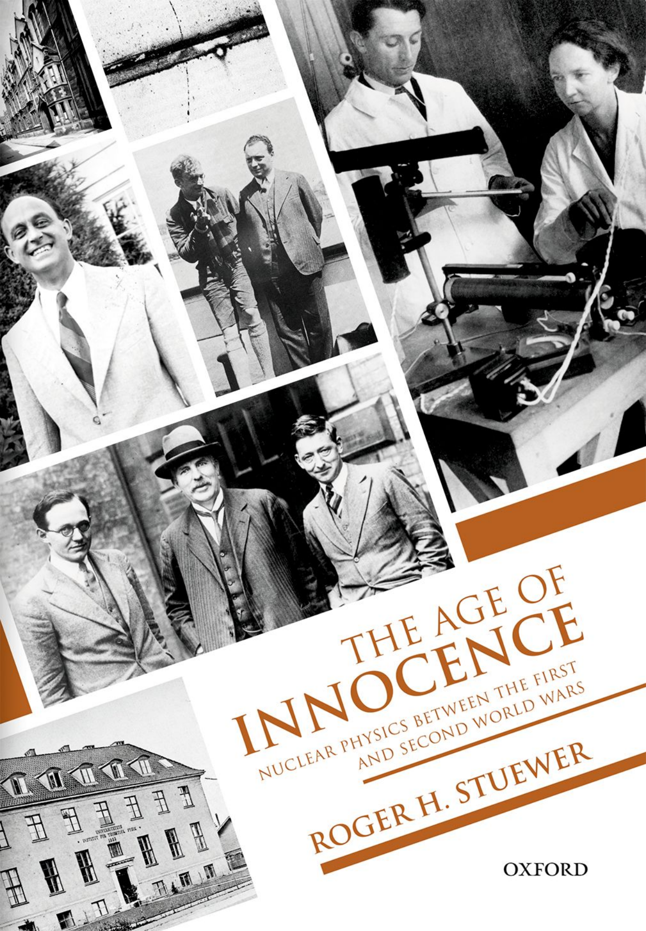

THE AGE OF INNOCENCE

NUCLEAR PHYSICS BETWEEN THE FIRST AND SECOND WORLD WARS

ROGER H. STUEWER

OXFORD

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To my father Martin who instilled in me perseverance and discipline; to my mother Esther née Westphal who instilled in me compassion and my love of teaching; to my wife Helga whose unwavering love and support has made everything in my life possible; to our son Marcus whose love, support, care, and technical expertise has enabled me to write this book; to our daughter Suzanne whose love, support, and wonderful artwork has been a constant inspiration to me.

And to the memory of John Rigden, my wonderful friend and colleague.

PREFACE

The nascent field of nuclear physics became the dominant field of experimental and theoretical physics during the two decades between the First and Second World Wars.

The period began with Ernest Rutherford's discovery of artificial nuclear disintegration in 1919 and his classical interpretation of it in 1920, both of which were challenged by physicists in Vienna in 1922–7. In 1928, George Gamow and simultaneously Ronald Gurney and Edward Condon took the first step out of the classical world when they conceived a quantum-mechanical theory of alpha decay. Four years later, in 1931–2, experiment and theory were fundamentally transformed by the discoveries of the deuteron, neutron, and positron, and by the inventions of the Cockcroft–Walton accelerator and cyclotron. Two years later, Frédéric Joliot discovered artificial radioactivity, Enrico Fermi conceived his theory of beta decay based on Wolfgang Pauli's neutrino hypothesis, and Fermi discovered the efficacy of slow neutrons in nuclear reactions. In 1936, stimulated by Fermi's discovery, Niels Bohr proposed his theory of the compound nucleus and Gregory Breit and Eugene Wigner proposed their theory of nucleus+neutron resonances, which together transformed the theory of nuclear reactions. Two years later, at the end of 1938, Otto Hahn and Fritz Strassmann discovered nuclear fission, which Lise Meitner and Otto Robert Frisch interpreted on the basis of Gamow's liquid-drop model of the nucleus.

These fundamental discoveries and inventions arose from a quest to understand nuclear phenomena; none were motivated by a desire to find a practical application for nuclear energy. In this sense, nuclear physicists lived in an Age of Innocence between the two world wars. They did not, however, live in isolation. Like all human endeavors, research in nuclear physics reflected the idiosyncratic personalities of the physicists who made the discoveries and created the inventions. The field also was shaped by the physical and intellectual environments of the countries and institutions in which they worked, and it was buffeted by the turbulent political events in the period. I therefore have set the experimental and theoretical developments in nuclear physics in the interwar period within their personal, institutional, and political contexts, and for authenticity and a sense of immediacy I have quoted extensively from autobiographies, biographies, recollections, interviews, correspondence, and other writings of physicists and historians.

I studied nuclear physics in undergraduate and graduate courses at the University of Wisconsin and worked for two years as a research assistant on the Wisconsin Tandem accelerator. I turned my research to the history of nuclear physics a decade later, after I organized a symposium in 1977 at the University of Minnesota on nuclear physics in the 1930s, where prominent experimental and theoretical nuclear physicists gave lectures and participated in the discussions. My research took me to archives in the United States and Europe, where I found significant correspondence and other materials that I incorporated into more than a dozen papers on the history of nuclear physics in the 1920s and 1930s. I integrated these studies and supplemented them with further research to write this book for a general audience of scholars, teachers, students, and the interested public.

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I incurred many intellectual debts over the years. As an undergraduate student at the University of Wisconsin, Edward E. Miller and Milton O. Pella were devoted mentors in physics and science education, and as a graduate student my major advisors, Heinz Barschall and Erwin Hiebert, were exemplary models of mastery and disciplinary integrity in physics and history of science. The same was true of Morton Hamermesh and Herbert Feigl, my department heads in physics and philosophy of science at the University of Minnesota, who created an inspiring and congenial environment for my teaching and research in the history of physics.

I have had superb undergraduate students, outstanding and successful graduate students, and wonderful colleagues at Minnesota, particularly Alan E. Shapiro, Robert W. Seidel, and Michel Janssen in history of science, and Ernest Coleman, George Greenlees, Serge Rudaz, Hans Courant, Steve Gasiorowicz, Misha Voloshin, Alfred Nier, Edward Nye, Ben Bayman, Homer Mantis, Russell Hobbie, Allen Goldman, Jake Waddington, and Norton Hintz in physics. I have also treasured the friendship and collegiality of physicist-historian Clayton Gearhart and of Lee Gohlike, founder of the Seven Pines Symposium. Beyond Minnesota, I have especially benefitted from the work of Martin J. Klein, Ruth Lewin Sime, Allan D. Franklin, and Laura Fermi, and from the long association with my wonderful friend and colleague John Rigden.

My references and bibliography attest to the extent to which I have profited from the work of other historians and physicists, particularly Lawrence Badash, Alan D. Beyerchen, Joan Bromberg, Laurie M. Brown, Jed Z. Buchwald, Per F. Dahl, Samuel Devons, Anthony P. French, John L. Heilbron, Lillian Hoddeson, Charles H. Holbrow, Gerald Holton, Daniel J. Kevles, Mary Jo Nye, Abraham Pais, Silvan S. Schweber, Spencer R. Weart, Charles Weiner, and Richard J. Weiss. Beyond the United States, the same has been true of Wolfgang L. Reiter, Walter Höflechner, Friedrich Stadler, Silke Fengler, and Carola Sachse in Austria, László Kovács in Hungary, Armin Hermann, Dieter Hoffmann, Jürgen Renn, and Klaus Hentschel in Germany, Anne J. Kox and Hendrik B.G. Casimir in the Netherlands, Finn Aaserud and Helge Kragh in Denmark, Dominique Pestre, Pierre Radvanyi, and Olivier Darrigol in France, Fabio Bevilacqua, Edoardo Amaldi, Salvo D'Agostino, Giorgio Dragoni, Nadia Robotti, and Luisa Bonolis in Italy, Manuel Doncel, José M. Sanchez-Ron, and Xavier Roqué in Spain, Ana Simões in Portugal, Maria Rentetzi in Greece, Imre Lakotos, Andrew Warwick, and Jeffrey Hughes in England, Andrzej Wróblewski in Poland, Yehuda Elkana, Mara Beller, and Issachar Unna in Israel, and Victor J. Frenkel in Russia.

I am grateful to Hans A. Bethe for permission to quote from his letter to Arnold Sommerfeld; to Aage Bohr and the Niels Bohr Archive for permission to quote from

Niels Bohr's correspondence; to Anne I. Goldman for translating Bohr's letters of January 20 and 24, 1939, to Otto Robert Frisch; to Lady Chadwick for permission to quote from her husband's correspondence; to Lady Cockcroft for permission to quote from her husband's correspondence; to Ulla Frisch for permission to quote from her husband's and Lise Meitner's correspondence; to Dietrich Hahn for permission to quote from his uncle's correspondence; to the California Institute of Technology Archives for permission to quote from Charles C. Lauritsen's correspondence; to Mrs. Ernest O. Lawrence for permission to quote from her husband's correspondence; to Richard N. Lewis for permission to quote from his father's correspondence; to Berta Karlik, Roman Sexl, and Herbert Vonach for access to Stefan Meyer's correspondence; to Sir Mark Oliphant for permission to quote from his correspondence; and to Peter H. Fowler for permission to quote from Rutherford's correspondence.

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Words cannot capture the magnitude of my debt to my wife Helga for her love and support over fifty-eight years of marriage. I also would not have been able to write this book without the personal care and technical expertise of our son Marcus. The memory of our daughter Suzanne has been kept alive in my mind and heart by her wonderful artwork.

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Cambridge and the Cavendish

THOMSON

The University of Cambridge was in mourning on January 14, 1918. Henry Montagu Butler, beloved classicist, humanist, Master of Trinity College for thirty-one years, died at the age of eighty-four. Who could fill the void?

Founded by King Henry VIII in 1546, Trinity College, the largest of the Cambridge Colleges, had been home to Newton and Maxwell, Byron and Tennyson, Macaulay and Thackeray. Its Mastership was an influential position of great dignity. As the Oxford poet Sir Francis Doyle proclaimed:

> If you through the regions of space should have travelled,
> And of nebular films the remotest unravelled,
> You'll find as you tread on the bounds of infinity
> That God's greatest work is the Master of Trinity.[1]

There were earthly blessings as well, as described by the fourth Lord Rayleigh: "The appointment is a very valuable one, in income amounting to about £3200,[a] with the Lodge, rent, rates and repairs free.... The Master of Trinity is better housed than the head of any other college at either of the ancient Universities [of Oxford and Cambridge], and has an excellent private garden, bordering the river Cam."[2]

Then unique among the Cambridge colleges, the Master of Trinity was not elected by the Fellows but was appointed by the Crown on the recommendation of the Prime Minister, in this case Lloyd George, who discussed the appointment with Lord Balfour, First Lord of the Admiralty, a Trinity man himself. Lloyd George's choice was Sir Joseph Thomson. "His super-eminence as a scientist was known, even to a barbarian like myself who never had the advantage of any university training."[3] Thomson was admitted to the Mastership in an ancient and elaborate ceremony on March 5, 1918,[4] only two weeks after Butler's death. He would be the last Master of Trinity to hold the post with tenure for life.[5]

Joseph John Thomson, or "J.J." as he was known to everyone, had been Cavendish Professor of Experimental Physics for thirty-four years. The Cavendish Laboratory was

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[a] In 1918 £3200 was about $9100, which in 2017 was about $147,500.

