# William Henry Bragg in Adelaide

## Beginning Research at a Colonial Locality

***By John Jenkin****

**ABSTRACT**

This essay presents an account of W. H. Bragg's earliest research program in Australia during the years 1904–1907: a study of the behavior of alpha particles from radioactive decay. It is suggested that problems associated with distance and isolation played a pivotal role in Bragg's thinking and acting during this period and that his use of two "advocates," Ernest Rutherford and Frederick Soddy, was essential to the success of the program. It is further argued that this account supports a substantial amendment of the center–periphery model of colonial science to embrace a much closer attention to place and locality; that is, it supports a polycentric model (in which the center might still be prominent).

WILLIAM HENRY BRAGG was one of the most important scientists of the twentieth century. He made the current biological revolution possible through the invention, with his elder son, William Lawrence Bragg, of the technique of X-ray crystallography. In their laboratories the daunting task of uncovering the atomic structure of materials, and of giant biological molecules in particular, was first tackled and then solved. Having themselves jointly won the 1915 Nobel Prize in Physics, they became mentors to others who would also win acclaim and Nobel Prizes.[1]

The pair had come to England only in 1909 and had started to work on the diffraction of X-rays by crystals only in 1912, when Lawrence Bragg was still a graduate student at Cambridge. It was possible for them to achieve so much in so short a time because of their previous experience and education in Adelaide, in the distant British colony of South Australia. It was here that William Bragg matured as a man, a teacher, and a research scientist and where Lawrence was born, raised, and then taught mathematics and physics

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[1] E. N. daC. Andrade, "William Henry Bragg, 1862–1942," *Obituary Notices of the Fellows of the Royal Society,* 1942–1944, *4:*276–300; and Sir David Phillips, "William Lawrence Bragg, 1890–1971," *Biographical Memoirs of the Fellows of the Royal Society,* 1979, *25:*75–143.

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by his father. There has been surprisingly little historical writing about this father-son pair. They do not receive a personal entry in the recent *Oxford Companion to the History of Modern Science,* for example, and their names have been largely absent from the recent celebrations to mark the fiftieth anniversary of the discovery of the structure of DNA (which took place in Lawrence Bragg's Cambridge laboratories).[2]

The development of science in the colonies of the Western European powers has been a subject of considerable study over the last fifty years. "Scientific colonialism" and "colonial science," "scientific imperialism" and "imperial science," science at the "center" and at the "periphery": the list of terms and models is extensive, but agreement as to their meaning, their application, and perhaps even their usefulness seems limited.[3] Indeed, in stressing the importance of "locality" in formulating any new framework for treating these issues, David Wade Chambers and Richard Gillespie have noted that "this is a tall order. It is no wonder that some have suggested it is unlikely that such a model will ever be devised, especially considering the cultural, social, and economic diversity of the cases for which the model must account!" A related question is the effect, or indeed the reality, of the concepts of "distance" and "isolation" for the scientist working at an outpost of a European power, and this too has been a topic of debate.[4]

Initiating and conducting a significant research program in a nineteenth-century European colony was a daunting task. The purpose of this essay is to explore the earliest research work of William Bragg (who was poorly trained in experimental physics) at the University of Adelaide in Australia (where facilities were limited and incentives small) in the years around 1900 (when scientific research was not widespread and when physics was undergoing a traumatic upheaval). As Roy MacLeod has suggested, "The sciences of discovery and invention have their own momentum, and their direct applications to imperial and colonial enterprise require careful case-by-case treatment, in which the history of science never forgets the context within which ideas and material culture intersect."[5]

It will be suggested that research success in such an environment depended on a multitude of factors, including previous education and experience (or the lack of it), local imperatives and opportunities (personal, academic, cultural, and economic), personal abil-

[2] J. L. Heilbron, ed., *The Oxford Companion to the History of Modern Science* (Oxford: Oxford Univ. Press, 2003).

