Atop the Physics Wave

RUTHERFORD BACK IN CAMBRIDGE, 1919–1937

In 1962, John Cockcroft (1897–1967) reflected back on the "Miraculous Year" (*Annus mirabilis*) of 1932 in the Cavendish Laboratory:

"One month it was the neutron, another month the transmutation of the light elements; in another the creation of radiation of matter in the form of pairs of positive and negative electrons was made visible to us by Professor Blackett's cloud chamber, with its tracks curled some to the left and some to the right by powerful magnetic fields."

Rutherford became Cavendish Professor and director of the Cavendish Laboratory in 1919, following the footsteps of J.J. Thomson. Rutherford died in 1937, having led a first wave of discovery of the atom.

Rutherford reigned over the Cavendish Lab from 1919 until his death in 1937. The Cavendish Lab in the 1920s and 30s is often cited as the beginning of modern "big science." Dozens of researchers worked in teams on interrelated problems. Yet much of the work there used simple, inexpensive devices — the sort of thing Rutherford is famous for. And the lab had many competitors: in Paris, Berlin, and even in the U.S.

It is tempting to simplify a complicated story. Rutherford directed the Cavendish Lab for 18 years, and yet many accounts focus exclusively on the dramatic year 1932, as John Cockcroft highlighted in the quote above. A more complete account asks what else was happening in the lab in 1932, what was happening in the dozen years before that, and in the five years that followed. One also needs to know how the events at the Cavendish Lab stacked up against events in the rest of the physics world.

Rutherford: Cavendish Professor of Physics

J.J. Thomson was appointed Master of Trinity College, Cambridge in 1919, and thus began Rutherford's remarkable final act in the story of nuclear physics.

Thomson's new position demanded his full attention, so he resigned as Cavendish Professor and as director of the Cavendish Laboratory. A board of electors, including Joseph Larmor (1857–1942) and Arthur Schuster, chose Rutherford to succeed Thomson. Rutherford shrewdly negotiated to be certain that Thomson would not interfere in the lab, but allowed him to keep a few rooms for himself, his assistant, and a few research students. Thomson in turn made certain Rutherford was elected a Fellow of Trinity College, with rights "to dine there when I please." (Eve, pp. 269–273). This promised peace between the two giants in the Cavendish Laboratory.

Life and Work in the Cavendish Laboratory for Rutherford

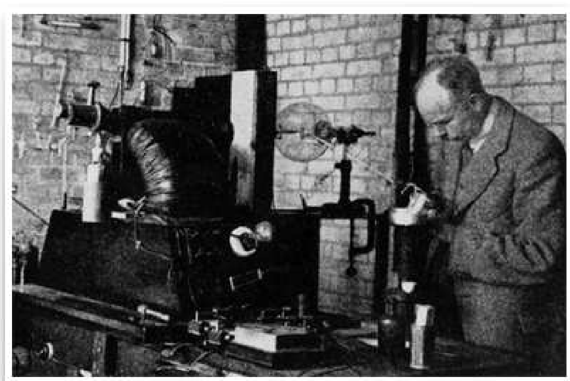
It is often said that Rutherford had little time for research of his own when he moved to the Cavendish Laboratory in 1919. True, he did have more administrative duties than at earlier stages in his career. Moreover, he did more for science beyond the lab, as president of the British Association for the Advancement of Science (1923) and of the Royal Society (1925–1930), as chairman of the Advisory Council of the government's Department of Scientific and Industrial Research (1930 on), and in 1933 he became president of the Academic Assistance Council. The latter helped Jewish scientist-refugees displaced by Nazi policies in Germany. He was also asked to give many lectures, including four lectures per year as Professor of Natural Philosophy at the Royal Institution in London from 1922 on.

Nevertheless, Rutherford continued to investigate the nucleus. Rutherford's McGill period emphasized research on naturally occurring radioactive decay. In Manchester, it was the nuclear theory of the atom. And as Cavendish Professor he disrupted the nucleus.

Rutherford brought this new field of research, the artificial disintegration of the nucleus, with him from Manchester to Cambridge. He brought his equipment and radioactive materials along, but most importantly, he invited his former student, James Chadwick, to join him in further experiments.

Such experiments always involved a bit of “What will happen if we do this?” However, Rutherford had several clear questions and goals in mind. He and Chadwick quickly found in 1919–1920 that nitrogen and other light elements disintegrated when hit with α (alpha) particles. The target emitted a fast particle of 1 unit positive charge. This happened with targets of nitrogen, oxygen, aluminum, and other light elements. Rutherford and his collaborators saw scintillations — flashes of light — when the high-speed particles hit a zinc-sulfide screen in a darkened room. Clearly, this particle was common enough to deserve a name. They called it the proton (Eve, p. 282).