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underwritten in 1870 by a bequest of £6300 (later raised to £8450) from the Chancellor of the University, William Cavendish, the seventh Duke of Devonshire. It was constructed in 1872–4 on the east side of Free School Lane in the heart of Cambridge (Figure 1.1). James Clerk Maxwell was elected as the first Cavendish Professor of Experimental Physics in 1871 and drew up the plans and oversaw the construction of the laboratory. On his death in 1879 at the early age of 49, he was succeeded by the third Lord Rayleigh for a tenure of five years, when it again became vacant. To succeed Rayleigh in 1884, the Electors, in an act of extraordinary boldness, chose J.J. Thomson, then barely twenty-eight years old.[6] Thomson had sent in his name as a candidate, never dreaming he would be elected, and when he was, he "felt like a fisherman who with light

Fig. 1.1 The entrance to the Cavendish Laboratory on Free School Lane in Cambridge. *Credit*: Copyright Cavendish Laboratory, University of Cambridge.

tackle had casually cast a line in an unlikely spot and hooked a fish much too heavy for him to land."[7] Thomson's competitors were stunned. He himself heard "that a well-known College tutor had expressed the opinion that things had come to a pretty pass in the University when mere boys were made Professors."[8]

Thomson bore a heavy responsibility. Maxwell and Rayleigh, the former a Scottish laird, the latter an English aristocrat, both wealthy, had made numerous and profound contributions to physics. Thomson, in complete contrast, was the son of a Manchester bookseller who died young, and had secured his education through the sacrifices of his mother and through his own wit and hard work. Born on December 18, 1856, he entered Owens College, Manchester, in 1871 at the age of fourteen, where he studied engineering, physics, chemistry, and mathematics under exceptional teachers. In 1876 he gained a minor scholarship to Trinity College, Cambridge, where he excelled in his studies and in January 1880 took the rigorous Mathematical Tripos Examination,[9] placing Second Wrangler after Joseph Larmor, the Senior Wrangler. He received his B.A. at the end of the academic year and was elected a Fellow of Trinity College on his first try (three were permitted). Four years later, in 1884, he was elected Cavendish Professor and a Fellow of the Royal Society.

The Cavendish became a Mecca for experimental physicists under Thomson, especially after 1895–6 when three events significantly enhanced its fortunes. First, in an institutional innovation in April 1895, the University Senate passed a new regulation that permitted graduates of other universities to enter Cambridge and receive the B.A. degree after two years of advanced study and the completion of a thesis judged to be "of distinction as a record of original research."[10] This regulation opened the doors of the University of Cambridge and the Cavendish Laboratory to talented "research students" from all corners of the globe. They were distinguished from "advanced students," as the physicist Edward Neville da Costa Andrade discovered in 1911. He had received his doctorate from the University of Heidelberg, his chemist friend Samuel E. Sheppard had received his from the University of Paris (the Sorbonne), and while both were admitted to work in the Cavendish they "had no status whatever." Their degrees were not recognized and neither was called doctor. Although, said Andrade, the University of Heidelberg, founded in 1386 after the oldest Cambridge college in 1284, "was perhaps unworthy of recognition," but the Sorbonne, founded earlier, in 1257, "might be accepted as a centre of learning." Since, however, they had "no recognized degrees" in Cambridge, they "had to ask permission of a tutor, unheard of outside Cambridge, if we wanted to be out after 10 o'clock at night, as we occasionally did."[11]

Second, a major scientific event occurred in November 1895, when Wilhelm Conrad Röntgen discovered X rays at the University of Würzburg, which opened up entirely new fields of research in physics. Third, another institutional innovation occurred in 1896, when the rules governing the 1851 Exhibition Scholarships were changed. Established in 1891 with funds from investments of the proceeds of the 1851 Great Exhibition in London, these scholarships were awarded competitively to students from selected universities in the British Commonwealth countries and were generally tenable for two years. After

1896, a recipient could no longer remain at their home university for a year but was required to transfer at once to another university. This requirement, together with the introduction of the new Cambridge research B.A. degree, strongly encouraged 1851 Exhibition Scholars to go to the Cavendish Laboratory for advanced research in physics. The first two research students to enter the Cavendish under the new regulations were the New Zealander Ernest Rutherford, who was followed within an hour by the Irishman John S. Townsend.[12]

Thomson established the Cavendish Laboratory as the world's foremost center for experimental physics. His "boundless enthusiasm, his endless fertility in suggestion, and his unequalled knowledge of the literature" made him an inspiring teacher, and his "quickness at mental arithmetic" enabled him to carry out complicated numerical calculations "in his head with sufficient accuracy." To J.J. a slide rule was "a waste of time." When challenged by one of his students who was using one, "he left his challenger standing at the post."[13]

Thomson garnered worldwide fame through his scientific achievements, particularly his discovery of the electron in 1897, which historians have shown is a complex and nuanced story.[14] He garnered a large scientific audience through his numerous articles and many books, the most famous being his *Conduction of Electricity Through Gases*, which went through three editions between 1903 and 1933 and served as a textbook for generations of research students. His son George described his work habits.

> J.J. did most of his theoretical work at home [at Holmleigh, West Road], sitting in a chair that had been Maxwell's [Figure 1.2], and mostly on scrap paper till it had reached the stage of being written up. He wrote a clear and beautiful hand, his one manual accomplishment. Unless he was lecturing... he stayed at work till nearly one o'clock, till lunch was nearly ready in fact, and then hurriedly walked to the laboratory. There he walked round visiting research students and giving advice.[15]

Unlike most experimental physicists, Thomson was clumsy with his hands, but he had an amazing talent for getting to the heart of the matter.

> [When] hitches occurred, and the exasperating vagaries of an apparatus had reduced the man who had designed, built and worked with it to baffled despair, along would shuffle this remarkable being, who, after cogitating in a characteristic attitude over his funny old desk in the corner, and jotting down a few figures and formulae in his tidy handwriting, on the back of somebody's Fellowship thesis, or on an old envelope, or even the laboratory cheque book, would produce a luminous suggestion, like a rabbit out of a hat, not only revealing the cause of trouble, but also the means of cure. This intuitive ability to comprehend the inner working of intricate apparatus without the trouble of handling it appeared to me then, and still appears to me now, something verging on the miraculous, the hall-mark of a great genius.[16]

Thomson's cumulative record of teaching and research was extraordinary: His research students included seven future Nobel Prize winners, twenty-seven Fellows of the Royal Society, and nearly eighty professors in a dozen countries worldwide.[17]

Fig. 1.2 J.J. Thomson sitting in a chair once used by James Clerk Maxwell in his study at Holmleigh in 1899. *Credit*: Rayleigh, Lord [Robert John Strutt, Fourth Baron Rayleigh] (1942), facing page 130; reproduced by permission. Robert A. Millikan carefully etched out the cigarette in J.J.'s left hand when he reproduced this picture in 1906; see Millikan, Robert A. and Henry G. Gale (1906), facing p. 482.

Thomson created an inspiring atmosphere of commitment and camaraderie in the Cavendish. He was highly imaginative, friendly, cheerful, never seemed to be ill-tempered, terribly absentminded, and in the running for the worst-dressed man in Cambridge.[18] Like many physicists, he was contemptuous of philosophy, regarding it as "a subject in which you spend your time trying to find a shadow in an absolutely dark room."[19] However, his son noted that "he was interested in finance, especially in investment, for which he had a certain flair." He had an "infectious laugh," was never "deliberately rude," and "was generous to his children" but "was definitely not to be trifled with." His "greatest hobby" was wild and cultivated flowers. He was "wholly unmusical, unless one counts a taste for Gilbert and Sullivan." His taste in pictures was "good if conservative." In literature he read mostly certain old favorites such as Trollope, Dickens, and Jane Austen. He "enjoyed biography" and "read detective stories and thrillers for distraction."[20]

At the Cavendish Thomson created new ways for drawing everyone in the Cavendish together, scientifically and personally. He founded the Cavendish Physical Society in 1893,[21] which met on alternate Tuesday afternoons while classes were in session to discuss papers presented by research students on work of current interest. Tea was served beforehand by J.J.'s wife Rose (née Paget), a former student whom he had married in 1890, and one or two other ladies.[22] A few years later, apparently on Rutherford's suggestion, a daily tea was established; it began at 4:30 P.M., lasted twenty to thirty minutes, and "was in many ways the best time in the laboratory day," with J.J. holding forth on every topic under the sun: "current politics, current fiction, drama, university sport," and "the personalities and idiosyncrasies of scientific men in other countries."[23] The highlight of the entire year was the annual Cavendish dinner at the beginning of the Christmas vacation. It was marked by good food and drink, toasts, stories, and boisterous singing. Paul Langevin, research student from Paris, set the standard at the first dinner, which was held on December 9, 1897, in the Prince of Wales Hotel on Sidney Street. He “sang the *Marseillaise* with such fervour that one of the waiters, a Frenchman, fell on his shoulder and kissed him.”[24] Songs were soon composed especially for the occasion, many by the mathematical physicist Alfred A. Robb, although one of the all-time favorites, “Ions Mine,” sung to the tune of “Clementine,” was composed in 1900 by J.J.E. Durack, an 1851 Research Scholar from Allahabad, India, with Thomson himself contributing the fourth verse.[25]

As Thomson drew research students to the Cavendish in increasing numbers, increases in staff and two extensions of the laboratory became necessary. The first, in 1896, cost about £4000 and was financed equally by the University and by student fees that Thomson, an astute money manager, had accumulated.[26] The second, in 1908, was financed largely by a bequest of £5000 from Thomson’s predecessor, the third Lord Rayleigh, from his Nobel Prize money,[27] although Thomson again contributed £2000 from accumulated student fees.[28] The press on space continued. By 1909, when Thomson celebrated his twenty-fifth anniversary as Cavendish Professor, no less than 225 physicists from all over the world had worked in the Cavendish, two-thirds of whom had come after 1895.[29] William L. Bragg recalled that around 1911, “There were too many young researchers (about forty) attracted by its reputation, too few ideas for them to work on, too little money, and too little apparatus. We had to make practically everything for ourselves, and even at that the means were meagre.”[30] That same year the young Danish postdoctoral student Niels Bohr also found that “it is not easy in the beginning to adjust oneself to the Cavendish Laboratory where there is such a lack of order and so little help for so many people....”[31] The total annual amount of money J.J. allocated for research averaged out to less than £15 per student.[32]

Three years later, in August 1914, the Great War broke out, and “the usual work of the laboratory stopped. The research workers went either to the front or to laboratories formed for developing and testing methods likely to be of use to the fighting services.”[33] By then, Thomson probably was the most decorated scientist in the world. He had received the Copley Medal of the Royal Society, its highest award, in 1902, the Nobel Prize for Physics in 1906, and over a dozen honorary degrees. He had been elected to over two dozen foreign and domestic learned societies. He had been knighted in 1908 and had received the most coveted honor of all, the Order of Merit in 1912, which had been instituted by King Edward VII a decade earlier and was limited to only twenty-four British subjects. Small wonder that Prime Minister Lloyd George recommended Thomson to succeed Henry Montagu Butler as Master of Trinity College in 1918.

Thomson and his colleagues thus were greatly amused when a paragraph appeared in the *Manchester Guardian* in which a prominent figure in the local government, intending to deprecate the value of book learning, wrote:

> There was... a clever boy at school with me, little Joey Thomson, who took all the prizes. But what good has all his book learning done him? Who ever hears of little Joey Thomson now?[34]

RUTHERFORD

Thomson's appointment as Master of Trinity immediately raised the question of his future relationship with the Cavendish Laboratory. He was determined, as he told his son George on February 26, 1918, "to retain the control of the Laboratory and research work," as least for the duration of the war.[35] His resolve soon weakened, however, and he decided to resign the Cavendish Professorship—provided that a worthy successor could be found. And to him there was only one: his former student Ernest Rutherford. By then, apart from Thomson himself, Rutherford was the most famous experimental physicist in England, if not the world.

