The Rutherford Memorial Lecture, 1954

Rutherford—his life and work, 1871–1937

By E. Marsden, F.R.S.

It is a great pleasure to be with you to-day and I owe that good fortune to your acceptance of the suggestion by the Royal Society which controls a fund of £100 000 collected in the Commonwealth and dedicated to the memory of Lord Rutherford. This fund provides for post-graduate training and research of selected young men and women but its Committee is also charged with the duty of arranging for the delivery of annual lectures in the Commonwealth countries in turn and dealing with some aspect of Rutherford's life or developments of the scientific work he inaugurated.

It seemed to the Committee that the first few lectures should be given by one or other of those who were fortunate enough to work with Rutherford in the heyday of his powers. Previous lectures were given by Sir John Cockcroft in New Zealand in 1952 and by Sir James Chadwick in Canada in 1953. It would be interesting perhaps to speculate on the subject-matter of some future Rutherford memorial lecture in South Africa when the nature of the forces holding together the atomic nucleus has been unravelled and we have advanced one stage further in our understanding of these subuniverses. The lecture might deal, equally appropriately, not with the subuniverse but with the constitution and evolution of the stars themselves, since atomic transformations appear to be the basis of the constitution energy and radiations concerned, and Rutherford himself often speculated on this subject.

I worked with Rutherford from 1907 to 1914 in Manchester and later for a short period in 1919 after the war. I was lucky to be allowed to take a very modest share in the experiments leading to his enunciation of the then revolutionary idea of a nuclear atom, almost a scale model of the solar system, and, later in his work, of demonstrating the first recorded case of artificial atomic transmutation—the dream of the alchemists of old. In New Zealand, where he was born, I also came to know much concerning his early upbringing and education—and its environment, and to realize and appreciate the part played by that environment in the moulding of his character and the development and unfolding of his genius, thus preparing him for the part he seemed almost destined to play in what is perhaps the most outstanding development of knowledge in all history. This new knowledge seems to usher in a fresh era—the atomic age—with all its social, economic and political consequences.

* Delivered in South Africa at Pretoria on 4 May 1954, Salisbury on 7 May 1954, Johannesburg on 14 May 1954, Rhodes University, Grahamstown on 20 May 1954, Stellenbosch on 25 May 1954, Cape Town on 26 May 1954.

I wish I could spread this talk over two sessions, one dealing with Rutherford the man and the other with the sequence and meaning of his discoveries. I remember when I held the position of research assistant in Rutherford's laboratory and at the very tender age of 23 I had charge of the distribution of apparatus among the numerous visiting workers who came from all countries to pick up acquaintance with methods of measurement and results in radioactivity. We did not have much equipment to share round and I had to watch that each rheostat and ammeter had as many hours use per day as possible and that each radioactive source was fully available. One of the visitors was the great S. Arrhenius from Sweden, then fairly old, and I used to linger often at his bench on my rounds to talk to and learn from him. On one occasion I expressed to him my admiration at the breadth and depth of his knowledge in almost every branch of physics and chemistry. 'Ah! Mr Marsden,' he replied, 'When I want to know about a subject I put myself down to lecture on it, then I have to study it'—I feel the same regarding the subject of the factors which contribute to greatness and genius. Rutherford had both these qualities. I want to learn from the preparation of this talk, and discussions with some of you afterwards, as to the contributions of nature and nurture in his make-up and characteristics. Environmental factors greatly influence intellectual development. Thus if I dwell too long over the description of his formative years please forgive me. We used to be told that the contributions of heredity and environment were about 50:50. I pose to you the question at any rate in regard to his character of greatness even if not to that quality of insight which is an attribute of genius whether the proportions should not be about 25:75? Do not put me down on that account as a follower of Lysenko. No environment can develop certain qualities which are not innate, it can only allow for their fuller development. In all walks of life more people fail from lack of grit than from lack of inborn cleverness. But the answer to my question is very relevant to the whole system of education and the development of that leadership of which we are so much in need and he was so outstanding an example.

To come to my more immediate task, Ernest Rutherford was born on 30 August 1871 the fourth of a family of twelve in a tiny hamlet of Brightwater, later called Spring Grove some 12 miles south-west of a small town Nelson on the north coast of the South Island of New Zealand. His early life is interwoven with the epic story of the early colonization of New Zealand, for the Nelson province had been found and founded only 29 years earlier, his father as a young boy and his grandparents having arrived from Perthshire in one of the first small sailing ships conveying the settlers. This early settlement was a private enterprise venture of the New Zealand Company in which, thanks to Henry Gibbon Wakefield, there was much practical idealism, albeit accompanied in the prospectus by rashly optimistic statements— probably not deliberately so—but tempting to would-be settlers. The immigrants were of good type and selected from sober, intelligent and mainly God-fearing applicants, most of them healthily dissatisfied with social conditions and opportunity in certain parts of Britain. They were knit together in a closely integrated community by the exigencies of the long perilous voyage (over six months) and by the necessity for co-operation in facing the problems of settlement. The colonists

were deliberately selected as a cross-section of the communities from which they originated—large farmers, small-holders, labourers, artisans and members of the professions but the area on which they settled was at first hemmed in by almost impassable mountains and they became more of a community of small-holders.

In these conditions there grew up a vigorous healthy democracy in which the common good was the main objective, which encouraged initiative and respected leadership, and in which each helped the other as the first principle of duty and loyalty yet with a strong core of practical common sense rather than artificial sentimentality. Those of us who were privileged to know Lord Rutherford will appreciate how much of his social and political outlook reflected the influence of this environment.

In spite of the primitive conditions, mutual education and the provision of schools for children were pursued to a degree which is well nigh astonishing, for in addition to a public, mainly residential secondary school—Nelson College— established in 1856 and endowed from land reserves, the primary school system was a model to the rest of the colony. In 1877, the year after Rutherford began attendance, the system was consolidated into a national system of 'secular compulsory and free' education—even at that time a bold experiment which caused New Zealand to be regarded as a very advanced country in educational matters. In this environment Rutherford's father James had grown up to be vigorous, self-reliant and resourceful, occupying himself as general contractor, bridge builder and at any job which was profitable at the time. He rode to his tasks on a wooden bicycle of his own construction. He married in 1866 Martha Thompson, who, with her young widowed mother, had emigrated from Hornchurch, Essex on the death of her husband who was said to have been an able arithmetician. Martha and her mother had moved to the more peaceful Nelson district from New Plymouth, where they first settled, because of the Maori wars in Taranaki, and mother and daughter in turn occupied the position of teacher in the small local primary school.

Rutherford's father built a small wooden house for his wife and there Ernest was born and had a healthy outdoor upbringing, the climate being equable, lat. 41°S. with some 35 in. of well-distributed rainfall and nearly 2500 h. of sunshine per annum. He progressed satisfactorily through the primary school standards until the family moved when he was eleven years old to the small seaside village of Havelock where the father set up a timber mill and also machinery for decortication of New Zealand native flax (*Phormium tenax*). He was a healthy, happy, merry and some-what boisterous lad who in his spare time from school and home chores including milking the family cow, roamed the countryside snaring pigeons and fishing. His wits were sharpened by the interplay and repartee of the rest of the lively family.