What was left behind in the target material? And what became of the α particle? This puzzle demanded close work. Rutherford concluded that the nitrogen target captured the α particle (with a charge of 2 positive units) and emitted a proton (with its charge of 1 positive unit), which meant the target now had a nuclear charge of 8 instead of 7. The nitrogen had become an isotope of oxygen. This provided a dramatic entrance for Rutherford into Cambridge life. The alchemical dream of transmutation had been realized by physicists in the lab. (Rutherford published *The New Alchemy* in 1937.)



Francis Aston is known as a researcher who worked mostly alone at the Cavendish Laboratory. However, his investigations of isotopes and very precise measurements of atomic weights were actually quite important to Rutherford's nuclear research in the 1920s.

Another researcher at the Cavendish Laboratory, Francis W. Aston (1877–1945), provided critical aid to this research. Aston had been J.J. Thomson's assistant from 1909 until World War I and perfected the use of electric and magnetic fields to analyze moving, charged particles. Aston developed the “mass spectrometer,” capable of precision separation of isotopes, techniques valuable in Rutherford's studies. (Isotopes are atoms with the same charge but with a different atomic weight.) Aston received the Nobel Prize in Chemistry for this work in 1922. He maintained a research room in the Cavendish throughout Rutherford's professorship.

Pre-occupied with the composition of the nucleus in 1920, Rutherford was asked to give a prestigious lecture to the Royal Society of London. With experimental experience no one else had, Rutherford speculated. He said that combinations of the ultimate particles — the proton and the electron — could produce as-yet undiscovered particles and materials. A nucleus of mass 2 and charge 1 (2 protons bound closely to an electron, he said) would be an isotope of hydrogen. (We would now say this nucleus had 1 proton and 1neutron.) Also possible, he suggested, was “an atom of mass 1 which has a zero charge.” (Eve, p. 281). In short, Rutherford called for searches that ultimately yielded deuterium, the neutron, and other surprises.

This 1920 Royal Society lecture set much of the agenda for Rutherford and his lab for the rest of his life. Through the 1920s Rutherford, his personal assistant George Crowe, and Chadwick used α particles to probe and prod the nucleus: to determine its size, to measure the energy of emitted protons, and they investigated the “barrier of very high potential which retained the nucleus intact, while checking the ingress of a foreigner” (Eve, pp. 298–299). They also searched unsuccessfully for more than 10 years for the neutron. To be sure, Chadwick and Crowe did much of the work, but Rutherford was always involved, asking questions, making suggestions, and celebrating or berating.

Listen to Chadwick talk about his and Rutherford's silly experiments

Rutherford's “Boys”

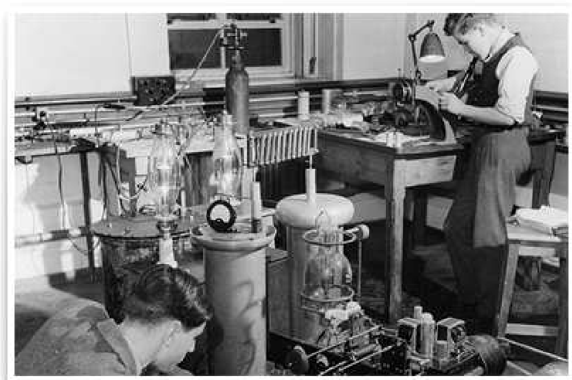
The Cavendish Laboratory in the 1920s and 30s was a busy and crowded place. In addition to Rutherford, Chadwick, Aston, and

Thomson, each year roughly thirty research students and a number of visitors were busily pursuing diverse researches. Some teams investigated problems related to Rutherford's and some researched other problems. Some Cavendish researchers, such as C.T.R. Wilson (1869–1959), located their work outside the lab. Some outsiders, such as the theoretician Ralph Fowler (1889–1944) of the Department of Mathematics, kept a room in the lab.

Mark Oliphant (1901–2000), an Australian who came to the Cavendish Laboratory as a research student in 1927, described the classroom experience of new students: Aston read directly from his book on isotopes. Arthur Eddington (1882–1944) discussed relativity, speculatively, and “almost without mathematics.” Douglas Hartree (1897–1958) provided thorough if pedantic lectures on quantum theory, while Nevill Mott (1905–1996) gave excellent quantum lectures. C.T.R. Wilson was so timid a speaker on atmospheric electricity that few students came to any lectures after the first. According to Oliphant: “...the lecturer himself was...clearly embarrassed by his inability to express himself.” On the other hand, John A. Ratcliffe's (1902–1987) discussions of the ionosphere “were the most lucid and best presented lectures I have attended.” (Oliphant, p. 24).