Born on August 30, 1871, near Nelson, New Zealand, on the north coast of South Island, Rutherford was the fourth child and second son of the co-owner of a flax mill who, as well as his wife, was the child of Scottish immigrants to New Zealand. He was enormously proud of his birthplace. In around 1910, a bishop asked him at a formal luncheon how many people there were in the South Island, and he was genuinely surprised to hear that it was only about 250,000. To confirm this small figure, he compared its population to that of the English town of Stoke-on-Trent. Rutherford, incensed, exploded:

> Maybe the population is only about that of Stoke-on-Trent. But let me tell you, sir, that every single man in the South Island of New Zealand could eat up the whole population of Stoke-on-Trent, every day, before breakfast, and still be hungry.[36]

Rutherford's pioneering youth molded his character—his enormous capacity for work, his single-minded dedication, his earthy sense of humor, his bluntness, his strong aversion to pomposity, his essential simplicity. "I am always a believer in simplicity," he said, "being a simple man myself."[37] He excelled as a student at Nelson College, a secondary school with around eighty pupils between the ages of ten and twenty-one, and at Canterbury College in Christchurch with five professors and around 150 students, where he completed his B.A. in 1892 and his M.A. in 1893, with double First Class honors in mathematics and physics.[38] He spent an additional year at Canterbury College repeating Heinrich Hertz's experiments on "wireless waves" and carrying out original research on "electric and magnetic phenomena in rapidly alternating fields,"[39] for which he received his B.Sc. in 1894. The following fall he fortuitously fell heir to an 1851 Exhibition Scholarship with a stipend of £150 per year, when the Auckland chemist James S. Maclaurin declined to accept it for personal reasons. Family history has it that when he heard the good news he was working in the field and threw down his spade, crying, "That's this last potato I will ever dig."[40] He arrived at the Cavendish as the first of Thomson's students under the new B.A. research regulations.

Soon thereafter, in November 1895, Wilhelm Conrad Röntgen discovered X rays, which Thomson and his new student Rutherford proved made gases electrically conducting. In 1896 Rutherford turned to Henri Becquerel's recent discovery of radioactivity, finding that uranium emits two types of "rays," a positive type of low penetrating power that he termed alpha rays, and a negative type of high penetrating power that he termed beta rays. The uncharged and still more penetrating gamma rays were discovered by the French physicist Paul Villard in 1900.[41]

Rutherford's entry into the new field of radioactivity set the course of his research career. In the fall of 1898, with Thomson's full support, testifying that he "never had a student with more enthusiasm or ability for original research than Mr Rutherford,"[42] he was appointed Macdonald Professor of Physics at McGill University in Montreal, Canada. He soon opened up a collaboration with the Oxford-educated chemist Frederick Soddy, which by 1902 led to their discovery of the laws governing the radioactive transformation of elements.[43] They explored their discovery until Soddy left for London in early 1903.

The following year Rutherford published his first book, *Radio-Activity*, which he dedicated to his mentor J.J. Thomson—and became greatly irritated when Soddy published a book with the identical title virtually simultaneously.[44] The following year, Rutherford (Figure 1.3) published a fifty-percent-larger second edition. His books and papers began to attract a trickle of foreign students to McGill,[45] among them the German Otto Hahn in 1905–6. Hahn noted that Rutherford, as Research Professor with no official duties, could do whatever interested him, since Professor John Cox actually directed the institute and supervised the lectures.[46] Hahn also noted that:

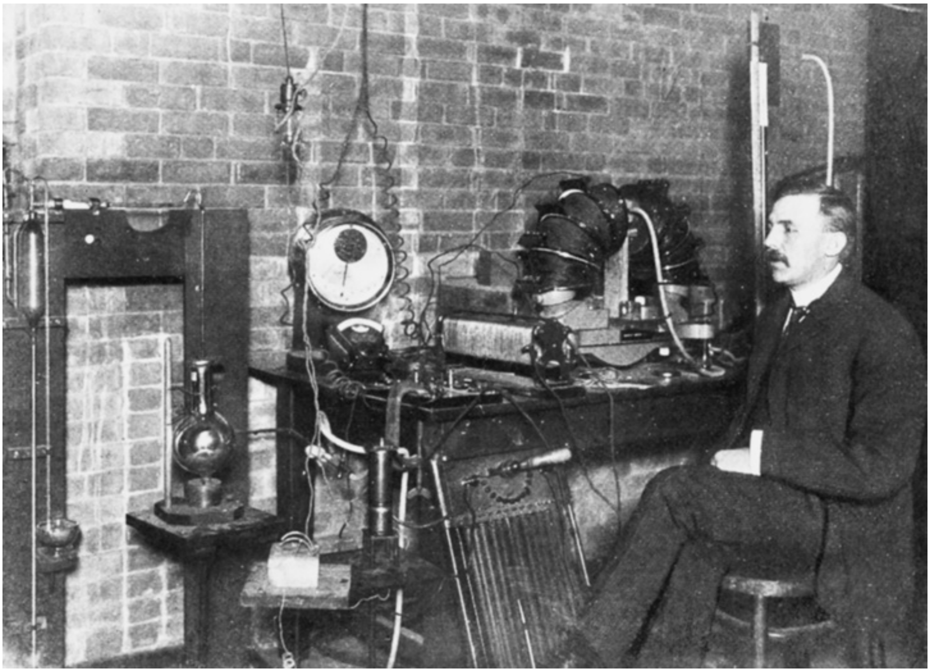

Fig. 1.3 Ernest Rutherford in his laboratory at McGill University in 1906. Note the white cuffs protruding from his left sleeve, on loan from Otto Hahn for the photograph. *Credit*: Website "Ernest Rutherford"; image labeled for reuse.

> Rutherford was a heavy smoker, switching from pipe to cigarettes and back without much interruption. Smoking was discontinued only when the donor of the Macdonald Physics Building, [Sir William Macdonald,] a very wealthy tobacco dealer, visited the Institute. In Macdonald's presence nobody was permitted to smoke, not even Rutherford. Although Macdonald had grown rich on tobacco [by selling Confederate tobacco to the Union army during the American Civil War], he was a violent enemy of smoking.[47]

Rutherford's researches began to bring him high honors: In 1903 he was elected a Fellow of the Royal Society; in 1904 he was invited to deliver the Royal Society's prestigious Bakerian Lecture, which had been established by a bequest of £100 by the English naturalist Henry Baker in 1774.[48] In 1905 he received the Royal Society's Rumford Medal, its second highest honor after the Copley Medal. That year he also was invited to deliver the Silliman Lectures at Yale University, which were published the following year as the third of Rutherford's books, *Radioactive Transformations*. Finally, in 1908 Rutherford won the Nobel Prize—for Chemistry, which he found both gratifying and amusing.[49]

Rutherford's rise to prominence was monitored closely in England, particularly by Arthur Schuster, Langworthy Professor of Physics at the University of Manchester, who offered to retire early if Rutherford would agree to succeed him—an offer that Rutherford accepted in 1907. Manchester then had a population of over 600,000 and was far from being an unpleasant industrial city. It was home to Chetham's Library, which was founded in 1653 and is the oldest free public reference library in the United Kingdom—where Karl Marx and Friedrich Engels began to write *The Communist Manifesto* in 1847. It also was home to the Manchester Literary and Philosophical Society, which was founded in 1781, and is the oldest provincial scientific society in England with a continuous history.[50] Its members included John Dalton (1766–1844) and James Prescott Joule (1818–89), whose statues frame the entrance to the Manchester Town Hall, which was completed in 1877. It probably is the only town hall in the world where two scientists are given such prominent recognition.

Rutherford (Figure 1.4) lost no time in getting settled in Manchester with his wife Mary (née Newton), whom he had married on a trip to New Zealand in 1900, and their six-year-old daughter Eileen. He enjoyed his new students; as he told his friend, Yale chemist Bertram Boltwood: "I find the students here regard a full professor as little short of Lord God Almighty. It is quite refreshing after the critical attitude of Canadian students. It is always a good thing to feel you are appreciated."[51]

Rutherford organized his classes and continued his researches with the help of Schuster's gifted assistant, the German, Hans Geiger, and his excellent Laboratory Steward, William Kay. "Geiger acted as a watch-dog over the research apparatus, and although he was a jealous guardian his popularity and prestige were high enough to enable him to do this without much friction."[52] In 1909, Rutherford asked Geiger to work with one of his research students, Ernest Marsden, to investigate how alpha particles are scattered when striking thin films of heavy elements such as lead and platinum. Two years later, Rutherford interpreted Geiger and Marsden's results by assuming the alpha particles were being scattered by a large concentrated positive charge at the center

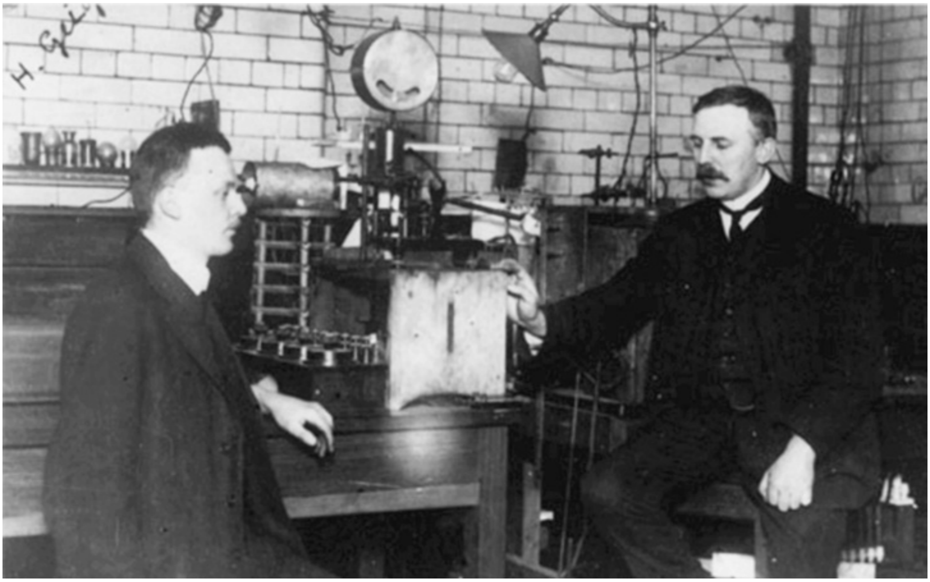

Fig. 1.4 Hans Geiger and Ernest Rutherford at Manchester *c.* 1910. *Credit*: Website "Hans Geiger and Ernest Rutherford"; image labeled for reuse.

of the target atom, the full implications of which would be recognized in 1913 with Niels Bohr's quantum atomic model. By that time, Rutherford's reputation had risen to the point where the "list of New Year's Honours for 1914" included his name "for the order of knighthood," which was conferred by King George V at Buckingham Palace on February 12.[53] The New Zealander of humble origin would henceforth be addressed as Sir Ernest.

Rutherford came into his own as a director of research during his Manchester years. He was fond of calling research a "Tom Tiddler's Ground," after the ancient children's game "where anything might turn up."[54] He attracted increasing numbers of talented students and postdoctoral researchers to Manchester, who dubbed him "Papa," although he was only thirty-nine in 1910. By then he had fifteen to twenty research children, and to draw his research family together he instituted a Friday afternoon colloquium series—with tea usually served by his wife Mary. He drove himself and his students relentlessly, creating the feeling, one of them said, "that we were living very near the centre of the scientific universe."[55] His students were extremely eager to show him results, one recalling that "ever since that time I have been quite certain that I understand exactly the feelings of a fox-terrier as, after killing a rat, he brings it into the house and lays it on the drawing-room carpet as an offering to his domestic gods."[56] In 1913, Rutherford published his fourth book, *Radioactive Substances and Their Radiations*, which was largely based on his and his students' researches. That year Lecturer Walter Makower and Hans Geiger, inspired by Rutherford's course on practical measurements in radioactivity, published a book of that title for use as a radioactivity laboratory manual.[57]

Pushing himself and his students constantly, but knowing when to ease up, admitting a mistake forthrightly, singing "Onward Christian Soldiers" loudly and off-key when pleased, storming about and cussing when displeased, throwing out earthy quips—these were basic ingredients of Rutherford's personality and of the atmosphere he created in his laboratory.