The father was a man of great character, mechanically ingenious and of fine disposition, straight and honourable in his business dealings. In private life his lovable nature manifested itself and he was ever doing unostentatious kindnesses to visitors and neighbours. The mother Martha was a truly remarkable woman of good education and character, thrifty and hardworking, a good organizer as indeed, with so large a family, she needed to be. She would assemble the family on Sundays

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for music and religious exercise, she playing the piano and the father the violin, followed by spelling bees and geography lessons using a map to illustrate world events as recorded in the newspapers as they came to hand. She maintained a good standard of use of language in the house. Only for a period following the death of two of the younger boys by drowning in the adjacent sounds did she lose her sunny disposition. She was the family treasurer but in spite of the demands on her purse the family on one occasion raised £10 towards the Indian famine fund. (It was characteristic of Ernest in later life that he was ever ready to assist a known worthy object, and help an unfortunate but deserving student. Similarly when awarded the Nobel prize in 1908 he made handsome gifts to his mother and the rest of the family.)

Mrs Rutherford had at that time a governess to assist with the younger children and the latter has recorded 'Ernest never needed to study; having read a school book once he knew it. He was a lively boy and I loved to see him and the other children at their mother's knee at prayer'. One can trace to this period the hymns which were engrained on his mind and which later he unconsciously and unknowingly regaled his co-workers on occasions, particularly 'Onward Christian Soldiers' when experiments were going well.

I have talked to Rutherford's parents and brothers and sisters. The home was calm, happy and united. The mother inculcated habits of good reading and concentration; she arranged for special tuition in Latin by the primary school teacher before normal class hours. There was provided for Ernest an excellent small book on physics by Professor Balfour Stewart published in 1880 which bears his name on the inside cover and the date July 1882. The preface to the book states 'The authors aim is not so much to give information as to endeavour to discipline the mind by bringing it into contact with nature herself. For this purpose a series of simple experiments have been described leading up to the truths in the science'. We can appreciate the endeavour to overcome the disadvantage of the lack of emulative stimulus of a small country school. Equally important was the inculcation from his father's example of the habit of work for practical aims, using simple means at hand. On one occasion Ernest worked out the quantities of excavation and spoil required for a local roadway.

The time came when Ernest was ready to compete for a scholarship to the provincial secondary school, Nelson College, valued at 50 guineas per annum. His eldest brother George had won this scholarship some years previously and although he had attended Nelson College for a period, according to a statement made by his mother on an occasion later, the family finances were such that he could not be spared to stay at the College for a period necessary to prepare for presenting himself for a University Entrance Scholarship. I cannot resist recalling the happenings at a village evening meeting in his honour when I accompanied him on a visit to the district in 1925, 39 years after the examination. It was a merry and jolly occasion. There was present the retired district inspector of schools, a Mr Lambert, and in the reminiscent vein he told the story of the scholarship examination which he had supervised in December 1896. He told of the rivalry between the various country schools, each ambitious to have one of its pupils gain

the coveted award. The local school committee had requested and been granted the privilege of having its candidates examined in their own school to avoid the disturbance of travelling and staying overnight in unaccustomed surroundings. Great local interest had arisen and when the day of examination arrived, a hot summer day, interested residents would present themselves at the open door at the schoolroom and in an anxious whisper ask the supervisor as to how the pride of the school was progressing. The supervisor had in the meantime perused the finished pages of the candidate's script as they lay alongside him. The awespoken answer to one query was 'he is doing fine, but he has made a bloomer in one question'. This was duly relayed to the hamlet and gloom ensued. However Ernest was a quick worker and he had time at the end to look over his answers and he duly discovered and rectified the error with the result that he won the scholarship with record marks. Geography 125/130; history 125/130; English 130/140, arithmetic 200/200. Total 580/600 and although Rutherford was about half a year older than the average of the other provincial candidates this success was remarkable when considered against the background of the one-teacher schools he had attended.

Thus he entered Nelson College accompanied thereto over the rough mountain forest track by his father, both on horseback. He was placed in the Vth form because of his prior knowledge of Latin. His secondary schooling was liberal; broad and not unduly specialized, although mathematics was his strong subject. There were only 80 pupils at the time and this allowed for such relations between masters and boys that together they could go for 'hikes' in the surrounding country at weekends—thus the story of Littlejohn, the mathematics and science master, and Rutherford, engaged in a geometry discussion illustrated by rough markings with a stick on the soil beneath them.

Rutherford, although he obtained prizes in most subjects and ultimately became head of the school, was by no means a bookworm or what is colloquially termed a 'swot'. He entered into the full life and games of the school in every way. He joined the military cadets and also played rugby as a forward. He was mechanically minded, tinkering with clocks and water-wheels. He enjoyed reading, music, and photography. Few special stories of his school experiences have been reserved, indicating that he was not looked on as exceptional or peculiar in mannerisms. However Mr C. H. Broad who was a classmate and later became headmaster of the school has stated 'What always struck me most about him was his extraordinary powers of concentration even in the midst of turmoil'. Such of his other fellow pupils as I have spoken to lit up with pleasure in recounting their recollections of him and none showed jealousy or envy.

I have spoken rather long perhaps of Rutherford's early boyhood, but I wish to draw attention to the advantage of such an environment in building a strong, healthy constitution and in creating habits of work and clear thinking yet still allowing for the development of initiative, enthusiasm and joy of work and living under natural rather than artificial city conditions of education and more organized amusement and entertainment. The human characteristics I have illustrated were engrained in his habits and attitudes and were always to the fore in his later life,

in fact they were preserved in his relations with colleagues and friends to a greater extent than is usual with most men, for he retained this happy boyishness throughout his whole life. I would not wish to infer that he was a copybook hero. There are many records of amusing mischievous episodes but none of vice. He could 'flash fire' on occasions when annoyed or thwarted but he soon calmed down and never showed malice.

Nelson College must have produced lasting and happy impressions on him, as he took the title of Lord Rutherford of Nelson when elevated to the peerage and his last words before he died were a request to his wife to provide a small gift of money to the college.

After three years secondary-school education he presented himself for the highly competitive university entrance scholarship although he had qualified for matriculation the previous year. His success enabled him to enter Canterbury College in February 1890 at the age of $18\frac{1}{2}$ years so that he was reasonably mature. The story is told that he was digging potatoes in the garden when the news came of his success and that he threw down the fork, presumably after finishing his task, with the exclamation: 'That's the last potato I'll ever dig.' It meant of course that he was no longer likely to be a small farmer.

The early establishment of Canterbury College was another example of the zeal for education shown by the early colonists. It had in Rutherford's time seven professors and about 250 registered undergraduate students. Two of the professors in particular influenced him, Cook whose mathematics was sound and orthodox and Bickerton who taught physics and chemistry and was highly original and stimulating although wide in his interests and enthusiasms and erratic in his methods. Again, as at his secondary school, Rutherford was highly placed in his class examinations although he had at least one close rival. He was liked by all his fellow students, was ever ready to assist and be assisted by them, and he took a full part in the activities of College societies, becoming secretary of the College scientific society where a wide variety of subjects was discussed. In his third year he qualified B.A. with a senior scholarship in mathematics and the following year he took his M.A. degree with first-class honours in both mathematics and physics. He returned for a fifth year to qualify for a science degree and started on research investigations of the magnetization of iron by high-frequency discharges from a Tesla coil; work in which he could have received little theoretical guidance other than stimulating enthusiasm from his professor. He showed considerable ingenuity in devising home-made apparatus for his measurements and established that such high-frequency damped oscillations could magnetize thin steel wire so that the arrangement could be used for detecting Hertzian or wireless waves across the 60 ft. iron shed in which he worked. This was before Marconi had been heard of although the latter perfected later the application of the principle and made it continuously recording.

