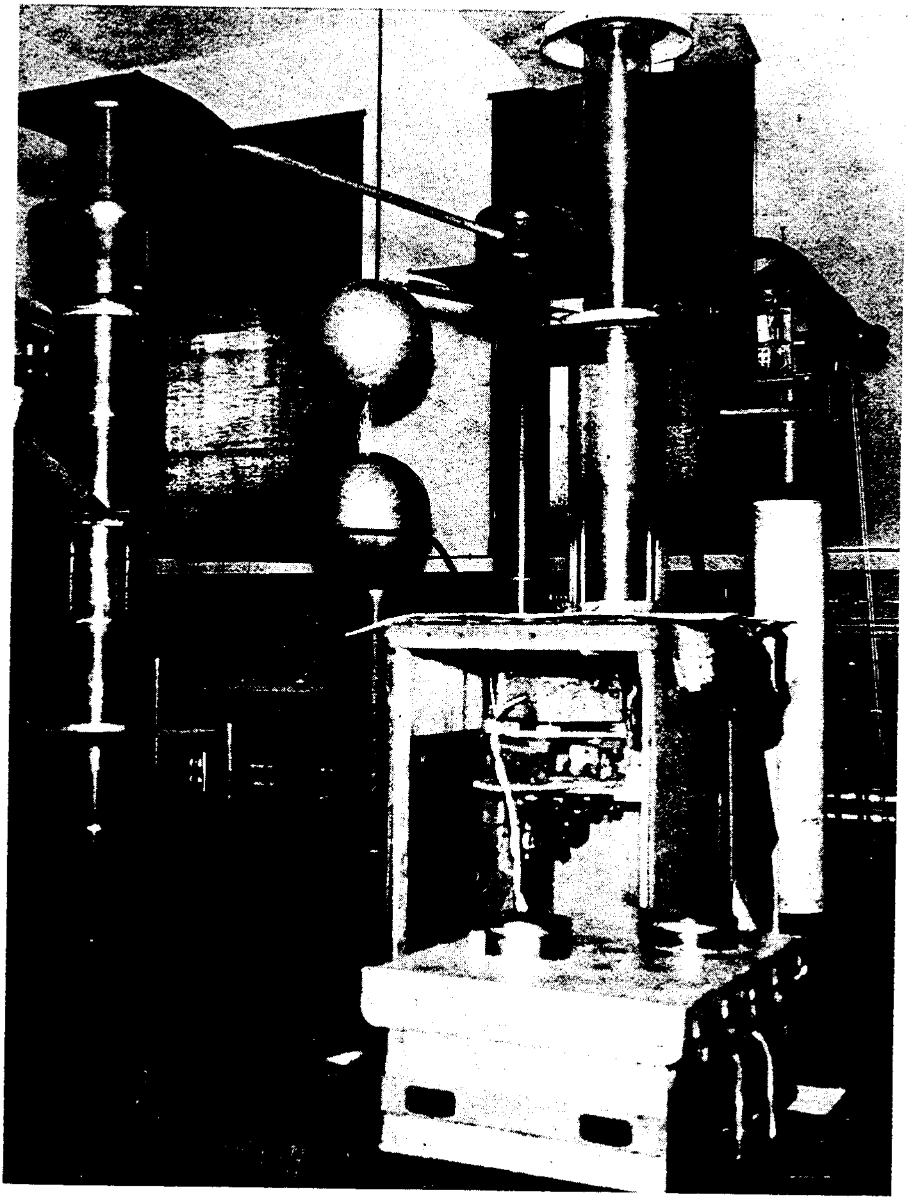


Fig. 2.



By courtesy of the Keystone Press Agency.

Fig. 3.

together and the joint made vacuum tight by pressing the compound with our fingers.

The proton source was of the type used by Aston, suitable power supplies being obtained from the belt-driven equipment on top of the tall white porcelain cylinder. Currents of up to about 10 microamperes accelerated by potentials of up to about 700 kilovolts were obtained. These were used to bombard various targets placed at the bottom of the tube. The disintegrations which were found to be produced are being described by Sir John Cockcroft in his Nobel Lecture.