The English experimental physicist Samuel Devons, who eventually became Rutherford's successor as Langworthy Professor of Physics at Manchester, from 1955 to 1960, took that opportunity to interview Rutherford's Laboratory Steward, William Kay, who recounted a memorable episode:

> I remember I was putting a string in a string electrometer you know. . . . They wasn't made in England, you know, not for our instruments. And I put this in and he stood over me. Well, I don't know whether you've ever put one of them things in, have you? You can't see the beastly things at all. Well, he stood over me, you know. "Be careful, be careful, be careful, be careful." And he got me as jittery as himself. And I got it in nicely, and tightened it up, and he started whistling, and I put my finger right through it, I don't know why. And he said, "What the deuce have you done, what the deuce have you done? What did you do that for?" "Oh," I said, "You shouldn't stand over me," I said, "You've got me on the jump." And after a bit he said, "It's quite right," he says. "Put the other one in." And he went in the corridor, and he didn't go far away, and he walked up and down the ground floor corridor whistling "Onward Christian Soldiers." That was nearly as bad as being on top of me! But we got it in. Oh, he understood quite well the ways of a human being, you know.[58]

Rutherford also understood that he created a certain element of fear, particularly in young or shy research students. But transcending everything was Rutherford's genius as an experimentalist, his sure physical intuition, his enormous capacity for prolonged hard work, his intense concentration, his boundless enthusiasm, his breadth of vision and generosity of spirit, and his deep personal interest in the lives and careers of his students and co-workers. He was a man who was committed to "the pure ardour of the chase, a man quite possessed by a noble work and altogether happy in it."[59] One of his research students, Harold Robinson, concluded:

> Perhaps the greatest single factor in Rutherford's success as a leader was his own obvious and enormous delight in experimentation. . . . I remember once wasting with him the whole of a fine Saturday afternoon in an obviously rather hopeless effort to purify . . . a very dirty little sample of radon. . . . The attempt ended [in failure] . . . but Rutherford's final comment, as he sucked contentedly at his pipe while we cleared up the mess, was: "Robinson, you know, I *am* sorry for the poor fellows that haven't got labs. to work in!"[60]

No one could be unaffected by Rutherford's greatness; it was as the German polymath Hermann von Helmholtz said of his teacher Johannes Müller: "Anyone who has once come in contact with one or more men of the first rank must have had his whole mental measuring-rod altered for the rest of his life."[61]

Rutherford's laboratory in Manchester, like Thomson's in Cambridge and many others throughout Europe, was decimated at the outbreak of the Great War in August

1914. Rutherford contributed to the war effort by helping to develop anti-submarine detection devices to combat the German U-boat threat. He turned his laboratory into a large water tank,[62] and took part in some experiments by holding the barrister and amateur scientist Sir Richard Paget by his heels with his head under water to monitor particular sound frequencies, because he had the gift of absolute pitch.[63] Still, as the war continued, Rutherford also found odd times to devote to experiments, trying to understand, as we shall see, some puzzling observations that Ernest Marsden had made in 1914–15.

THE FOURTH CAVENDISH PROFESSOR

By the time the guns of August sounded in 1914, none of J.J. Thomson's other students had achieved the scientific distinction that Rutherford had; by the time the guns were silenced, none of Thomson's students was more natural than Rutherford to consider as the fourth Cavendish Professor of Experimental Physics. Feelers were soon put out to Rutherford. Niels Bohr, who had spent four postdoctoral months with Rutherford in Manchester in the spring of 1912, and two years there during the war as lecturer in physics in 1914–16, visited Manchester again at the time of the Armistice in November 1918. He heard "Rutherford speak with great pleasure and emotion about the prospect of his going to Cambridge, but expressing at the same time a fear that the many duties connected with this central position in the world of British physics would not leave him those opportunities for scientific research which he had understood so well how to utilise in Manchester."[64]

That was not Rutherford's only fear. Thomson formally resigned the Cavendish Professorship in March 1919 to accept another professorship especially created for him, but Rutherford began to worry about the length of Thomson's shadow. Would J.J. interfere with the affairs of the Cavendish, compete for resources and research students, oppose changes in organization and teaching responsibilities? Joseph Larmor, Thomson's better in the Mathematical Tripos of 1880 and now holding Newton's chair as Lucasian Professor of Mathematics at Cambridge, served as intermediary and saw to it that J.J. met all of Rutherford's concerns. J.J. assured Rutherford that he would adopt a strictly hands-off policy. Rutherford then telegraphed Larmor on March 29, 1919, conveying his willingness to stand for the chair, to which Larmor responded that "in my view you have beyond all question taken the right course and your mind will at length be at rest."[65] As the only candidate for the chair, Rutherford was promptly elected on April 2. To make everything crystal clear, however—to remove any possible source of friction—Rutherford insisted on drafting a formal agreement with Thomson that delimited in meticulous detail their respective spheres of influence. It was a document, as Rutherford's official biographer put it, "which would make a lawyer weep."[66]

Rutherford did not take his decision to move to Cambridge lightly. By 1919 he had spent twelve happy and highly productive years in Manchester, and he had been treated generously by the University: his annual salary at £1250 was one of the highest academic salaries in Britain, and the Manchester administration was prepared to go even higher, and to offer other amenities as well, if Rutherford would stay. In the end, however, the lure of the Cavendish was too great for, as Rutherford wrote to his mother on April 7, 1919, "after all it is the chief physics chair in the country and has turned out most of the physics professors of the last 20 years."[67] That was a direct tribute to Thomson, and also clear recognition of the unparalleled attractive power of Cambridge and the Cavendish Laboratory. With Rutherford, the Cavendish would again have a leader who not only would preserve its pre-eminent research tradition, but also one who was committed to carrying it to an even higher level of distinction.

Rutherford's transfer to Cambridge was cause for jubilation among those who mattered most to him, the research staff and students at the Cavendish Laboratory. Alfred A. Robb, mathematical physicist and lyricist, set pen to paper and added a song to the Cavendish repertoire. He called it "Induced Activity," which first appeared in the fifth edition (1920) of the *Post-Prandial Proceedings of the Cavendish Society*. Sung to the tune of "I Love a Lassie," its first verse and chorus went:

We've a professor,
A jolly smart professor,
Who's director of the lab in Free School Lane.
He's quite an acquisition
To the cause of erudition,
As I hope very briefly to explain.
When first he did arrive here
He made everything alive here,
For, said he, "the place will never do at all;
I'll make it nice and tidy,
And I'll hire a Cambridge *lidy*
Just to sweep down the cobwebs from the wall."

He's the successor
Of his great predecessor,
And their wondrous deeds can never be ignored:
Since they're birds of a feather,
We link them both together,
J.J. and Rutherford.[68]

As the lines suggest, Rutherford found J.J.'s housekeeping less than perfect, and one of the first things he did was to clean the Cavendish and whiten its walls.

It was time for a change at the Cavendish. When Rutherford arrived in mid-1919, Thomson was sixty-two and Rutherford forty-seven. J.J.'s scientific star had reached its zenith a decade or so earlier and then slowly begun to set. During the pre-war years his theorizing was idiosyncratic. He proposed, for example, a series of atomic models unfettered by logical consistency. As his biographer remarked: "J.J. was not inclined to be dogmatic about his atomic theories, and indeed he was quite prepared to change them, sometimes without making it altogether clear that he had wiped the slate clean."[69] Rutherford, as usual, was more direct: In 1914 he wrote to his Yale friend Boltwood that J.J.'s most recent atomic model was "only fitted for a museum of scientific curiosities."[70]

With the outbreak of war, J.J. allowed his subscriptions to German scientific journals to lapse, and he never renewed them. After the war, much of his writing displayed little appreciation of the profound changes that had taken place in atomic theory. Physicist Charles G. Darwin (grandson of the great Charles) told Bohr in a letter of May 30, 1919, that after reading J.J.'s last paper in the *Philosophical Magazine*, he felt like shaking J.J., as he "seems to disregard everything that has been done since about 1900."[71] As Master of Trinity, J.J. loomed large in Cambridge, where he was a stimulating lecturer and conversationalist, but scientifically he had fossilized. A naughty ditty made the rounds that unquestionably applied to him:

And when you cease to contribute
to fundamental knowledge
You can always become Master
of a Cambridge College.[72]

Rutherford, by contrast, was full of intellectual vigor, was the undisputed leader in the field of radioactivity and the emerging nuclear physics, and was eager to face the scientific challenges confronting him. He and his wife Mary took up residence in Newnham Cottage, a substantial house with a fine garden on Queen's Road, which they leased from Gonville and Caius College. The Australian Mark Oliphant, Rutherford's future research student and colleague, observed: "Normally, Rutherford walked to and from the Cavendish, and he was close to his College, Trinity, where he dined on Sundays."[73] He described the residence in some detail:

> There was a very fine drawing room, dominated by a concert-size grand piano. This room looked over the garden in which Lady Rutherford took great pride. Rutherford's study was to the left, immediately after entering the house. Like the desk, the room was littered with books and papers.... Occasionally... Lady Rutherford would tidy it all up, arranging everything with meticulous care....
>
> Lady Rutherford had a short, dumpy figure, and many who met her found her aggressive and opinionated.... [But] her outward manner concealed a woman of great warmth of character, who was the helpmate of Rutherford in all that he did.... Keenly interested in music, she played the piano well, and would listen after dinner to any concert of note from the B.B.C. However, after a few moments Rutherford would move to his study to work or to read. He did not have any appreciation of other than loud, martial music, to which he could stamp his feet or attempt to sing, considerably off key ....
>
> The Rutherfords occupied separate bedrooms, and there were no overt acts of affection between them. Yet they were devoted to one another. Lady Rutherford understood little or nothing of her husband's work, but she was very proud of the honours which were showered upon him, and reacted violently to any criticism. She treated him in all ordinary matters as she would a child, still attempting to correct his faults when eating, for instance. I never heard him retort impatiently or angrily, as would most men when treated in that way.[74]

Their home was concisely described as "a comfortable, tasteless, academic home, lacking in grace or inspiration, run by three or four servants in the manner of the times, with a wife whose main interest was in her garden, for a husband whose main interest was in his laboratory."[75] Still,

> Rutherford read very widely and retained an enormous amount of the knowledge he gained in this way. While this reading was omnivorous in his younger days, towards the end of his life he preferred biography, not by any means confined to the lives of scientists. He learned much of notable men of the past. He knew surprising details of the life and work of the great experimental scientists, and of Captain Cook….[76]

The Cambridge physicist-turned-novelist C.P. Snow recorded that:

> Archbishop [Cosmo] Lang was once tactless enough to suggest that he supposed a famous scientist had no time for reading. Rutherford immediately felt that he was being regarded as an ignorant roughneck. He produced a formidable list of his last month's reading. Then, half innocently, half malevolently: "And what do you manage to read, your Grice?" "I am afraid," said the Archbishop, somewhat out of his depth, "that a man in my position really doesn't have the leisure…." "Ah, yes, your Grice," said Rutherford in triumph, "it must be a dog's life! It must be a dog's life!"[77]

On most Sunday mornings Rutherford enjoyed a game of golf at the Gog Magog Golf Club, three miles southeast of the Cambridge city center, with his physicist colleagues Francis W. Aston, Geoffrey I. Taylor, and Ralph H. Fowler. One of his research students, Philip I. Dee, once was told "that when sharing a ball with Aston…he liked to put the ball into a bunker to hear Aston complain about having to extract it…."[78]

RUTHERFORD REIGNS SUPREME

Rutherford pursued his researches at the Cavendish Laboratory first alone, and then with his former Manchester student James Chadwick, as he grappled with a host of demands on his time and energy: He directed the laboratory, taught and lectured widely, and engaged in numerous professional activities. His present post was vastly different from his former. At Manchester he had been alone at the top, so to speak, while in Cambridge the various colleges supported through their fellowships and appointments other outstanding physicists who either worked in the Cavendish or had close connections with it. J.J. Thomson still had laboratory space in the Cavendish and the services of his Laboratory Steward, Ebenezer Everett. Others were there as well. C.T.R. Wilson was elected a Fellow of Sidney Sussex College in 1900, was appointed Jacksonian Professor of Natural Philosophy in 1925, and shared the 1927 Nobel Prize for Physics for his invention of the cloud chamber. Francis W. Aston was elected a Fellow of Trinity College in 1920 and won the 1922 Nobel Prize for Chemistry for his discovery of a large number of isotopes with his innovative mass spectrometer. Ralph H. Fowler was elected a Fellow of Trinity College in 1914 and was appointed Lecturer in Mathematics in 1920. He served as a mathematical consultant to the Cavendish physicists, and came into close personal contact with Rutherford and his wife when he married their daughter Eileen in 1921. A mutual friend, the astrophysicist Edward A. Milne, noted: "They had four children. Eileen died shortly after the birth of the fourth, in December 1930. The best epitaph on Eileen was Fowler's own brief phrase: 'She was a great spirit.'"[79]

The Cavendish researchers worked in a kind of "three-tier mediaeval organization" of masters, journeymen, and apprentices.