He presented his thesis with an application for the 1851 Exhibition Scholarship. There was another good candidate; a chemist, J. C. Maclaurin. It is always difficult for the university authorities to assess the relative merits of candidates who present work from the various University Colleges and in different sciences, fortuitous

factors influence the choice. At first Maclaurin secured the nomination and he was certainly a fine man and exceptionally able. His thesis was a valuable contribution to the cyanide process for gold extraction. His brother was R. C. Maclaurin who was later one of a band of close personal friends at Cambridge, another being de Villiers of South Africa. R. C. Maclaurin afterwards became a great president of the Massachusetts Institute of Technology, Boston, U.S.A.

Rutherford, thinking he had missed the award, took a temporary teaching post at a local secondary school where he was not very successful as an orthodox disciplinarian. He also entered into correspondence with a college friend who had gone to Edinburgh and with a view to entering on a medical course there on easy financial terms—there were few postgraduate scholarships in those days. However in the meantime Maclaurin had married and accepted a post as New Zealand Government analyst and was unable to take up the scholarship, which was then offered to and accepted by Rutherford. The scholarship was of value of £150 per annum but there was no allowance for travel to Britain, so Rutherford had perforce to borrow, from his father and eldest brother, and this necessitated careful living for the first years of his career in England. He travelled by a ship which called at Australian ports. He visited the university physics departments there and at Adelaide he met Professor, afterwards Sir William H. Bragg, thus inaugurating a friendship which became closer as they advanced in years. He had decided to work under Professor J. J. Thomson at the Cavendish Laboratory, Cambridge, and in the meantime had studied all J. J.'s published papers.

On his arrival at Cambridge in October 1895 he continued to work on his magnetic detector. He drew favourable notice to himself by detecting wireless signals up to a distance of 2 miles and describing his results at the British Association in the following year and publishing later in the *Transactions of the Royal Society* (A, **189**, 1. 1897). They were important pioneer investigations.

In the meantime great scientific and even public excitement had arisen over the discovery of X-rays by Roentgen at the end of 1895 and the later observations by J. J. Thomson that these rays had the power to produce temporary electrical conductivity in air. This discovery of X-rays was not quite the isolated accident which is sometimes made out. During the previous decades the subject of spectroscopy had been under investigation in many European university laboratories, and the longer it was studied the greater the complexities appeared, especially in gases rendered luminous by electric discharge under reduced pressure. To clear up the difficulties it became necessary to examine more closely the electrical discharge itself and this cleared the way for great advances. Plucker had found that as the gas in a spectrum tube was gradually exhausted the lead-in conductor or cathode becomes surrounded by a luminous glow which expands as exhaustion proceeds. Hittorf & Goldstein in turn found that with further exhaustion the glow separates out from the cathode as indeed Faraday had noticed and a dark space appears which was found to be traversed by the so-called cathode rays which could cast shadows as a luminescent pattern on the walls of the tube. Roentgen found that his X-radiation set out from the place where the cathode rays strike an obstacle. In the original experiment this was the luminescent wall of the glass tube but,

as subsequently found, a metal target acts better. I mention these developments because they explain why Henri Becquerel in France, considering that the X-rays were somehow connected with the fluorescence, was led to try to obtain X-radiation from the various phosphorescent and fluorescent materials of which he had a good collection from his father and he discovered that uranium and its salts emitted a continuous radiation (February 1896) which was however later found to be independent of its state of fluorescence. Madame Curie discovered in 1898 that thorium showed similar properties and she coined the word 'radioactivity'. In conjunction with her husband she also made the significant observation that while all chemically prepared uranium compounds were active, approximately in accordance with their content of the uranium element. Pitchblende—which is a uranium mineral—was weight for weight decidedly more powerful. This led the Curies ultimately to the discovery of radium and of polonium by chemical separation from the pitchblende.

To return to Rutherford; in view of the excitement following Roentgen's discovery of X-rays he dropped his wireless work and joined his professor (Easter 1896) in an investigation of the nature of the electrical conductivity which the rays imparted to gases. He made the important observation that the electric current between two parallel metal plates in air traversed by X-rays increases as the distance apart of the plates was decreased, contrary to the ordinary application of Ohm's law to solids and liquids. They also discovered that as the voltage between the plates was increased the current rose to a maximum which they called the 'saturation value' and which depended only on the intensity of the radiation. From a brilliant series of experiments J. J. Thomson and Rutherford were able to explain the main features of the conductivity on the hypothesis that charged ions were produced by the radiation throughout the volume of the gas.

They went on with Zeleny to measure the velocity of the ions under electric forces and Rutherford measured their rate of recombination and its governing laws so that a good picture emerged of the whole process which led to his remark that 'Ions are jolly little beggars, you can almost see them'. Following Becquerel's announcement he tried uranium and found that its radiations were able to produce ions in a gas with similar properties to those produced by X-rays. This was probably for him the most important event in his career for it directed his work towards radioactivity, which subject was to occupy him for the rest of his life. His next result was the discovery that uranium emitted two kinds of radiation, one very easily absorbed and with limited range which he called α and one fully a thousand times more penetrating which he named β.

By this time the tenure of Rutherford's 1851 Exhibition Scholarship was coming to an end and although he had obtained another scholarship in the meantime, the Coutts Trotter, it would provide only sufficient for bare maintenance until such time as he might possibly hope for a college fellowship. There had naturally been a suspicion of a little jealousy on the part of a few that the Coutts Trotter should have been awarded to one who had not gone through the regular Cambridge degree course and Rutherford feared that similar feelings might arise in regard to the possible award to him of a fellowship. Such consideration combined with a natural

desire to marry Mary Newton of Christchurch, to whom he had been affianced before he left New Zealand, were probably the main factors in his decision to apply for a position which had become vacant at McGill University in Canada. The post was known as the Macdonald Professorship, having been endowed by Macdonald along with excellent laboratory buildings. The salary was £500 per annum which Macdonald thought sufficient as he himself, although a millionaire, lived on £250 per annum. Rutherford was successful in obtaining the position thanks to a strong recommendation from Thomson and he sailed for Canada in September 1898, working almost to the last day before sailing writing up for publication papers describing his work to date. He had already planned his work at Montreal. He wrote to his fiancée regarding the vacation period in the following year 'Am I to go to New Zealand to fetch you to look after me and become Mrs Professor, or am I to wait another year to get enough cash to do it in style?' In the end they waited until May 1900. His only child Eileen was born in 1901.

Rutherford was greeted in Montreal with that genuine friendliness and hospitality for which Canada is famous. The atmosphere at McGill was more in tune with Rutherford's colonial personality than was the more traditional Cambridge at the time. We can count it fortunate for science and for Canada that his appointment was so timed. Above all, however, Rutherford was fortunate in that his exuberant friendly nature found such a ready response, fortunate that his senior colleague Cox gave him such loyal support and relieved him of much of the routine work of organization and teaching and fortunate again that Macdonald later provided finance to purchase first a quantity of radium with which to work and secondly a liquid-air machine without which some of his best experiments could not have been performed. Rutherford was now on his own resources with at first no one at hand with whom to discuss his particular line of investigation. In how many similar cases of scientists taking up Dominion or Colonial appointments has the appointee been unable to overcome the initial difficulty of starting work quickly enough to keep up with the frontier of advance in their particular specialization and settle back to the useful but less inspiring position of being a teacher only?