The discovery that light elements could be disintegrated by artificially accelerated particles gave an additional impetus to development work on the various methods of producing them. The only other direct method which has been found suitable is that of the Van de Graaff machine[15]. In it an electrical charge is sprayed on to a fast-moving belt and is thus carried to the high-voltage electrode. It is suited to nuclear disintegration work because, like all electro-static machines, it readily gives small currents at high voltages. They are usually operated under pressure in a steel cylinder in order to increase both output current and voltage. They appear to be very convenient and economical for voltages in the range from about one to about five million volts.

Later development of the indirect methods. As the size of cyclotrons increases and faster particles are produced, a difficulty arises due to the relativistic increase of mass of the particle. The particle tends to get out of step with the accelerating voltage. This limits the number of times the particles can be allowed to travel round. Hence higher accelerating voltages must be applied to the dees. This means greatly increased high-frequency power and a larger gap in the magnet to give increased clearances. These difficulties can be avoided by the use of an alternating potential whose frequency changes during the course of the acceleration of a particle, but its results in the output current being reduced to a burst of fast particles at the end of each duty cycle of the high-frequency change. Appreciable current can be obtained because of the principle of phase stability (McMillan[16], Veksler[17], Oliphant[18]) which operates when relativistic speeds are reached. The effect produced is that particles, which are tending to get out of step with the accelerating voltage, have their phase automatically changed so as to bring it back to the phase stable point. Hence there is no objection to having the many accelerations necessary when quite low voltages are used on the dees, and no restrictions are placed on the exact way in which the frequency is changed. This is the method of the frequency-modulated cyclotron or synchro-cyclotron. The largest of these machines gives particles of about 350 MeV energy. To go to higher energies will require the construction of larger magnets than have yet been built and their cost is likely to increase with at least the cube of the pole diameter. A considerable saving in the cost of the magnet can be effected if a particle can be made to move in a circle of constant radius for the whole of its acceleration. This is done in the synchrotron by increasing the magnetic field gradually during the course of the acceleration. The magnet must be laminated and, as its time constant is large, burst of fast particles are obtained only at intervals of the order of 10seconds. The method promises to be useful in the range 1,000 to 10,000 MeV. The latter figure may well be the economic limit of the method.

A linear accelerator has the advantage that no magnet is required and that its cost should not rise much more steeply than with the energy of the particles required. Recent progress made in microwave technique has made it possible for energies of up to about 30 MeV to be obtained and the method may well prove to be useful for much higher energies.

Looking to the future, it is difficult to see how particles of energy greater than 10,000 MeV can be produced economically by existing methods. Further progress may have to await the introduction of new ideas.

1. E. Rutherford, *Phil. Mag.*, 37 (1919) 581.
2. J. Slepian, U.S. *Patent No. 1, 645, 304* (1927); filed (1922).
3. K. Wideröe, *Arch. Electrotech.*, 21 (1928) 387.
4. E. T. S. Walton, *Proc. Cambridge Phil. Soc.*, 25 (1929) *469.*
5. E. O. Lawrence and M. S. Livingston, *Phys. Rev.*, 40 (1932) 19.
6. D. W. Kerst and K. Serber, *Phys. Rev., 60 (1941) 53.*
7. D. W. Kerst, *Phys. Rev.*, 60 *(1941)* 47.
8. G. Ising, *Arkiv Mat. Astron. Fysik,* 18, Nr. 30 (1925) 45.
9. D. H. Sloan and E. O. Lawrence, *Phys. Rev., 38 (1931)* 2021 .
10. G. Gamow, Z. *Physik, 51 (1928) 204;* 52 (1928) 51.
11. J. D. Cockcroft and E. T. S. Walton, *Proc. Roy. Soc. London,* A129 (1930) 477.
12. J. D. Cockcroft and E. T. S. Walton, *Proc. Roy. Soc. London,* A136 (1932) 619.
13. M. Schenkel, *Elektrotech. Z.*, 40 *(1919)* 333.
14. C. R. Burch, *Proc. Roy. Soc. London,* A123 (1929) 271.
15. R. J. van de Graaff, *Phys. Rev., 38 (1931) 1919.*
16. E. M. McMillan, *Phys. Rev., 68 (1945)* 143.
17. V. I. Veksler, *J. Phys. U.S.S.R., 9 (1945)* 153.
18. M. L. E. Oliphant, Proposal submitted to Directorate of Atomic Energy, Department of Scientific and Industrial Research, London, 1943.