> The journeymen... were birds of passage, already in possession of some status. Younger than the master, they followed his ideas, and the master supervised their work. The apprentices helped the journeymen and the master kept a somewhat condescending eye on them.[80]

The masters Wilson, Aston, and Fowler were not beholden to Rutherford, although Rutherford, being Rutherford, drove them when he could. The journeymen were directly responsible to Rutherford as director of the laboratory. In addition to Chadwick, they included Charles G. Darwin and Edward V. Appleton in the early 1920s. Darwin received his B.A. at Cambridge in 1910, then left for Manchester, but returned to Cambridge as Lecturer and Fellow of Christ's College in 1919, where he remained until 1924 when he was appointed Tait Professor of Natural Philosophy at the University of Edinburgh. Appleton received his B.A. at Cambridge in 1914, was elected a Fellow of St. John's College in 1919, and was appointed Assistant Demonstrator in the Cavendish in 1920, a position he held until 1924 when he was appointed Wheatstone Professor of Physics at King's College, London.

Four additional journeymen were soon on the scene: Charles D. Ellis, John D. Cockcroft, Ernest T.S. Walton, and Peter Kapitza. Kapitza made an immediate and strong impression on Rutherford when he arrived from Leningrad (then Petrograd) in the summer of 1921. His first conversation with Rutherford, in one of its versions, went something like this. Rutherford: "Sorry, I have no room for you." Kapitza: "How many research students do you have?" Rutherford: "About thirty." Kapitza: "What is the usual accuracy of your experiments?" Rutherford: "About three percent." Kapitza: "Well, that's one part in thirty, so you won't even notice me."[81] Rutherford accepted him, but "bluntly told him that communist Propaganda would not be tolerated."[82] So in 1922 Kapitza gave a reprint of one of his papers to Rutherford that bore the inscription: "The author presenting this paper with his most kind regards, would be very happy if this work will convince Professor E. Rutherford in two things," the second of which was that "the author came to the Cavendish Laboratory for scientifical work and not for communistical propaganda."[83] Kapitza anticipated that Rutherford would not accept this reprint, so he had brought along another uninscribed one that he then gave to Rutherford.

By the fall of 1921, Kapitza was calling Rutherford "Crocodile," because, as he later told the Scottish writer and academic Richie Calder, "the crocodile is the symbol for the father of the family and is also regarded with awe and admiration because it has a stiff neck and cannot turn back."[84] Kapitza told his mother in a letter of November 1, 1921, that when Rutherford "is displeased you had better look out," that his "intellect is quite unique and he has a remarkable flair and intuition."[85]

In the laboratory, Mark Oliphant recalled that Rutherford "carried in his waistcoat pocket several pieces of pencil, not more than two inches in length and often shorter, with very blunt points," which when using "he held in an awkward manner between thumb and forefinger." Their bluntness made his words or figures "all but indecipherable," but "he did arithmetic rapidly and with surprising accuracy." He "smoked interminably," occasionally a cigar or cigarette but usually a pipe, which "produced sparks and even flame, like a volcano," peppering his waistcoat with small holes and leaving red hot grains of tobacco on papers on his desk.[86]

Kapitza adapted immediately to the Cavendish and its traditions and in 1922 inaugurated a new one: the Kapitza Club, which met informally each term, usually on Tuesday evenings in the college rooms of one of its members. John Cockcroft, who was elected to the club in 1924, described it in a letter to his wife Elizabeth:

> It consists of 12 members—all the bright young sparks of the Cavendish, and they read papers to each other, weekly, on recent work in physics. When no-one reads a paper they have what is diabolically known as "five minutes." You go round the alphabet and have to get up and talk for that space of time in turn.[87]

The latest discoveries in physics often received their first critical analyses at a meeting of the Kapitza Club.

Apprentices flocked to Rutherford and the Cavendish. After the Armistice on November 11, 1918, veterans, assisted by government grants, arrived in large numbers, some like Cockcroft with the "sickly smell" of poison gas embedded forever in their memories.[88] In all, between January and June of 1919 over 2200 students matriculated in the University of Cambridge, including 400 naval officers whose studies had been interrupted by the war.[89] Among the physicists who then received Cambridge B.A. degrees and became research students in the Cavendish were Charles D. Ellis (B.A. 1920), Patrick M.S. Blackett (B.A. 1921), Edmund C. Stoner (B.A. 1921), Herbert W.B. Skinner (B.A. 1922), Cecil F. Powell (B.A. 1925), Norman Feather (B.A. 1926), Philip I. Dee (B.A. 1926), Nevill F. Mott (B.A. 1927), and Louis H. Gray (B.A. 1928). All were eventually elected Fellows of the Royal Society, and three (Blackett, Powell, Mott) later won Nobel Prizes in Physics. Among the apprentices who had received first degrees elsewhere were Mark Oliphant (B.A. Honors, Adelaide 1922), Harold R. Robinson (B.A. and D.Sc., Manchester, 1911 and 1917), John D. Cockcroft (M.Sc., Electrical Engineering, Manchester 1922), Ernest T.S. Walton (M.Sc., Dublin 1927), Leslie F. Bates (B.A., Bristol 1916), Bernice Weldon Sargent (B.A., Honors, 1926, M.A., 1927, Queen's University, Kingston, Ontario, Canada), and Harrie S.W. Massey (B.A., Melbourne 1929). All went on to have distinguished careers in physics.

As a teacher, Kapitza recalled that Rutherford delivered his lectures to undergraduates "with great enthusiasm," using "hardly any mathematical formulae," but many diagrams and "very precise but restrained gestures," which showed "how vividly and picturesquely" he thought.[90] He insisted "that the most important thing a teacher must learn is not to be jealous of the successes of his pupils," and that "the greatest quality of a good teacher should be generosity." Reciprocally, he said: "My pupils keep me young."[91]

In around 1930, physicist Samuel Devons took a course from Rutherford on "The Constitution of Matter" for advanced students (but which was open to all), with lectures for around forty students in the old "Maxwell" room, the main lecture theater of the Cavendish, on Monday, Wednesday, and Friday at noon. His lectures were formal in style but were "highly personal" and gave "a quasihistorical, or rather biographical, account of the development of 'atomic' physics of the past few decades," with no attempt to separate their development from his own life's work.

> There was no doubt that we were listening to a great man relating an epic story, rather like the story of some great scientific expedition as told by its leader. We were being told not so much what Rutherford (or anyone else) thought about this or that, but rather how Nature did its work and how this had been discovered. It was, as Rutherford was so fond of emphasizing, "the facts" that were important.[92]

In research, Kapitza ventured an explanation of Rutherford's success in a letter to his mother on July 6, 1922:

> [The] English school develops individuality on an extraordinary scale; it gives limitless room for a personality to show itself.... Here they often do research so absurd in its ideas that in our country they would have been simply laughed out of court. When I enquired as to the reason this research had been started at all, I learned that these were young men's ideas, and Crocodile values a man's initiative so much that he not only permits the man to work on his own subjects but at times even encourages him and tries to put some sense into these schemes, which are sometimes absurd.... The second factor is the striving to obtain results. Rutherford is very much afraid that a man may work without achieving results, since he knows that this may kill the man's desire to work. Therefore he does not like to give a difficult assignment. When he does give such a hard task, this means that he simply wishes to get rid of the man....[93]

Kapitza developed a close personal relationship with Rutherford and, as C.P. Snow observed, he "flattered Rutherford outrageously, and Rutherford loved it." "He once asked a friend of mine whether a foreigner could become an English peer; we strongly suspected that his ideal career would see him established simultaneously in the Soviet Academy of Sciences and as Rutherford's successor in the House of Lords."[94]

Kapitza and many other young physicists flourished under Rutherford, but a few were discouraged, if not crushed by him. Blackett came to resent Rutherford's authoritarianism,[95] and even Chadwick had a falling out with Rutherford in the early 1920s.[96] A particularly harmful case, however, was that of Edmund C. Stoner, a sensitive, introverted man who suffered from poor health. Stoner found that Rutherford "was not invariably as helpful and stimulating to the young research student as is generally supposed." He could be "genially complimentary" when progress was made, but when things went badly, he "could make the most devastating comments in his naturally loud voice," which often seemed to be "extremely unfair" and discouraging, Stoner never became accustomed to Rutherford's "bark," nor to his "forceful dominance" in discussions, and except for one time in his home, he "never found conversation with him easy." Nevertheless, he was "very kind" in 1923 during Stoner's illness and treatment for diabetes, and afterwards he continued to recognize Rutherford's "outstanding greatness" in physics and to feel that his judgments of people and views of academic and social problems, "though often ill-considered in expression," were right in their essentials.[97]

The relationships between master and journeymen and apprentices thus were as varied as most human relationships. The final tally, however, was beyond dispute: The success of the Cavendish rested primarily on the leadership of its master. Cockcroft identified four of its components. First, Rutherford was "a Director who was passionately devoted to getting new results in nuclear physics, with little interest in sidelines." Second, "Rutherford devoted great care to the selection of research students and his staff. The only point which counted in selecting staff was their promise for research." Third, "the general intellectual environment" was enriched by the presence of "great seniors" such as Thomson, Aston, Wilson, and Fowler, and by distinguished visitors. Finally, Rutherford kept the organizational structure of the Cavendish simple and lean: "There were no committees, but responsibility for different parts of the laboratory work was delegated," and instead of making critical decisions unilaterally, "Rutherford had a system of 'polling the jury,' consulting senior staff members individually on important new issues." In sum, the Cavendish had "a good director, clear objectives, good selection of staff, a good intellectual environment and an efficient but minimal organization…."[98]

Rutherford and the Cavendish thus were in a superb position to assume a commanding role in the development and transformation of the nascent field of nuclear physics.

NOTES

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4. Thomson, Joseph John (1936), pp. 241–2.
5. Trevelyan, George Macaulay (1949), p. 49.
6. Kim, Dong-Won (2002), pp. 51–5.
7. Thomson, Joseph John (1936), p. 98.
8. Ibid.
9. Warwick, Andrew (2003), pp. 66–84.
10. *A History of the Cavendish Laboratory 1871–1910* (1910), p. 91.
11. Andrade, Edward N. da C. (1962), p. 510.
12. For a full account of the new research students, see Kim, Dong-Won (2002), pp. 97–102.
13. Rayleigh, Lord [Robert John Strutt, Fourth Baron Rayleigh] (1942), pp. 150–1.
14. Davis, Edward A. and Isobel J. Falconer (1977); Buchwald, Jed Z. and Andrew Warwick (2001), Chapters 1–5, pp. 19–167; Navarro, Jaume (2012), pp. 73–85.