[3] There is a large literature on these topics. Two major collections of papers are Patrick Petitjean, Catherine Jami, and Anne Marie Moulin, eds., *Science and Empires: Historical Studies about Scientific Development and European Expansion* (Dordrecht: Kluwer, 1992); and Roy MacLeod, ed., *Nature and Empire: Science and the Colonial Enterprise, Osiris,* 2nd Ser., 2000, *15,* which includes an extensive bibliography. The following contain articles and references not only to the Australian situation but also to these topics more generally: Nathan Reingold and Marc Rothenberg, eds., *Scientific Colonialism: A Cross-Cultural Comparison* (Washington, D.C.: Smithsonian, 1987); R. W. Home and S. G. Kohlstedt, eds., *International Science and National Scientific Identity* (Dordrecht: Kluwer, 1991); Home, ed., *Australian Science in the Making* (Cambridge: Cambridge Univ. Press, 1988); and MacLeod, ed., *The Commonwealth of Science: ANZAAS and the Scientific Enterprise in Australasia* (Melbourne: Oxford Univ. Press, 1988). Mention should also be made of Lewis Pyenson and Susan Sheets-Pyenson, *Servants of Nature: A History of Scientific Institutions, Enterprises, and Sensibilities* (New York: Norton, 1999), and references therein to their earlier work; and Bruno Latour, *Science in Action* (Cambridge, Mass.: Harvard Univ. Press, 1987).

[4] David Wade Chambers and Richard Gillespie, "Locality in the History of Science," in *Nature and Empire,* ed. MacLeod, pp. 221–240, on p. 227 n 29. See also Chambers, "Locality and Science: Myths of Centre and Periphery," in *Mundialización de la ciencia y cultura nacional,* ed. Antonio Lafuente, Alberto Elena, and M. L. Ortega (Madrid: Doce Calles, 1993), pp. 605–617. On the concepts of distance and isolation see Chambers, "Does Distance Tyrannize Science?" in *International Science and National Scientific Identity,* ed. Home and Kohlstedt, pp. 19–38; and David Knight, "Tyrannies of Distance in British Science," *ibid.,* pp. 39–53.

[5] Roy MacLeod, "Passages in Imperial Science: From Empire to Commonwealth," *Journal of World History,* 1993, *24:*117–150, on p. 127.

ities and characteristics (including initiative and adaptability), a significant network of colleagues (in Australia and overseas, offering encouragement, advice, and assistance), and an amount of good fortune. It will be concluded that only a special set of circumstances and abilities enabled Bragg to prosper, that his experience was not common, and that a "typical" colonial scientific experience may not exist.

Bragg was born and raised in England and arrived in Adelaide in 1886. Fresh from success in Parts I, II, and III of the Cambridge Mathematical Tripos and after less than a year of study in J. J. Thomson's Cavendish Laboratory, he took up the joint Elder Chair of Mathematics and Experimental Physics at the University of Adelaide. In the early years he was very active in university and community affairs; this was also a period of social and academic maturation, during which Bragg courted and married Gwendoline Todd, the third daughter of Sir Charles Todd, the South Australian postmaster general, government astronomer, and superintendent of telegraphs. Regarding research, Bragg said of himself, "For seventeen years I worked steadily in Adelaide. It never entered my head that I should do any research work." While this statement may typify Bragg's modesty and self-effacing personality and has been accepted by later scholars, the truth is very different.[6]

## ENCOURAGEMENT TO RESEARCH

Bragg's major research work in Adelaide during the years 1903–1909 can be divided into two areas: the study of alpha particles and the way in which they lose energy by ionization after expulsion from radioactive atoms, and an investigation of the nature of X-rays and gamma rays. The latter work, where Bragg adopted a particle model for these rays, has been examined by Bruce Wheaton in *The Tiger and the Shark: Empirical Roots of Wave-Particle Dualism.*[7] Here I wish to explore Bragg's study of the former topic and chart the long journey he traveled, finally placing himself at the forefront of worldwide research in the new physics.

It is helpful to contrast Bragg with his close contemporary, Richard Threlfall, at the University of Sydney. Both were chosen by English selection committees and both arrived in Australia in 1886. Threlfall was twenty-five years old, Bragg twenty-three. Their personalities, however, were quite different. Bragg recalled that, as a schoolboy, he "liked peace and was content to be alone with books or jobs of any sort," while Threlfall early developed a strong sense of self-confidence and self-sufficiency.[8] Bragg was private and withdrawn, Threlfall gregarious and outgoing.