In Rutherford's case, he plunged quickly into his researches; fortunately, only simple apparatus was required apart from the quadrant electrometer which was a capricious instrument which he learned to replace by home-made electroscopes. Following further investigations confirming the two types of radiation from uranium and experiments on ionization produced by ultra-violet light and by heated platinum he turned his attention to thorium and assisted by Owens, the lecturer in electrical engineering, some very perplexing observations were made. The conductivity produced in air by some compounds of thorium and particularly the oxide thoria was found to vary in a very erratic manner. For example, a slight draught of air caused by the opening and shutting of the door of the room often altered markedly the movement of the electrometer needle. It was found that the conductivity persisted when the thoria was covered with a few sheets of filter paper. By passing a steady current of air over the thoria the activity was much reduced. In these respects thorium compounds were very different from uranium from which the radiation was constant. Finally, by passing a current of

air over thoria through a long tube and by examining the conductivity at different parts of the tube he found that the radioactive effect of the gas decayed with time according to a definite geometrical law, falling to half value in approximately one minute. It thus seemed clear that the thorium emitted some substance which could be carried away in a gas stream and he gave the name 'emanation' to this unknown substance. Contemporaneously he noticed that all substances remaining in contact with the emanation themselves became active. This excited radioactivity, as he called it, decayed with time according to the same exponential law as the emanation, but falling to half value in about eleven hours. The active deposit was found to be soluble in certain solutions but not in others and could be dissipated by heat.

The discovery of thorium emanation was followed elsewhere by Dorn in 1900 who discovered radium emanation with a half-value period of 3·8 days. This too, as Mme Curie found, gave rise to induced activity. In England also Sir William Crookes ingeniously extracted by chemical methods a substance uranium-X from uranium nitrate which thereby became weaker in activity while the new substance uranium-X decayed with a half-value period of 1 month and the original uranium recovered at a corresponding rate. Thus the properties of radioactive substances began to appear very complicated. Rutherford had in the meantime attracted several workers to join in the chase and his laboratory became a hive of activity. Among others he was joined by the lecturer in physical chemistry F. Soddy and together they planned a general attack on the phenomena, Soddy doing the chemical work and Rutherford the measurement of the various radiations. Soon they discovered thorium-X produced from thorium and intermediate between thorium and the emanation and with a half-value period of 4 days independent of age. I was at a Physical Society function in London in 1948 and R. S. Willows described graphically a visit he paid to Rutherford at the time. Rutherford had many experiments in progress with different extracted substances and in different rooms on various floors of the laboratory. Willows had to rush with Rutherford from room to room in a breathless series of measurements which could not be delayed and the discussions had to take place en route or during the course of the measurements.

Gradually Rutherford sorted out the phenomena, all products seemed to have characteristic half-life periods, some emitted α-rays, some β-rays and some seemed to be rayless but produced other products which were active. As to the emanation, they proved it to be of high molecular weight analogous to the rare monatomic gases found in the atmosphere, quite unaffected by chemical reagents but capable of condensation by liquid air. The great contrast in the physical and chemical properties of thorium-X and emanation gave them the first definite clue that radioactivity was a consequence of successive transformations of elements and led to the enunciation of the disintegration theory—this was written in a paper for publication and in sending it via Sir William Crookes Rutherford wrote (1902):

'I am sending you a manuscript by Mr Soddy and myself on the radioactivity of thorium. We know that thorium-X like uranium-X, loses its activity in a geometrical progression with time, yet the deactivized thorium regains its activity

with time. I think we have conclusively proved that most of the radioactivity is due to the production of thorium-X by the thorium at a (practically) constant rate and that this thorium-X decays with time. The equilibrium point is reached when the rate of production is balanced by the rate of decay. We have strong evidence that uranium and radium behave similarly, only that the time rate of change is different. All these processes are independent of chemical and physical conditions and we *are driven to the conclusion that the whole process is subatomic*. I believe that in the radioactive elements we have a process of disintegration or transformation going on which is the source of the energy dissipated in radioactivity.'

A year later came an even clearer statement; writing of a single radioactive substance the principle is laid down 'The rate of change of the system at any time is always proportional to the amount remaining unchanged'—'the proportional amount of radioactive matter that changes in unit time is a constant' called the radioactive constant. This constant is of course simply connected with the half-life period and its reciprocal is the average life of the atoms. Another way of expressing the same meaning is that the radioactive constant expresses the probability for each atom that it shall disintegrate in the next succeeding time interval adopted. Thus if λ is the radioactive constant and N the number of atoms present at any time then in a next succeeding small interval of time dt the most probable number of disintegrations will be $N\lambda dt$. Rutherford with consummate skill mastered the radium family also. Radium—emanation—radium A, B, C, D, E and F all in linear descent. He identified radium F with Mme Curie's polonium. He presented the whole story complete to the Royal Society in his 1903 Bakerian lecture which is a classic (*Phil. Trans.* A, **204**, 169, 219, 1904).

There was still much work to be done on the radioactive transformations between radium and the ultimate parent uranium for example. His great friend Boltwood at Yale had established the constant ratio of the quantities of these elements in radioactive minerals as was predicted by the disintegration theory. Work was also needed on the series of products between thorium and thorium-X and the place of the actinium family. Many workers were attracted to his laboratory to study these and allied problems relating to the radiations themselves and workers in many foreign laboratories freely corresponded with him, trusting him implicitly to safeguard priorities of discovery. Among those who came to work with him was Otto Hahn who afterwards discovered the fission products of uranium. I can best describe the spirit of the work by quoting from Hahn's reminiscences (*New atoms—Otto Hahn*).

'I made up my mind to get a good grounding in this new field of study by working under Rutherford at Montreal, for Rutherford was already regarded as the leading authority on radium. Travelling in those days was a much simpler matter than it is to-day. You simply picked your berth and took your departure. No necessity for visas and such things.

'The atmosphere in the Rutherford laboratory was most exhilarating. Those who were with him at that time have all contributed largely towards the rapid development of radioactivity. The apparatus we used in those days would appear very primitive to-day. We made our own β- and α-ray electroscopes out of a largish tin

can or other sheet metal box with a smaller tobacco or cigarette box placed on top. The leaf holder was insulated with sulphur because in those days we had no amber. In his α-ray experiments Rutherford used a rather ancient Töpler pump for extracting the air. On the other hand, the field of study was so new that it was an easy matter to taste the joys of discovery.

'In Montreal everybody without a trace of jealousy recognized Rutherford as the leader of scientific research. His enthusiasm and abounding energy infected us all and it was the rule rather than the exception to work at the laboratory after dinner. Many an evening too was passed at his house and most of the time of course we talked shop, sometimes a mixed joy for the hospitable Mrs Rutherford.'

Hahn goes on to recall examples of Rutherford's natural jolly disposition and states 'This joyous youthful naturalness was one of the qualities that rendered intercourse with Rutherford such a pleasure'.

Hahn proceeds to recall that even in 1906–7 chemists in Germany as elsewhere had not fully recognized the importance of the atomic disintegration theory and tells of other suggested explanations advanced at a symposium in Berlin. 'I contradicted' he says—'possibly in rather a spirited manner—because after all I had through Rutherford attained a pretty good knowledge of the processes. In Germany however a young man should really have more respect for a Geheimrat and I was advised to exercise a little more discretion, but we had never been expected to exercise discretion of that kind in democratic Canada.'