15. Thomson, George Paget (1964), pp. 92–3.
16. Rayleigh, Lord [Robert John Strutt, Fourth Baron Rayleigh] (1942), pp. 174–5.
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23. Rayleigh, Lord [Robert John Strutt, Fourth Baron Rayleigh] (1942), p. 53.
24. Thomson, George Paget (1964), p. 96.
25. Satterly, John (1939a), pp. 179–80; Davis, Edward A. and Isobel J. Falconer (1977), p. 134.
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27. *A History of the Cavendish Laboratory 1871–1910* (1910), p. 11.
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30. Quoted in Caroe, Gwendolen Bragg (1978), p. 30.
31. Niels Bohr to Harald Bohr, October 23, 1911, in Bohr, Niels (1972), p. 531.
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33. Thomson, Joseph John (1926), p. 44.
34. Quoted in Rayleigh, Lord [Robert John Strutt, Fourth Baron Rayleigh] (1942), p. 269.
35. Ibid., p. 208.
36. Quoted in Russell, Alexander Smith (1954), pp. 66; 96.
37. Quoted in Andrade, Edward N. da C. (1963), p. 306.
38. Campbell, John (1999), pp. 47, 72, 155.
39. Ibid. pp. 190, 205.
40. Ibid. pp. 188, 192.
41. Gerward, Leif (1999).
42. Quoted in Eve, Arthur Stewart (1939), p. 55.
43. Trenn, Thaddeus J. (1977).
44. Eve, Arthur Stewart (1939), p. 90.
45. Heilbron, John L. (1979), pp. 62–3.
46. Hahn, Otto (1970), p. 71.
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2

European and Nuclear Disintegration

THE GREAT WAR

On June 28, 1914, the Bosnian Serb nationalist Gavrilo Princip assassinated Archduke Franz Ferdinand of Austria, heir to the Austro-Hungarian throne, and his wife Sophie, Duchess of Hohenberg, in Sarajevo, the capital of Bosnia. A month of diplomatic maneuvering between the Central Powers of Austria-Hungary and Germany and the Allied Powers of Britain, France, and Russia failed to resolve the crisis, and on July 28, Austria-Hungary declared war on Serbia. On July 30, Russia, in support of its protégé Serbia, ordered general mobilization against Germany, and on August 1, Germany mobilized and declared war on Russia. On August 2, Germany attacked Luxembourg, on August 3, Germany declared war on France, and on August 4 on Belgium. That evening the United Kingdom declared war on Germany. As the war expanded, the Ottoman Empire and Bulgaria joined the Central Powers, and Italy, Japan, the United States, and other countries joined the Allied Powers. By the time of the Armistice on November 11, 1918, more than seventy million military personnel, including sixty million Europeans, had been mobilized.[1]

Mobilization

Austrian biochemist Erwin Chargaff, born in 1905, recalled the rapid mobilization of the Central Powers.

> We were spending the summer in Zoppot on the Baltic Sea. One afternoon at the end of June [1914], we were watching the younger sons of Emperor Wilhelm II playing tennis; an adjutant came and whispered something into the imperial ears. They threw down their rackets and went away: the Austrian Archduke Franz Ferdinand had been assassinated. The nineteenth century had come to an end. . . .[2]

German physicist Walter Elsasser, born in 1904, also recalled the rush of events after Austria-Hungary declared war on Serbia on July 28:

> Overnight, posters appeared at all public places with "Mobilization" printed in huge block letters on top of lengthy instructions for those about to be called into service. . . . The words

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> "ein frisch-fröhlicher Krieg" (a fresh-and-jolly war) were repeated endlessly in the newspapers and by the public speakers who sprouted everywhere like daffodils in spring.[3]

Otto Hahn, Rutherford's former student in Montreal, now in Berlin, recalled:

> On 28 June 1914—it was a Sunday—my wife, my father-in-law, and I were coming home from a walk, when we learned . . . that Archduke Franz Ferdinand of Austria and his wife had been assassinated in Serbia. . . . On 31 July it was officially announced that war was threatening, and on 1 August Russia declared war and general mobilization was proclaimed. . . . The die was cast, and hardly anyone had any doubt of our winning this just war. The Emperor's declaration: "I no longer recognize parties, I recognize only Germans," had its effect. Even the Social-Democrats, who had always been branded *vaterlandslose Gesellen* ("unpatriotic riff-raff") joined in.[4]

The Allied Powers also mobilized rapidly. Marie Curie in Paris recalled that the mobilization, which was announced on August 1st, "was a general wave of all France passing out to the border for the defense of the land. All our interest now centered on the news from the front."[5] One of Curie's biographers described the scene in more detail:

> Paris was in uproar. The little white notices of mobilisation had appeared on the streets at about 5 o'clock at the end of a wonderful day of summer sun. Before darkness fell, parades with massed tricolors accompanied by bands pouring out *La Marseillaise* were sweeping up and down the cobbles. Before the night was out a few German-owned shop-fronts were smashed in and a few stores looted. The Government, it was rumoured, was to move to Bordeaux, and within hours, trains crammed with women and children were, like the Government, steaming out of the capital to the safety of more distant places. Marie Curie herself had been at Montparnasse station and had seen some sign of panic there which she found unbecoming in her fellow-countrymen and women.[6]

Mobilization in England also was immediate. Physicist Edward Appleton remembered that he and William L. Bragg agreed that their collaborative research in Cambridge would have to stop, as both were going to sign up for military duty. Appleton was assigned to guard a reservoir on the outskirts of Cambridge.

> It was an all-night business, and of course we were told to look out for enemy agents who were likely to poison the water supply for Cambridge. . . . There we were, fixed bayonets and everything, posted at each corner of the reservoir. In the middle of the night I captured a little man who seemed to be snooping round the place. He tried to explain what he was doing, but, as this seemed to be my big moment, I wasn't in the mood for listening. But eventually, to my intense disappointment, I had to realise that I'd captured the night-watchman himself.[7]

The 81-year-old Henry Montagu Butler, Master of Trinity College, expressed his deep regret in a letter to Sir George Trevelyan on September 17, 1914:

> Personally I have been from boyhood a lover of Germans, but this wicked war—wicked in its origin, brutal in its conduct—sickens me. I cannot help fearing that there will be no return of friendly feeling between the two nations till long after you and I have passed away.[8]

The Manifesto of the Ninety-Three

Nothing did more to incite the estrangement, indeed hatred, of scientists in England than the Manifesto to the Civilized World, signed by ninety-three German scientists and published on October 4, 1914. The signatories included the past and future Nobel Laureate chemists Adolf von Baeyer, Emil Fischer, Fritz Haber, Walther Nernst, Wilhelm Ostwald, and Richard Willstätter, the past Nobel Laureate physicists Philipp Lenard, Max Planck, Wilhelm Conrad Röntgen, and Wilhelm Wien, and the renowned mathematician Felix Klein. Its purpose was to "protest to the civilized world . . . the lies and calumnies" of Germany's enemies in the "struggle that has been forced on her." It comprised six paragraphs, each beginning with the words, "*It is not true*," the first one being, "*It is not true* that Germany is guilty of having caused this war."[9] The Berlin physiologist Georg Nicolai drafted a counter-manifesto, which only he and Albert Einstein and two others signed.[10] Einstein, in a letter of August 2, 1915, to his esteemed Dutch colleague Hendrik A. Lorentz lamented:

> It is curious in Berlin. Professionally, scientists and mathematicians are strictly internationally minded and guard carefully against any unfriendly measures taken against their colleagues living in hostile foreign countries. Historians and philologists, on the other hand, are mostly chauvinist hotheads. The well-known and notorious "Manifesto to the Civilized World" is being deplored by all level-headed people here. The signatures had been given irresponsibly, some without prior reading of the text. That is how it was for Planck and Fischer, for ex[ample], who have supported upholding international ties in a very resolute manner.[11]

German chemist Richard Willstätter said that his French colleagues "never forgave me for having been one of the signers" of the Manifesto. Still, he was unapologetic, arguing that:

> The outbreak of war overtook us like a natural disaster. . . . The professors were convinced that Germany bore no responsibility for the war and that war had taken it by surprise—a conviction which they expressed in the Proclamation of the Ninety-Three, but unfortunately allowed a poet to clothe in unsuitable style. The war appeared to us to be a defensive one.[12]

That was not how it was seen in England. Physicist Oliver Lodge stated bluntly:

> Seldom indeed in any war is the issue so clear as in the present one. The tearing up of treaties, the contempt of the written word, the treachery, the lying, and above all the unspeakable cruelties, put our enemy outside the pale of civilization, and he should be boycotted with firmness and decision. The sooner these evils are eradicated from the planet the better, and now is the time for attacking them in concentrated form.[13]

The hatred of Germany extended to German-born physicists who had had long and distinguished careers in England; foremost among them was Rutherford's predecessor in Manchester, Arthur Schuster (Figure 2.1). Born in Frankfurt am Main in 1851 into a wealthy Jewish family, he was baptized as a youth, had graduated from the local *Gymnasium*, and had moved with his family to Manchester in 1870 when Frankfurt was

Fig. 2.1 Arthur Schuster in around 1932. *Credit*: Website "Arthur Schuster"; image labeled for reuse.

annexed by Prussia.[14] The following year he entered Owens College, studying mathematics, physics, and chemistry under distinguished teachers. He left Manchester in 1872, obtained his doctorate at the University of Heidelberg in 1873, returned to England, and entered the Cavendish Laboratory in 1874, where he worked for five years under James Clerk Maxwell until his death and then under the third Lord Rayleigh. He was elected a Fellow of the Royal Society in 1879 and as its Secretary in 1912. Two years later, early in the war, the fourth Lord Rayleigh recalled that:

> the hysterical outbreaks of spy mania made difficult the position even of British subjects of long standing who had been born in Germany. Schuster was one of the sufferers, and the fact that he had installed at his house a wireless receiving set for getting the time from the Eiffel Tower station gave a handle for the most grotesque misrepresentations. Attempts were even made to eject him from his position as Secretary of the Royal Society, but . . . these attempts fell far short of success. To Schuster, however, all this came as a rude shock.[15]

Schuster never forgot the way some of his prominent English colleagues supported him:

> Early on during the War, I was one morning surprised to find paragraphs in the daily press stating that a wireless apparatus had been found and "seized" in my house, with more or less veiled references to the purpose for which the apparatus was likely to have been erected. . . .
>
> Though I knew that the implied accusation was not likely to impress my friends, the matter, in view of my position at the time [as Secretary of the Royal Society], was serious, and it

> was with fear and trembling that I entered the Athenaeum a few days later and selected a solitary place in the coffee-room. I was leaving again directly after luncheon, and as I was putting on my coat in the hall I suddenly felt someone stepping up behind to help me. Surprised at this politeness, which is somewhat unusual in the Club, I turned round and looked into the kindly face of Lord [Frederick] Roberts, with whom I had no personal acquaintance. The hall was then full of members of the Club, and it was obvious that the action was intended to be, and in fact was, a demonstration. Such incidents are not likely to be forgotten.[16]

Schuster also never forgot the support he received from J.J. Thomson and others.