Rutherford also lectured on the atom, with great enthusiasm, but not always coherently or well prepared. Oliphant relates one time when Rutherford reached an impasse in a lecture and said to the class: “You sit there like a lot of numbskulls, and not one of you can tell me where I've gone wrong.” (Oliphant, p. 26).

Research groups, led by strong individuals, worked on many questions and new devices around the Cavendish Laboratory. Patrick Blackett (1897–1974), at the lab since 1919, directed improvements in cloud chambers for nuclear and cosmic ray research. Aston concentrated on a new, more precise mass spectrometer. Peter Kapitza (1894–1984) developed strong magnets and studied the effects of strong fields on materials. Mark Oliphant, John Cockcroft, and E.T.S. Walton (1903–1995) explored ways to accelerate charged particles. Also in the late 1920s, Rutherford encouraged the search for electronic means of detection of nuclear events to replace the scintillation method. C.E. Wynn-Williams (1903–1979) led the way with his “scale-of-two counter,” but many members of the lab were inspired by the success of Hans Geiger and Walther Müller's electronic radiation detector — the Geiger–Müller tube — in 1928. Wynn–Williams' detectors proved essential in nuclear research in the 1930s.



Despite Rutherford's fabled preference for small, improvised apparatus, he also supported the development of high-voltage equipment. This equipment allowed new research in high energy particles and at ultra-low temperatures. Credit: British Information Services, 30 Rockefeller Plaza, New York, NY, courtesy AIP Emilio Segrè Visual Archives.

A last example of a research group was far afield from nuclear physics. Its leader, Ratcliffe, came to the Cavendish Laboratory as a student in 1921 and began research in 1924. When E.V. Appleton (1892–1965) left in the mid 1920s, Rutherford asked Ratcliffe to direct work in radio and atmospheric geophysics. His group contributed greatly to ionospheric physics and later to radioastronomy. This work shared something with nuclear physics: a great reliance on electronics. Hence, although the topics differed, everyone benefitted from advances in instrumentation in the Cavendish Lab.

The *Annus mirabilis* of 1932

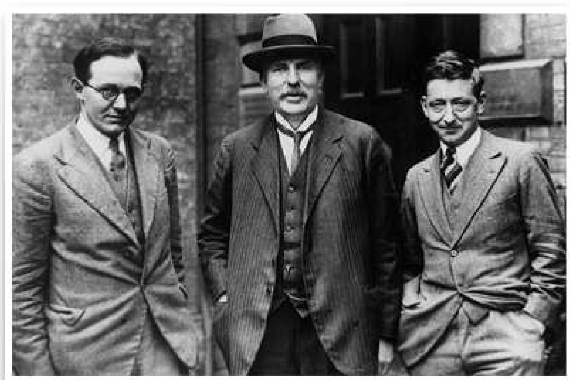
Rutherford's researchers produced three major nuclear developments in 1932. In February, Chadwick announced the detection of the neutron. In April, John Cockcroft and E.T.S. Walton disrupted the nucleus using artificially accelerated protons. And late in the year, Patrick Blackett and Giuseppi Occhialini (1907–1993) demonstrated the existence of the positron. What led to these remarkable achievements?

Chadwick had been seeking experimental evidence of the neutron throughout the 1920s. Although he had other successes during the decade, every attempt to detect the neutron was a dead-end until 1932. This should not be a surprise. With no electrical charge, a neutron would not show itself in the same ways that charged particles do.

Rutherford and Chadwick's systematic study of nuclear disintegration in their first year at Cambridge, combined with Aston's precise mass spectrometry work, attuned them to paying close attention to atomic weights in “nuclear reactions.” When Walther Bothe (1891–1957) and H. Becker observed some unusually penetrating radiation in 1930 and when in early 1932 Irène (1897–1956) and Frédéric Joliot-Curie (1900–1958) asserted similar results to be due to γ (gamma) rays, Rutherford and Chadwick just didn't think that the sums added up (Hendry, pp. 7–9).

Chadwick set off to test this γ-ray hypothesis. He used the same radiation from beryllium as the others did, aimed the radiation at paraffin (a rich source of proton ejecta), measured the range of these protons, and also measured how these rays from beryllium impacted various gas atoms. He did, however, have better detection equipment. He concluded that γ-rays could not produce these effects and that the beryllium radiation must be a neutrally charged particle of roughly the mass of a proton. He had found evidence of the neutron. This was, to be sure, indirect evidence. He had not "seen" a neutron, but the effects were consistent with such a particle. Chadwick announced the "discovery" of the neutron in a paper sent to the journal *Nature* on 10 February 1932. (The experiment was somewhat more complicated than explained here, but this discussion catches the most important points.)

The second great event of the *Annus mirabilis* of 1932—the first use of a particle accelerator to produce a nuclear disintegration—had also been years in the making. Since Rutherford's earliest work, the main source of fast charged particles had been the decay of naturally occurring radioactive materials, such as radium. And the most common particle emitted in these experiments was the α particle, or helium nucleus.