Another quotation I would like to make is one from McNaughton, Professor of Classics at McGill, who had shot many a satiric dart at scientists and their doings; 'plumbers' and 'destroyers of art' he had called them. He wrote as follows (*McGill University News*, April 1904) 'We paid one visit to the Physical Society. Fortune favoured us beyond our deserts. We had stumbled in upon one of Dr Rutherford's brilliant demonstrations of radium. It was indeed an eye-opener. The lecturer seemed himself like a large piece of the expensive and marvellous stuff he was describing. Radioactive is the one sufficient term to characterize the total impression made upon us by his personality. Emanations of light and energy swift and penetrating and strong enough to pierce a brick wall or the head of a Professor of Literature appeared to sparkle and coruscate from him all over in sheaves. Here was that rarest and most refreshing spectacle—the pure ardour of the chase, a man quite possessed by a noble work and altogether happy in it.'

But I must refrain from these reminiscences and 'get on with it' as Rutherford would say. Apart from his interest in the transformations themselves Rutherford was keenly alive to the problem of the exact nature of the radiations themselves and particularly the α-rays which were to be his particular interest for the rest of his life—used as tools to probe other atoms. J. J. Thomson had already shown that cathode rays were corpuscles or electrons with a mass 1/1840 of that of hydrogen and always the same whatever their origin. It was soon found that β-particles were similar but with speeds up to over 95 % of the velocity of light and with a mass varying as speed increased in accordance with deduction from the relativity theory. The α-particles were something much more massive. Rutherford tried to deflect them in a strong magnetic field in order to

decide whether they were particulate or some type of X-radiation. After many failures on account of the smallness of the effects he obtained from the Curies a stronger source of radium and he was able to show that the α-rays were positively charged particles projected from the radioactive atoms with high velocity and the value of the ratio of charge to mass deduced from the measurements indicated that they might well be helium with a double electric charge. Although this explanation would account for the presence of helium in radioactive minerals he did not rest until by experiments several years later he had developed a method which allowed of no ambiguity.

This proof of the material nature of the α-particles gave definiteness to the disintegration theory by suggesting a more reasonable explanation of the complete alteration of chemical properties of atoms after transformation. I must pass over so much of his other activities in Montreal and those of his band of colleagues; Rutherford was ever loyal to them in question of credit and priority. He pointed out quantitatively the influence of radioactive considerations in questions of geological and terrestrial history. He was ever ready to give lectures to various educational organizations. He demonstrated the use of wireless, his old love, from trains and even took part in investigations of vibrations in buildings produced by nearby trains. He wrote monumental books on the whole subject of radioactivity.

At this stage in his career although he had refused several lucrative and tempting posts offered to him at famous universities in the U.S.A. where he had a host of warm friends, Rutherford was approached by Professor A. Schuster of Manchester who wished to retire and stated that he would be glad to do so if he could be assured that Rutherford would succeed him; he did so in 1907. Schuster was head of a good school of physics and an excellent laboratory with facilities for research, he also offered to provide the finance for a readership in mathematical physics which was subsequently held in turn by Bateman, Darwin and Bohr all of whom, particularly Niels Bohr, were later to contribute so effectively to Rutherford's field of work. I well remember his inaugural lecture in September 1907 with J. J. Thomson and Schuster present, all smiling in happy reunion. Rutherford immediately threw himself into the development of a radioactive school. He was fortunate in that Schuster had bequeathed to him a most able experimental assistant, Hans Geiger, who was to collaborate with him later in such important work and who gave his name to the well-known Geiger counter. He attracted a band of research workers from almost every country in Europe, those obtaining most fame being probably Niels Bohr and Moseley. He was fortunate also in obtaining the loan of a large amount of radium, 450 mg, from the Vienna Academy which was used to supply emanation and active deposit for use in the various experiments. It made possible one of the first major pieces of work, i.e. that of Rutherford and Geiger in which the number of α-particles emitted per second from a gram of radium was directly counted for the first time and also the electrical charge carried by each α-particle. Preliminary calculation showed that the ionization current in a gas due to a single α-particle might be just on the verge of the magnitude necessary for direct detection, but the practical difficulties proved too great with the apparatus then available. Rutherford conceived the idea of

utilizing the property of ionization by collision in a strong electric field to multiply the effect and this method proved successful. Thus the first radioactive particle counter was evolved. Later Geiger perfected the instrument so that it would also count β-particles. The results of this work had far-reaching consequences. It supplied a value for the unit electric charge hitherto known only approximately. It enabled the calculation of much general atomic and molecular data, e.g. the number of molecules per cubic centimetre in a gas. There was one important by-product also. Several years earlier Max Planck in Berlin had made a theoretical estimate of the fundamental unit of electric charge with which Rutherford's value agreed closely, thus indicating the further likelihood of the truth of the premises made by Planck. These embodied the so-called quantum theory. Although Planck's quantum theory in its application to radiation and thermodynamics had found much support, particularly in Germany, yet owing to the difficulty of its visualization as a physical model or in terms of classical physical concepts, his results were looked on by some as fortuitous. Rutherford and Geiger's direct result overcame much of this scepticism and as we shall see later Bohr's attention was attracted to the further consequences of the quantum theory with important results.

At about the same time as the counting of individual α-particles Rutherford with Royds made a beautiful experiment which directly proved that each α-particle when it loses its charge or acquires two neutralizing electrons becomes an atom of helium. An emanation glass container was made with thin walls such that the α-particles passed through the walls and were collected in an outer tube. The spectrum of helium appeared and the volume of helium produced corresponded sufficiently exactly to the number of α-particles involved as known from the counting experiments.

The next experiments were concerned with the so-called scattering or deflexion of α-particles when passing through matter. It was known that α-particles from different atoms of the same radioactive substance are ejected with practically the same initial velocity. As they pass through the surrounding gas or through metal foils they are slowed down by successive collisions with the electrons in the atoms in their path so that they have practically the same 'range'. They also suffer minute deflexions in such encounters which in the aggregate cause the so-called scattering or dispersion of a narrow beam of the particles. Geiger, at Rutherford's suggestion, carried out measurements of the magnitude of this effect. He found that expressed in terms of per atom traversed the most probable angle of scattering was very small but was proportional roughly to the square root of the atomic weight of the atoms traversed. I was assisting in these experiments and at Rutherford's suggestion I looked for and was fortunate enough to observe a special kind of scattering involving very large deflexions and for any given angle, e.g. 60°, the number scattered, although small, varied roughly according to the square of the atomic weight of the scattering material. I remember well the pride with which I reported these results to Rutherford, something like that of a cat delivering a choice mouse to his mistress. A few days later Rutherford suggested that Geiger and I should round off the experiments in a form suitable for publication.

He pondered over these remarkable results for several weeks. Such ponderings and related calculations were generally made in the quiet of his study at home but out of it emerged his inspiration of a nuclear atom with the positive charge of electricity in a very small nucleus at the centre and electrons in outer planetary orbits somewhat similar in relative spatial dimensions to a solar system in miniature—a brave conception in view of its reversal of the ideas current at the time in which the positive electricity of atoms was considered as dispersed in a relatively large sphere. The solution was a direct answer to the problem he set himself to solve, i.e. the origin of the huge forces necessary to deflect the swift moving α-particles and brushing aside the great objection to such a theory on classical ideas, i.e. those relating to the atom's stability and its ability to emit line spectra.