A related fate befell the much younger physicist Frederick Lindemann. Born in Baden-Baden in 1886, he attended the *Gymnasium* and Technical University (*Technische Hochschule*) in Darmstadt and became research assistant to Walther Nernst at the University of Berlin in 1911. He was independently wealthy, an excellent tennis player, and well connected to German aristocrats, including Kaiser Wilhelm II. Nernst's first biographer observed that:

> This comfortable world came to a sudden end in August 1914. Lindemann had to get out of Germany in a hurry, leaving the tennis tournament at Zoppot [where the young Erwin Chargaff also was present], which he had hoped to win. Almost overnight . . . there was poor Lindemann, with a Hun name, a Hun education and, worst of all, even a Hun birth certificate. It was inevitable that most people [in England] with whom he now came into contact should regard him as a German and some of them were convinced that he was a German spy. . . .
>
> This transition from a rich young tennis champion, who enjoyed the hospitality of princes, to a suspect outcast, had a profound influence on Lindemann. He became withdrawn to avoid exposing himself to slights and insults. Secretiveness about his personal life developed into a mania and he discouraged personal approaches by a stand-offishness which was easily mistaken for arrogance.[17]

The Horror of the War

The slights suffered by Schuster and Lindemann were as nothing compared to the carnage on the battlefield, as described by the English author and journalist Harold Begbie:

> A battlefield is only the outline of War. Fill it up with agonizing anxiety, with burning prayers, with maddening sleeplessness, with tears and sobs and groans; fill it up with the heart's capacity for utmost grief and sharpest pain; fill it up with suffering, the suffering of women and children, till the outline is as pitted with these things as a map of London is pitted with names, and then you may have some idea, some faint idea, of the range of a heavy gun and the flight of a bullet.[18]

Marie Curie, who headed an X-radiological service on the battlefield, cried out:

> I can never forget the terrible impression of all that destruction of human life and health. To hate the very idea of war, it ought to be sufficient to see once what I have seen so many times, all through those years: men and boys brought to the advanced ambulance in a

> mixture of mud and blood, many of them dying of their injuries, many others recovering but slowly through months of pain and suffering.[19]

On the other side of the conflict, Richard Willstätter proclaimed:

> It was a time when a human life meant little. Berlin's young students were being mowed down on the battlefields of Flanders, and along the ever-expanding front lines the numbers of the dead and wounded were piling up to the hundred thousands and higher.[20]

Among the young scientists who were cut down in the prime of their lives were Rudolf and Gustav Nernst, sons of Walther Nernst, Jan Danysz, Marie Curie's Polish co-worker, Henry G.J. Moseley, Rutherford's brilliant student at Manchester, Robert C. Bragg, William H. Bragg's younger son, Friedrich (Fritz) Hasenöhrl, Ludwig Boltzmann's successor and Erwin Schrödinger's teacher in Vienna, Christopher Fowler, Ralph H. Fowler's younger brother, and Herbert Herkner, Max Born's former student at Göttingen.

The brutal trench warfare dragged on and on and saw the first use of poison gas on April 22, 1915, when the Germans used chlorine gas at the Second Battle of Ypres, in violation of the Hague Convention.[21] Tanks were first used by the British on September 15, 1916, during the Battle of Flers-Courcelette, part of the Somme offensive. In the Naval War, Britain began a naval blockade of Germany soon after the outbreak of the war, which German U-boats attempted to break, and on May 7, 1915, one torpedoed the passenger liner RMS *Lusitania* with 1959 passengers and crew aboard, 1198 of whom lost their lives, among them 128 Americans. Germany then promised not to target passenger ships, but broke that promise in January 1917 and adopted a policy of unrestricted U-boat warfare, realizing that the United States would soon enter the war, which it did on April 6, 1917. By the summer of 1918, 10,000 American soldiers, including Puerto Ricans to whom the U.S. Congress had granted citizenship in 1917, were arriving daily in France.[22]

Armistice and Aftermath

The war ended with the signing of the Armistice on November 11, 1918. The Russian Revolution, actually a series of revolutions in 1917, forced the abdication of Tsar Nicholas II on March 15, 1917, after ruling Russia for twenty-two years. The Bolshevik leaders ended the participation of Russia in the war by signing the Treaty of Brest-Litovsk with the Central Powers on March 3, 1918. The German Kaiser Wilhelm II abdicated on November 9, 1918, and fled to the Netherlands, after ruling the German Empire and the Kingdom of Prussia for thirty years. The Emperor of Austria and King of Hungary, Franz Joseph I, died on November 21, 1916, after ruling the dual monarchy for sixty-eight years. He was succeeded by his grandnephew Charles I, who refused to abdicate but renounced his participation in state affairs on November 12, 1918; his attempt to restore the monarchy ended with his death on April 1, 1922. The Sultanate of the Ottoman Empire was abolished on November 1, 1922, the Republic of Turkey was established on

October 29, 1923, and the Caliphate was abolished on March 1, 1924. By then four empires and their imperial families had vanished, the Russian and the Romanovs, the German and the Hohenzollerns, the Austro-Hungarian and the Hapsburgs, and the Ottoman and the Ottomans.

Their dissolution occurred within the context of five postwar treaties between the Allied and Central Powers. The Treaty of Versailles, signed on June 28, 1919, exactly five years after the assassination of Archduke Franz Ferdinand and his wife Sophie in Sarajevo,[23] required the return of Alsace-Lorraine to France, the ceding of various territories to Belgium, Lithuania, Czechoslovakia, and Poland, and the designation of Danzig as a free city. Article 231, the deeply humiliating "guilt clause," required Germany to accept responsibility for causing the war by her aggression, and to pay reparations equivalent to $5 billion in gold, ships, securities, or other commodities to the Allied countries.

Four more treaties followed. The Treaty of Saint-Germain-en-Laye, signed on September 10, 1919, required Austria to cede over sixty percent of its prewar territory to Czechoslovakia, Poland, Romania, Italy, and the Yugoslav Kingdom of Serbs, Croats, and Slovenes.[24] The Treaty of Neuilly-sur-Seine, signed on November 27, 1919, required Bulgaria to return Southern Dobruja to Romania, and to cede various territories to Greece and to the Yugoslav Kingdom of Serbs, Croats, and Slovenes.[25] The Treaty of Trianon, signed on June 4, 1920, required Hungary to cede seventy-two percent of its prewar territory, mainly to Czechoslovakia, Romania, and the Yugoslav Kingdom of Serbs, Croats, and Slovenes.[26] The Treaty of Sèvres, signed on August 10, 1920, marked the beginning of the dissolution of the Ottoman Empire, requiring the renunciation of all non-Turkish land, and parts of her Turkish land, which resulted in the British Mandate of Palestine and the French Mandate of Syria.[27] It led ultimately to the establishment of the Republic of Turkey after the Treaty of Lausanne, signed on July 24, 1923, was accepted by Mustafa Kermal Ataturk and Turkish nationalists.[28]

Taken as a whole, these five postwar treaties transformed the map of Europe, with profound consequences for the world.

The Human Cost of the War

Life changed dramatically after the war. "Before 1914," the celebrated Austrian writer Stefan Zweig recalled, "the earth had belonged to all. People went where they wished and stayed as long as they pleased. There were no permits, no visas, and . . . I traveled from Europe to India and to America without passport and without ever having seen one."[29] Theoretical physicist Max Born concurred: "I shall tell you how I lived, . . . for instance, . . . how easy it was to travel: no passport required, no exchange problems, as you could get foreign money to an almost fixed value, very little customs formalities, excellent hotels everywhere, fast trains, not crowded and not expensive, and so on."[30] Instead, Europe was now beset by intense hatred, political upheaval, economic uncertainly, and massive unemployment.

In Cambridge, the Cavendish Laboratory had been decimated during the war. Teaching and research "virtually ceased." Military personnel were billeted in parts of the Cavendish. Most researchers had left the Cavendish "to fight Germans," and those who remained then left "to participate in war-related scientific research."[31] The American physicist Arthur Holly Compton arrived at the Cavendish for a year of research in the fall of 1919 and was struck by the many students pouring back to resume their studies:

> Among them were those who had been crippled and blinded. The class room was rare that did not have crutches leaning against a chair. But what sank most deeply into my soul was the awareness that so many were not there who should have been.[32]

About 16,000 Cambridge men had served in the armed forces, 2652 of whom had been killed, 3460 had been wounded, and 497 were reported as missing or prisoners. The names of 600 Trinity men who fell in the war were inscribed on the panels of the Trinity College Chapel.[33] Some men and women were comforted by spiritualism, which had deep roots in England before the war. Physicist Oliver Lodge's son was killed in Flanders in 1915, and his spiritualist memorial of 1916, *Raymond*, became a runaway bestseller, going through six editions in two months.[34]

Total casualties on both sides of the conflict were staggering beyond belief: 9,911,000 dead, 21,219,500 wounded, and 7,750,000 missing. Anyone who has seen the battlefield at Verdun, France, is struck dumb by fields upon fields of graves, as far as the eye can see. Accompanying this grievous loss of life and limb were searing psychological scars, many from the gas warfare. As John Cockcroft told his mother, "you sniff the stuff you make a dive for your helmet and it's on. You never forget to take it with you after one experience of it. Never shall I forget its sickly smell and the memories it brings back."[35] One veteran who arrived in Cambridge after the war to read English, J.B. Priestley, wrote: "Nobody, nothing, will shift me from the belief, which I shall take to the grave, that the generation to which I belong, destroyed between 1914 and 1918, was a great generation, marvelous in its promise. This is not self-praise, because those of us who are left know that we are the runts."[36] Another Englishman reflected that the war had "created that tragic mood which was a part of the air we breathed."[37]

RUTHERFORD'S DISCOVERY OF ARTIFICIAL NUCLEAR DISINTEGRATION

The Cambridge physicist-turned-novelist C.P. Snow painted a sensitive portrait of Rutherford (Figure 2.2):

> He was a big, rather clumsy man [just under six feet tall], with a substantial bay window that started in the middle of the chest. I should guess that he was less muscular than at first sight he looked. He had large staring blue eyes and a damp and pendulous lower lip. He didn't look in the least like an intellectual. Creative people of his abundant kind never do, of course, but all the talk of Rutherford looking like a farmer was unperceptive nonsense.

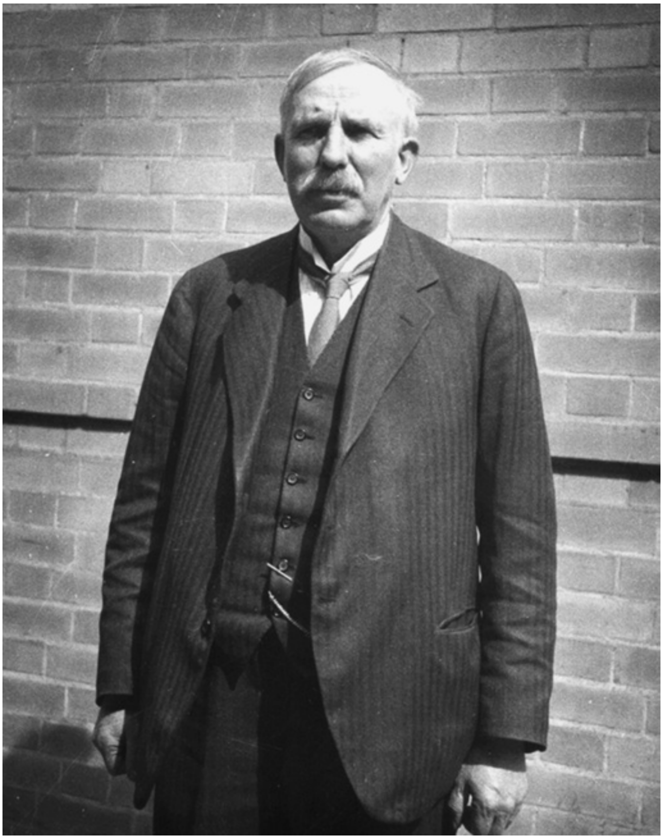

Fig. 2.2 Ernest Rutherford at the Cavendish. *Credit*: Courtesy of Paul Harteck; reproduced by permission of Lawrence Badash.

> His was really the kind of face and physique that often goes with great weight of character and gifts. It could easily have been the soma of a great writer. As he talked to his companions in the street, his voice was three times as loud as any of theirs, and his accent was bizarre. In fact, he came from the very poor: his father was an odd-job man in New Zealand and the son of a Scottish emigrant. But there was nothing Antipodean or Scottish about Rutherford's accent; it sounded more like a mixture of West Country and Cockney.[38]

When Rutherford arrived in Cambridge he knew exactly what research he intended to pursue. Just before leaving Manchester, he had made a fundamentally new discovery: He had found that RaC ($_{83}Bi^{214}$) alpha particles, when incident on a nitrogen nucleus, can disintegrate it. His discovery originated in certain surprising observations that his student Ernest Marsden had made in 1914–15. Marsden had used an experimental technique that Rutherford had pioneered: the observation of scintillations—tiny spots of light produced when charged particles such as alpha particles strike a "scintillation screen," a thin glass plate covered with zinc sulfide crystals containing a slight metallic impurity such as copper. Marsden recalled that on train journeys, Hans Geiger "would urge him not to put his head out of the window, lest a chance smoke particle should impair his efficiency as a human scintillation counter."[39]

Rutherford had employed the scintillation technique continuously since 1908, after he and Geiger had proved that a single alpha particle produces a single scintillation. Now, in his first experiments in 1914, Marsden had sent alpha particles through a long tube containing hydrogen and had observed nothing surprising. When, however, they struck a thin film of wax surrounded by air he observed an anomaly: He counted more scintillations than he had expected to see, and he suspected that the excess scintillations were being produced by hydrogen nuclei that had been emitted along with alpha particles from the radioactive source. He was unable to pursue this observation, because in early 1915 he accepted a professorship of physics at Victoria College in Wellington, New Zealand. Soon thereafter, however, he was back in Europe on active duty on the Western Front.[40] Rutherford, with his characteristic sensitivity to the careers of his students, wrote to Marsden, requesting permission to pursue his anomalous observation. Marsden willingly consented, and Rutherford then embarked on a series of experiments that would occupy all of his spare time for research throughout the duration of the war.