Cockcroft, Rutherford, and Walton in 1932, shortly after they accelerated protons against a lithium target, splitting the lithium nucleus into two alpha particles, i.e., helium nuclei. This demonstrated not only the "transmutation" of elements, but also Einstein's formula $E=mc^2$, since a slight loss of mass produced energetic alpha particles. Credit: UK Atomic Energy Authority, courtesy AIP Emilio Segre Visual Archives.

Like other physicists in the 1920s, Rutherford wanted to find ways to accelerate electrons, protons, and α particles artificially. That is, with a machine. Indeed, he had urged attention to particle accelerators in his 1927 Presidential Address to the Royal Society. True, he did not want to spend a lot of money to do it and he discouraged building a machine bigger than necessary. Nevertheless, he wanted a particle accelerator. As he said in that address:

"It has long been my ambition to have available for study a copious supply of atoms and electrons which have an individual energy far transcending that of the a and β-particles from radioactive bodies. I am hopeful that I may yet have my wish fulfilled, but it is obvious that many experimental difficulties will have to be surmounted before this can be realised on a laboratory scale."

***Proceedings*, Royal Society, 1927).**

With arrival in the Cavendish Lab of new students with engineering background, this dream was soon achieved.

Listen to Dr. Phillip Dee talk about the historical significance of Rutherford's work

Merle Tuve (1901–1982) and Gregory Breit (1899–1981) in the U.S. worked on a Tesla coil and a Van de Graaff generator to produce high voltages to accelerate charged particles. Meanwhile at Cambridge, T.E. Allibone (1903–2003) (from the Metropolitan-Vickers electrical company) attempted a similar machine. There were others, but the best known is Ernest Lawrence (1901–1958), who first tried to build a linear accelerator, and then built his famous cyclotron in 1930.

John Cockcroft, with a degree in electrical engineering from the University of Manchester, came to Cambridge in 1922. In 1924 he joined Kapitza in his industrial-scale effort to produce large magnetic fields. Cockcroft also was considering Rutherford's accelerator challenge. He was joined in 1927 and 1928 by T.E. Allibone and Ernest Walton. Together and alone, they considered a circular accelerator and others of several designs but could not overcome design difficulties or the limitations of a lab that was not yet supplied with a standard high-voltage alternating current.

Work was sped up at Cambridge after a visit by the Russian theoretical physicist George Gamow (1904–1968) in 1929. Cockcroft recognized the implications of Gamow's theoretical work. He concluded that a 300,000 volt proton accelerator could penetrate the nucleus of target material and might produce a nuclear reaction.

Now the Cambridge team had only to design and build the machine! It's a long story, but by 1932 Cockcroft had been joined in the experimental work by Walton and they were ready to try to disintegrate atoms. Cockcroft and Walton were always looking for leaks in the evacuated machinery. On 13 or 14 April, Ernest Walton had observed scintillations on a screen, indicating that their accelerated protons, impinging on lithium, had split the lithium nucleus and produced two α particles.

The last dramatic development of 1932 at the Cavendish was the demonstration by Patrick Blackett and Giuseppe Occhialini of the existence of the “positive electron” or positron. Usually the discovery of the positron is credited to Carl Anderson at California Institute of Technology. Although Blackett and Occhialini's research was contemporaneous with Anderson's, Blackett had held back his announcement until he had solid evidence. This was typical of a Rutherford team.

Patrick Blackett left the Cavendish Laboratory in 1933 to accept a professorship at Birkbeck College, London, then in 1937 to Manchester. There he was Langworthy Professor, Rutherford's former position. He later contributed to Operational Research and to paleomagnetism. Credit: University of Cambridge, Cavendish Laboratory.

The solid evidence consisted of cloud chamber photographs that showed two particles spiraling in opposite directions from a common point. Blackett and Occhialini had the advantage of Blackett's decade of improvement of the cloud chamber and of Occhialini's familiarity with a technique developed in Italy by his mentor, Bruno Rossi (1905–1993). Rossi's technique used two Geiger-Müller counters in a straight line to trigger an action, when a charged particle tripped both counters in quick succession. Blackett and Occhialini put these two ideas together. In their device, cosmic rays (or charged particles in nuclear experiments) took their own pictures. Their experiments now produced photographic evidence 80% of the time (Hendry, pp. 7–30, passim). Because Anderson published his announcement first, he received the 1936 Nobel Prize in Physics for the discovery of the positron.

There is much more to each of these three stories from the *Annus mirabilis* of the Cavendish Laboratory. This telling, however, gives you some idea of the excitement enjoyed by Ernest Rutherford and his researchers in 1932. It should be remembered, however, that this excitement came after 12 years of hard work.

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