As usual Rutherford wished to consolidate his theory as soon as possible. I had in the meantime taken a position in London but he awarded me a fellowship to return to Manchester and carry out with Geiger the detailed tests of the consequences of the theory, e.g. variation of the effect with velocity, scattering material, and angle, etc. The work established the theory on a sound basis. It involved the individual counting by eye by the scintillation method one by one of over a million α-particles. When I look back and consider, in the light of modern knowledge of safety standards, the nearness of our heads and bodies to the large sources of emanation and the time of exposure to the radiation I marvel that it did us so little physical harm. Fortunately, within two years the experiments of Moseley in the same laboratory gave a more precise significance, in terms of the numerical order of elements in the periodic classification, to the effective number of positive charges in the nucleus of various atoms indicating that the all important property of an atom in its relation to physical and chemical phenomena was not the atomic weight but the so-called atomic number, i.e. the number of effective units of positive electricity contained in its nucleus which was of course also equal to the number of orbital electrons whose positions determined the chemical properties. One important consequence of this was an understanding of the chemical properties of atoms of successive radioactive products, i.e. the emission of an α-particle reduces the atomic number by 2 and alters the valency accordingly and emission of a β-particle increases the atomic number by 1. The theory also led to the enunciation by Soddy in 1911 of the idea of isotopes, i.e. atoms with the same atomic number or nuclear charge and thus having identical chemical properties yet varying in the number of units of atomic mass. The new Rutherford atom did however pose the great problems of stability and of explaining the number of lines in the spectra of hydrogen, for example, an atom of which according to the theory contained one orbital electron only. Rutherford had to suppose electrons as describing orbits, otherwise the attraction of the positive nucleus would draw them immediately into it just as in the case of the planets and the sun in the solar system. On Newton's classical laws the orbit of the electron should be a circle or ellipse of size varying in a continuous way and from atom to atom depending on its history. It seemed impossible to conceive of such an atom giving a line spectrum of emission of light with so many fixed discrete frequencies.

Niels Bohr supplied the answer by an ingenious combination of Rutherford's atom with the principles of the quantum theory and which gave a better physical conception of both. He conceived the orbits as not varying continuously but having stationary states. The lowest one, the one with the least energy—the ground state —is truly stable, the others are excited states excited by collision or radiation. The position and character of the orbits is defined by certain quantum relations depending on one or more whole numbers. When they are disturbed they sometimes radiate but the wave-length or colour of the light they emit is not random and continuous but falls into the sharp lines of the hydrogen spectrum. An atom may return or change to states of lower energy whether by further collision or spontaneously but when it does, the frequency of the emitted light radiation is equal to the change of energy between the states from which it starts and finishes respectively divided by Planck's universal constant 'h'. As to the transitions themselves, their causes and speed of action, the idea was that it was not a question of the moment of transition but of the probability. This simple concept enabled Bohr to calculate to an amazing degree of accuracy the various series of spectra of hydrogen and helium, for example, and even to deduce that the so-called Pickering series belonged to helium and not to hydrogen as was confirmed by Evans in Rutherford's laboratory. It is interesting to read the correspondence which was exchanged between Bohr and Rutherford as the former worked out and wrote up the hypothesis for publication. Rutherford wrote 'How does the electron know when it leaves one orbit which of the others it is going to settle in?' Rutherford also admonished Bohr to make the paper shorter and more concise so as to make it easier for the reader and therefore more likely to be widely read. Perhaps I ought to apply the same advice in this lecture!

Science in spite of all its revolutions is conservative and a new conception of this sort, although a great and far-reaching simplification, takes time to come into general understanding; a generation has to die and the new generation learn to think in the new concepts.* The same was true of Newton's laws, Maxwell's electromagnetic theory etc.

I must now return again to the question of encounters of α-particles with the nuclei of atoms which started all this discussion of atomic structure. Experimental consideration had so far been limited to heavier atoms i.e. to cases where the recoil of the nucleus in collision did not have serious effects. In a collision with a hydrogen nucleus (a proton as it is now called) the nearest approach could be calculated to be 1.7×10^{-13} cm, assuming both acted as point charges and the inverse square law of force still held, a distance which is less than the diameter of an electron. Thus it became of interest to investigate such collisions. Elementary considerations of a head-on collision of an α-particle of mass 4 with a hydrogen nucleus of mass 1 showed that the latter should take on a velocity 1.6 times that of the incident α-particle and have a range or penetrating power 4 times as great. In early 1914 therefore I decided, naturally with Rutherford's encouragement, to investigate these effects—a sort of game of atomic marbles. In general, the results proved to be as anticipated. A serious anomaly showed itself however when the

* The Reith Lectures 1954, J. R. Oppenheimer (*The Listener*).

experiments were made in air using as source of hydrogen a thin film of wax of approximate composition $C_{27}H_{56}$. Too many fast penetrating H particles were observed and it seemed possible that some of them might arise from the source. At this stage World War I broke out and the laboratory team was dispersed and the experiments so far carried out were hurriedly written up.

Rutherford, on his return from a visit started before the war with the British Association to Australia and New Zealand showed great interest in the results and with characteristic selflessness and consideration wrote to ask if I 'minded' if he followed up the work and in the next four years, in such intervals as he could spare from his activities in connexion with experiments on the development of Asdic for the navy, he repeated and extended the experiments with extraordinary results. In considering the work of Rutherford in this period, assisted only by the laboratory steward Mr W. Kay, the difficulties of making accurate observations of such feeble scintillations using the microscopes then available, and the tremendous complexity of the radiations which he found to be involved, one cannot but be filled with admiration for his pertinacity, his intuition in making deductions from the results of each experiment, and his boldness and directness of attack following each clue presented. He had the intuition to try out the experiment in oxygen and nitrogen separately and the crowning achievement was the observation that in the case of collisions of an α-particle with a nitrogen nucleus the latter was transformed and a hydrogen nucleus ejected at great speed. Later the reaction was worked out as follows

$$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H + \text{energy}.$$
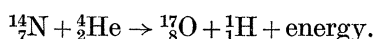
Blackett a few years later confirmed the assumption by a remarkable observation and photograph of the tracks in a cloud chamber.

This result of Rutherford's was the first observation made of artificial transformation of one element into another 'the deliberate transformation of matter'. Previously we could watch and study but not control atomic changes. It gave the clue to and was the start of a whole series of observations of such transformations.

In his Bakerian lecture in 1920 describing the nitrogen transformation and discussing the constitution of atomic nuclei generally Rutherford forecasted a much more effective 'bullet' for the shattering of atoms—the neutron. 'Under some conditions', he wrote, 'it might be possible for an electron to combine closely with the hydrogen nucleus (proton) forming a kind of neutral doublet. Such an atom (neutron) would have novel properties... it would be impossible to contain it in a closed vessel. On the other hand it should enter readily the structure of atoms and may either unite with the nucleus or be disintegrated by its intense field. The existence of such particles seems almost necessary to explain the building up of heavy elements'. Prophetic words to be realized experimentally by Chadwick 12 years later.