Marsden's tentative interpretation intrigued Rutherford, because if true it meant that radioactive elements could undergo a hitherto unknown mode of disintegration by emitting hydrogen nuclei. Rutherford also wondered, as he said in a lecture in Washington, D.C., in April 1914, if heavy elements might be created in the interior of stars if an alpha particle or hydrogen nucleus collided with the nucleus of an atom and caused either its "disruption" or combined with it.[41] To explore these possibilities experimentally, Rutherford only had the help of his talented Laboratory Steward, William Kay, so progress was slow, and it took him around three years, until the end of February 1917, to devise and construct his basic experimental apparatus, as shown in Figure 2.3. It consisted of a small rectangular brass box (18 × 6 × 2 cm) fitted with two stopcocks on its upper surface through which various gases could be admitted or exhausted, and it had a small rectangular opening (10 × 3 mm) on its right side that was closed with thin metallic absorbing foils S, beyond which was a scintillation screen F in front of a low-power observing microscope M. A RaC ($_{83}\mathrm{Bi}^{214}$) source D, mounted on a movable upright arm, sent alpha particles through the gas in the chamber, and since he knew that they can pass through about 7 cm of air, his plan was to insert foils S of greater absorbing power so that any scintillation he observed had to be produced either by alpha particles of greater energy, or by other particles emitted by one of the gases in the chamber.

Rutherford eliminated the possibility that Marsden's particles were ionized carbon, oxygen, or nitrogen *atoms*, so he then conjectured that they had been expelled from the *nuclei* of these atoms. He tested carbon and oxygen by admitting first carbon dioxide, then oxygen, into the chamber, and found that the number of scintillations actually *decreased*. He then reasoned that the third gas, nitrogen, could be tested by admitting dried air into the chamber. Since oxygen and nitrogen are the main constituents of air,

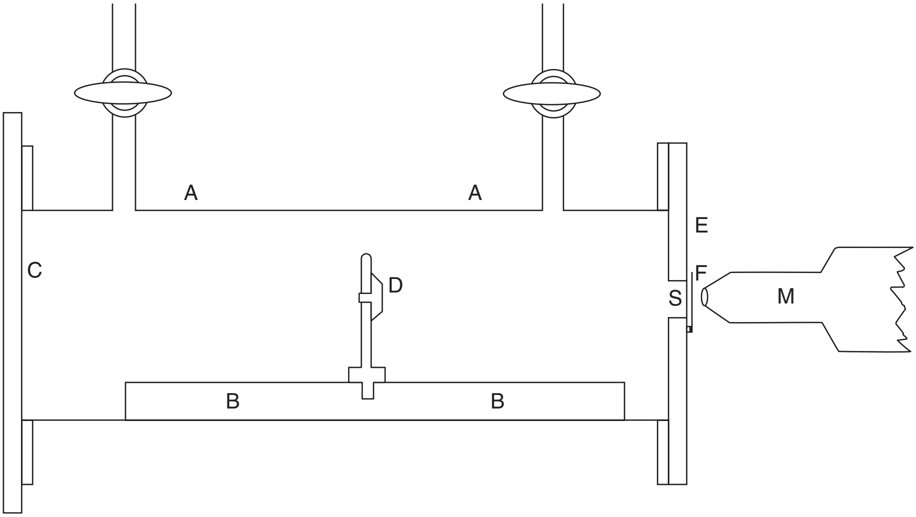

Fig. 2.3 Rutherford's experimental apparatus, which he designed at the end of 1917 and used at Manchester in early 1919 to prove that RaC alpha particles can disintegrate the nitrogen nucleus with the emission of hydrogen nuclei. *Credit*: Rutherford, Ernest (1919a), pp. 543, 551.

and since he now had eliminated oxygen, only nitrogen or one of the rare constituents of air remained as a possible source of Marsden's particles. He therefore admitted dried air into the chamber—and hit pay dirt. Instead of decreasing, the number of scintillations greatly *increased*. To exclude the possibility that they were produced by particles from one of the rare constituents of air, he introduced pure nitrogen into the chamber—and again observed a large number of scintillations. Marsden's particles were definitely being expelled from nitrogen *nuclei*.

The only question now was what was their exact identity, which could be answered unambiguously by deflecting them in a magnetic field, since the radius of deflection is inversely proportional to the mass of the particle, but because of Rutherford's limited time and equipment he could only make some preliminary measurements, which nonetheless convinced him that the expelled particles were "probably atoms of hydrogen, or atoms of mass 2."[42]

Rutherford was quite confident of this conclusion by November 1917,[43] but he wanted unassailable evidence for this. A few days later, on December 9, 1917, he wrote to his friend Niels Bohr:

> I am detecting & counting the lighter atoms set in motion by α [alpha] particles & the results, I think, throw a good deal of light on the character & distribution of forces near the nucleus. I am also trying to break up the atom by this method.[44]

Six months later, he told Bohr that he was "still uncertain of the true explanation of the anomalies I obtain but I am sure something very fundamental will ultimately come out of it."[45] And on November 17, 1918, six days after the Armistice, he confided to Bohr:

> I wish I had you here to discuss the meaning of some of my results on collision of nuclei. I have got some rather startling results, I think, but it is a heavy & long business getting *certain* proofs of my deductions. Counting weak scintillations is hard on old eyes, but still with the aid of Kay I have got through a good deal of work at odd times the past four years.[46]

Two months later, in January 1919, Marsden—now Major Marsden of the New Zealand Division Signals Company—paid a brief visit to Manchester and saw at first hand the great extent to which Rutherford had pursued his 1914–15 observations.[47]

Three months later, in April 1919, Rutherford reported his results in the *Philosophical Magazine*, where they were published in June, just as he was preparing to move from Manchester to Cambridge. It is "difficult to avoid the conclusion," he wrote, that he had observed "atoms of hydrogen, or atoms of mass 2," so,

> we must conclude that the nitrogen atom is disintegrated under the intense forces developed in a close collision with a swift α particle, and that the hydrogen atom which is liberated formed a constituent part of the nitrogen nucleus.[48]

That was indeed a "very fundamental" conclusion, because it meant that hydrogen nuclei had to join electrons and alpha particles as fundamental constituents of nuclei. Moreover, it meant that in addition to the "natural" disintegration of heavy radioactive elements like radium or uranium, the nucleus of the light element nitrogen could be disintegrated "artificially" using experimental techniques under the control of man.

Rutherford's discovery generated intense excitement among physicists. On June 6, 1919, he lectured on it at the Royal Institution in London, where Frederick Lindemann, who had recently been appointed as Dr. Lee's Professor of Experimental Philosophy and Head of the Clarendon Laboratory at the University of Oxford, was in his audience and was greatly impressed by it. By that fall, Rutherford's discovery was on the lips of physicists everywhere, as Niels Bohr told Rutherford in a letter of October 20, 1919:

> You may be assured that everybody here [in Copenhagen] who has any interest in physics or chemistry is most enthusiastically interested in the progress of your work; and [George de] Hevesy who sent me a letter from Berlin on his departure told me that scientists there were almost not speaking of anything else. Also [Arnold] Sommerfeld, who came to Copenhagen [from Munich] some weeks afterwards and gave some lectures to the Physical Society, was deeply interested and mentioned in his lectures some beautiful considerations he had developed in connection with your results.[49]

Sommerfeld, in fact, was so impressed with Rutherford's discovery that he included a discussion of it in an appendix to the first edition of his influential treatise, *Atombau und Spektrallinien*.[50]

Just as Rutherford had exhibited his theoretical prowess in 1911 in proposing his nuclear model of the atom, he now argued that his discovery of artificial disintegration could be understood on the basis of a definite model of the nucleus.[51] He noted that the atomic weight of nitrogen is 14 units, and hence is of the form $4n + 2$, where n is an integer, so he proposed that the nitrogen nucleus consists of a central core of mass 12 surrounded by 2 hydrogen nuclei. He explained:

> If the H nuclei were outriders of the main system of mass 12 . . . the [incident] α particle in a collision comes under the combined field of the H nucleus and of the central mass. . . . The general results indicate that the H nuclei, which are released, are distant about twice the diameter of the electron ($7 \times 10-^{13}$ cm.) from the centre of the main atom.[52]

Rutherford refined his model in light of further experiments, reporting his considerations in a second Bakerian Lecture at the Royal Society on June 3, 1920. He first eliminated any ambiguity about the nature of the particles expelled from nitrogen. His magnetic-deflection experiments had now proven that they are "swift atoms of positively charged hydrogen" with a range of about 28 cm in air; hence, most significantly, that "hydrogen is one of the components of which the nucleus of nitrogen is built up."[53]

Hydrogen, however, was not the only component. The long-range hydrogen nuclei emitted by both nitrogen and oxygen were accompanied by "much more numerous" particles of about 9 cm in range in air. Rough magnetic-deflection experiments showed that these short-range particles were doubly charged and of mass 3, which he therefore designated as X_3^{++} particles. This meant "that the nitrogen nucleus can be disintegrated in two ways, one by the expulsion of an H atom and the other by the expulsion of an atom of mass 3 carrying two charges."[54] Their constitution could be inferred from "the analogy with helium": Since the helium nucleus, the alpha particle, consists of four H nuclei and two electrons for a net positive charge of two, the X_3^{++} particle should consist of three H nuclei and one electron. It therefore "seems very likely that one electron can also bind two H nuclei and possibly also one H nucleus." The former would be a heavy isotope of hydrogen, the latter "an atom of mass 1 which has zero nucleus charge."[55] Thus, based on his belief in the existence of the X_3^{++} particle, Rutherford predicted the existence of both the deuteron and the neutron a dozen years before they were discovered experimentally.

Rutherford's belief in the existence of the X_3^{++} particle compelled him to extend his models of nitrogen, oxygen, and other light nuclei. The ones he proposed for three isotopes of lithium (${}_3Li^6$, ${}_3Li^7$, ${}_3Li^8$) and for isotopes of carbon (${}_6C^{12}$), nitrogen (${}_7N^{14}$), and oxygen (${}_8O^{16}$), are shown in Figure 2.4, where the negative signs represent nuclear electrons, and the circles with the numbers 1, 3, and 4 inside represent the hydrogen nucleus, the X_3^{++} particle, and the alpha particle. Rutherford actually constructed models of these isotopes out of red and white balls (positive and negative particles) for a lecture he delivered at a meeting of the British Association for the Advancement of Science in Cardiff in 1920.[56] Note that only the nitrogen nucleus (${}_7N^{14}$) consists of both hydrogen nuclei and X_3^{++} particles. It therefore could be disintegrated in two ways, one by the "expulsion of an H atom," leaving a "residual nucleus" of charge 6 and mass 13, "an isotope of carbon," another by the "expulsion" of an X_3^{++} particle, leaving a residual nucleus of charge 5 and mass 11, an "isotope of boron."[57] In the first case, his belief that the residual nucleus should be an isotope of carbon followed directly from his picture of the nitrogen disintegration process as a billiard-ball collision between the incident alpha particle and a nitrogen nucleus.