At this stage of his career (1919, shortly after the end of the war) Rutherford accepted a call to be Director of the Cavendish Laboratory, Cambridge, in succession to his former professor Sir J. J. Thomson and such men as Maxwell and Rayleigh. This position he occupied for the next 18 years until his death in 1937. Although he did not himself make any further world-shaking discoveries such as the three

I have endeavoured to outline, his powers never manifested themselves to better effect than in his leadership of the Laboratory, the glorious traditions of which he upheld in every way. He consolidated the wider frontier opened up by his discovery of artificial disintegration and his brilliant team kept in the van of progress until practical use of atomic energy was on the horizon, although of course this was not the conscious aim of the work. I will endeavour to sketch briefly the main course of the successive discoveries. First, with Chadwick, he extended the work on nitrogen to such elements as boron, fluorine, sodium, iodine and phosphorus and showed that all these odd atomic number elements could be transformed by α-particle bombardment with the subsequent emission of hydrogen nuclei. This advance was largely facilitated by technical improvements in the microscopes for counting scintillations. Electronic valve methods of counting particles were not perfected until 1932. It was indicated that a kind of synthesis of the atomic nuclei took place in which the α-particle was added to nuclear structure and a portion emitted a period of the order of a millionth of a second later. This was clearly shown in the beautiful experiments of Blackett in which he took photographs of tens of thousands of tracks and was ultimately rewarded by seeing the looked-for effect in the cloud chamber. The results of the various experiments also gave a clearer picture of the forces surrounding and near to the nuclei of atoms and indicated a paradox in the case of heavy nuclei, for example, in that there must be an electric potential barrier of some 10 000 000 volts, whereas α-particles can be emitted from some of these nuclei, e.g. uranium, at energies of the order of 6 000 000 volts. The solution of this problem was provided by a visiting Russian scientist Gamow based on the new so-called wave mechanics under development by Schrödinger and this solution led Cockcroft and Walton to try the effect of protons artificially accelerated by high voltage electrical apparatus. They were ultimately successful in April 1932 when a target of lithium was bombarded by 600 000 volt protons. A scintillation screen set up near the target showed a stream of artificially produced α-particles resulting from the break-up of the lithium nuclei:

$$\mathrm{^{7}_{3}Li + {}^{1}_{1}H \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + energy.}$$
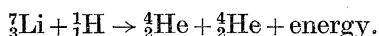
This was an epoch-making achievement in that it was a wholly man-controlled nuclear transformation. It was even more important, for it proved quantitatively for the first time the validity of Einstein's equation

$$W = mc^2$$

(where W = energy produced in ergs; m the loss of mass, and c the velocity of light) expressing the equivalence of mass and energy originally announced in 1908. The transformation indicated in the scheme reproduced above involved a loss or disappearance of mass from 7·0182 (Li) + 1·0081 (H) i.e. 8·0263 to 2 × 4·0039 (He) i.e. 8·0078 or 0·0185 units which was found to equate fairly accurately to the kinetic energy of the α-particles produced as deduced from their speed. This result of Cockcroft and Walton led to the construction in other parts of the world of more powerful voltage machines and other similar devices for accelerating ordinary protons, deuterons (^{2}H) and helium nuclei, notably the first cyclotron of Lawrence

in California. It established the use of Einstein's equation in its application to such transformations, and later this had such important consequences in the practical study of nuclear energy.

In the same year (1932) as Cockcroft and Walton's achievement, Chadwick made the experimental discovery of the neutron. Professor and Mme Joliot Curie had found that the radiation produced when α-particles bombard beryllium had unique properties but it was difficult to devise a picture of the process. Chadwick showed that the new radiation was probably material with about the same mass as a proton and his deduction that it consisted of neutrons has stood the test of time. Incidentally, in the same year Anderson discovered the positron and Urey deuterium. Following on, Feather at Cambridge found that, as Rutherford had forecast in 1920, the neutron is very effective in producing nuclear transformation, particularly when slowed down to so-called thermal speeds by simple multiple collisions. The reason is, of course, that, being uncharged, it is not repelled by the positive charge of the nucleus and can make contact with it more readily. Fermi of Italy, however, made a more comprehensive study and examined the reactions with most elements. He made observations with uranium and obtained four distinct radioactive products and was at first led to believe that in neutron capture followed by emission of β-particles, certain of what he called transuranic elements had been formed but had only a short life.

At about this stage Rutherford may have begun to see the practical possibilities of obtaining energy from atomic transformations, for in the Watt Anniversary Lecture in 1936 he stated 'The recent discovery of the neutron and the proof of its extraordinary effectiveness in producing transformations at very low velocities opens up new possibilities, if only a method can be found of producing slow neutrons in quantity with little expenditure of energy'. In other pronouncements to other audiences he was more cautious. Alas, he was not to live to see his speculative prognostications realized; after a short sharp illness he died 19 October 1937, but before referring to this further I will try to complete the story of the birth of practical atomic energy.

Following Fermi's observations with uranium bombarded by neutrons, Otto Hahn of Berlin, who had worked with Rutherford in Montreal and was an experienced radiochemist, took up the running and by careful chemical work assisted by Strassmann found late in 1938 that one of the products from uranium was barium—a highly unexpected result. He also later obtained or confirmed evidence of the production of other medium atomic number elements e.g. lanthanum and cerium. Thus by the bombardment with neutrons uranium had been split up into two nuclei of moderate weight, the one barium and the other— as was soon discovered—krypton. Their nuclear charges 56 and 36 respectively add up to 92, that of uranium. Lise Meitner and Frisch in Bohr's laboratory in Denmark, as refugees from Nazi Germany, were the first to give the explanation, i.e. that fission of the nucleus had taken place into two major fragments and it was deduced from Einstein's equation that tremendous energy was liberated. The mass of the highest known isotopes of barium and krypton add up to 224 while the uranium-235 which had undergone fission after absorbing a neutron had the

20-2

mass number 226. Apart from the possible loss of mass by radiation from the fragments before barium and krypton appeared, there seemed a possibility that several neutrons were emitted directly in the fission explosion. The actual experimental proof of this was given first by Joliot Curie and his co-workers in France and independently by workers in the United States to whom Bohr, as a visiting lecturer, had given the news of the antecedent developments by Meitner and Frisch.

Theoretically this opened up the realization of a chain reaction, i.e. a reaction in a bulk of uranium continued by new neutrons from fresh fissions and with this a practical technical utilization of the energy set free in fission, each pound of fissile material uranium-235 producing as much heat energy as 1000 tons of good coal. In recording this more recent history of the steps leading to atomic energy I am sure you will have been struck, as I have, with the interplay of the various stages of development between workers in many different countries. Science is truly international. There is less free and prompt exchange of research information in the subject nowadays.

Realizing the significance of the work for potential war purposes and the war having broken out, the leading workers voluntarily arranged for suppression or delay of further publications and this was later made mandatory. It is a matter of history how the huge industrial effort required for more immediate atomic bomb production was taken over by the United States with consequences which burst on an astonished world at Hiroshima. We have now come to a stage where atomic energy for civil power production is an economic proposition for many countries where conventional fuels are scarce or dear and as time goes on even these later limitations may disappear. It is a question of 'knowhow', of engineering and of metallurgy and the choice of natural or enriched atomic fuels, moderators and coolants. We are at the same stage of relative development as was the crude use of steam about 125 years ago except that we have a firmer basis of calculation of the results and the tempo of progress is quicker.

Recently there has been interest in the so-called hydrogen bomb which is based on a principle different from that of breaking down the heavy fissile materials uranium-235, plutonium or uranium-233, although it needs a small uranium or plutonium bomb as detonator. It is based on the principle of building up hydrogen and/or its isotopes deuterium or tritium into helium or possibly with other light atoms such as lithium. When such combinations of these very light nuclei occur there is a loss of mass. Thus for example the mass of helium is 4·0039 units and if it is built up of protons and neutrons of mass approximately 1·0081 each there is a loss of mass of $4·0039 - 4 \times 1·0081 = 0·029$ unit which must in terms of Einstein's equation appear as energy and of the same order per pound of material as when fission of uranium takes place. However, for the action of nuclear combination to take place the hydrogen or hydrogen isotope nuclei must bombard each other with such speeds that the repellent electric forces are overcome. This can be calculated on the kinetic theory to involve a temperature of some 20 000 000 degrees. Hence in order to initiate this explosion the only known method is to use the centre of an exploding uranium bomb. The great 'advance', if we can call it such, of this

H bomb is that there is no upper limit to it except the carrying capacity of the aeroplane, etc., for the deuterium, tritium or lithium deuteride contained. The particularly unpleasant thing about this method of producing energy is that it does not at present appear likely that as in the case of uranium, it can be used for peaceful purposes. We can reach the temperature of 20 000 000 degrees or more only for millionths of a second and not for any length of time. A so-called 'slowly controlled' reaction is not yet considered probable.

On the theoretical side and more free from security measures but with what practical applications no one can foresee, there are still great problems in course of investigation. They concern the nature of the very near nuclear forces which hold the protons and neutrons together inside the nucleus. The understanding of these questions is still very rudimentary. There are nearly 300 different sorts of stable nuclei and with different properties. In addition there are many hundred unstable radioactive nuclei produced by collision methods and which have a limited life. It has been necessary to introduce the idea of internal nuclear attractive forces applicable only for short distances and of a different nature to and falling off with distance more rapidly than electric or magnetic forces. Although there is evidence of asymmetry of shape and spin in these particles which might bring magnetic forces into play, but these seem to be far too low in magnitude. It appears likely that a theory of nuclear structure must essentially be a wave theory such as Bohr and others developed for the electron structure of the outer atom. All the elementary particles concerned have some wave-like properties and every wave such as light or γ-rays have some discrete particle-like properties. There are signs of regularity and order in the structure of nuclei. Certain types of nuclei are unusually stable and abundant in nature, those which contain definite numbers of neutrons or protons e.g. 2, 8, 20, 50, 82 and 126. The so-called 'shell' model of geometrical structure of the nucleus conceives successive shells of 2, 6, 12, 30, 32 and 40 particles. Each nuclear particle is supposed to move in a sort of planetary orbit. The big electric machines, cyclotrons and the like, are being used to produce high-energy particles to probe these structures.

Meanwhile, a new field of physics is exciting great interest, that relating to a study of a new series of still smaller particles than neutrons, protons or α-particles and which are produced when protons and neutrons, etc. of very great energy collide. These particles named 'mesons' were first discovered in the so-called cosmic rays but are now being produced by the giant electric machines giving of the order of 1 000 000 000 volts. They are named μ-mesons, π-mesons, τ-mesons, κ-mesons, neutral and charged V-particles and hyperons. The approximate masses of these new particles in terms of the electron mass are (see Blackett, *The Listener*, 18 March 1954) 207; 263; 273; 966 and even greater than the proton (1840), i.e. as much as 2190 to about 2600. They are all not necessarily fundamental particles; some of them are probably complex in structure. They are mainly investigated by their tracks in the emulsion of photographic plates of very fine grain and are produced, by using very big machines mainly in U.S.A. laboratories or the cosmic rays from nature's super cosmotrons situated in space among the stars. It seems likely that an understanding of these mesons may throw light on

internal nuclear forces and problems. We are waiting for another Rutherford to gather up all the evidence and produce from it an outstanding generalization or new principle to light the path to a fuller understanding of these sub-universes and of the more basic laws of nature.

I am coming to the end of my story. I appreciate it has been more of the nature of a history than the announcement of some new sensational facts of discovery. The subject of nuclear fission suffers from the handicap that many of its results are only tardily being taken off the secret list. Rutherford died before these aspects of secrecy arose. It is probable that they would have been repugnant to him for he was essentially an internationalist; probably no scientist in history has been, during his lifetime, so much respected and trusted internationally. In 1933 he had given evidence of his international sympathies by becoming Chairman of the Academic Assistance Council set up to care for the interests of academic victims of the Nazi persecution. At his laboratory in Manchester for example he had working with him men and women from Japan, Germany, Denmark, Sweden, Holland, Russia, Poland, Austria, Italy, U.S.A. and practically all the Commonwealth countries while his correspondence shows that he was in active correspondence with scientific leaders from all these and other countries. Since his day his particular science has become more a matter of direct and sponsored development by governments. When we read in the recent book by Dean (*The report of the atom*) that for the last decade nearly 5 % of the huge construction resources of the U.S.A. have been applied to the testing out and application of the single idea and uses of atomic energy and largely for weapons of destruction, and no doubt a similar effort has been made in the U.S.S.R., we begin to appreciate a little of what is meant by certain ideas of man's mastery over nature and the high importance in national and world affairs of what Sir Henry Tizard calls the 'strategy of applied science'. This calls for a high level of thinking and philosophy on the part of our leaders and corresponding level of understanding on the part of the community as a whole. What is right for one country is not necessarily right for another at the same time and what is right for one brief period of history is not necessarily always right.

It is of course a commonplace that the discoveries and applications of science are the leading features of the present age. It was only in the nineteenth century that instances became numerous, e.g. the electric telegraph and the dynamo, where science preceded or led the way to practice. Before that time invention and other improvements in the arts had proceeded for the most part slowly and gradually and independent of organized science or set the pace for scientists to follow. The nineteenth century thus saw the growth of scientific knowledge and method to a point where its advance was universally hoped and striven for as a method of obtaining proper human desires and improving living conditions. We have now, however, in the middle of the twentieth century arrived at a position where many people are becoming afraid that science, in some of its directions of advance, has become the arbiter of our destiny instead of the servant. I myself do not take so gloomy a view; moreover, interest in knowledge itself will always remain a potent force in mankind, even though the expression of this

interest may for brief periods be overshadowed by the struggle for power, yet it must ultimately benefit and link together people of all nations and races.

I do agree however with the scientific historian Dingle, and this is the excuse for what I have tried to say to-night, that we ought to survey broadly and historically the change that has come about so that we can understand it and, by understanding it, hope again to achieve the mastery of our own accomplishments. The present is the child of the past and is moderated and qualified thereby. Man is primarily the thinking animal, so that the history of his thought and speculation must be the most important part of his whole history. I have endeavoured to deal with only a small and specialized part of that history—a big advance it is true and arising from the emergence of one of those great men who seem in history to arise in the world, and in a local environment which allows for their right development, about once in a century or so.

As to Rutherford, the subject of my talk to-night, I can best conclude with the tribute of Sir James Jeans given at the time of his reading of the Presidential address to the Indian Science Conference in January 1938 which had been prepared by Rutherford about two months before his untimely death.

'Those of us who were honoured by his friendship know that his greatness as a scientist was matched by his greatness as a man. We remember and always shall remember with affection his big energetic exuberant personality, the simplicity, sincerity and transparent honesty of his character, and perhaps most of all, his genius for friendship and good comradeship.

'In his flair for the right approach to a problem as well as in the simple directness of attack he often reminds us of Faraday, but he had two advantages which Faraday did not possess—first exuberant bodily health and energy, and secondly, the opportunity and capacity to direct a band of enthusiastic co-workers. Great though Faraday's output of work was, it seems to me that to match Rutherford's work in quantity, as well as in quality, we must go back to Newton. In some respects he was more fortunate than Newton; Rutherford was ever the happy warrior—happy in his work, happy in its outcome, and happy in its human contact.'