At Cambridge, Bragg followed the traditional path through the Mathematical Tripos.

[6] W. H. Bragg, "In the Days of My Youth," *T.P.'s and Cassell's Weekly,* 3 Apr. 1926, p. 834, copy in William Henry Bragg Papers, Archives of the Royal Institution, London, file 39, no. 2 (items in this collection are hereafter cited as **Bragg Papers,** with the box or file and item numbers shown as, e.g., 39/2). See also G. M. Caroe, *William Henry Bragg, 1862–1942: Man and Scientist* (Cambridge: Cambridge Univ. Press, 1978), p. 2; and J. L. Heilbron, "The Scattering of α and β Particles and Rutherford's Atom," *Archive for History of Exact Sciences,* 1968, *4:*247–307, on p. 256. For more general information on Bragg see John Jenkin, *The Bragg Family in Adelaide: A Pictorial Celebration* (Adelaide: Adelaide Univ. Foundation, 1986); Jenkin, "The Appointment of W. H. Bragg, FRS, to the University of Adelaide," *Notes and Records of the Royal Society of London,* 1985, *40:*75–99; Jenkin, "A Unique Partnership: William and Lawrence Bragg and the 1915 Nobel Prize in Physics," *Minerva,* 2001, *39:*373–392; and R. W. Home, "The Problem of Intellectual Isolation in Scientific Life: W. H. Bragg and the Australian Scientific Community, 1886–1909," *Historical Records of Australian Science,* 1984, *6:*19–30.

[7] Bruce R. Wheaton, *The Tiger and the Shark: Empirical Roots of Wave-Particle Dualism* (Cambridge: Cambridge Univ. Press, 1983), Ch. 4.

[8] W. H. Bragg, autobiographical notes, unpublished and untitled (ca. 1927, 1937), Bragg Papers, 14E/1, on p. 12. On Threlfall see R. W. Home, "First Physicist in Australia: Richard Threlfall at the University of Sydney, 1886–1898," *Hist. Rec. Aust. Sci.,* 1986, *6:*333–357.

After surprising both himself and others with his third place, he entered the Cavendish Laboratory to study practical physics under Richard Glazebrook. Once he arrived in Adelaide he found that his extraordinary teaching duties—he was solely responsible for pure and applied mathematics and physics and practical physics at all levels, evening lectures to music students, and a large examination load for secondary as well as university students—fully occupied his attention.[9]

Threlfall enrolled in the less-fashionable Cambridge Natural Sciences Tripos and was unusual in achieving first-class honors in both physics and chemistry. After graduation he gained valuable teaching experience as a demonstrator in the Cavendish Laboratory and a college lecturer in physics. J. J. Thomson rated him "one of the best experimenters I ever met."[10] Threlfall began a varied program of research immediately upon his arrival in Sydney. "Precision" and "exact measurement" were his watchwords. However, because he moved more and more into industrial work, Threlfall did not participate in the new physics after 1900, and after his return to England in 1898 he devoted himself to industrial electrochemical studies.

Bragg matured much more slowly, both personally and scientifically. Indeed, the remoteness of Adelaide was crucial to his development, for it allowed him, slowly and methodically, to mature, to become self-confident and self-reliant in teaching, research, and community relations, and to develop his own ideas and programs. Threlfall said lightheartedly, many years later, that going to Sydney was "the greatest mistake of my life"; but for Bragg, "going to Australia was like sunshine and fresh invigorating air."[11] The nature of the experience of working at a colonial outpost depends very much on the person concerned.

Despite his retrospective claim, it is clear that Bragg began to contemplate the possibility of doing research very soon after his arrival in Australia, when he visited Threlfall in Sydney during the long summer vacation of 1887/1888 and attended the inaugural meeting of the Australasian Association for the Advancement of Science (AAAS) later in 1888. By 1890, at the latest, Bragg had begun to wrestle seriously with physics problems whose solutions could not be found in the standard textbooks; not surprisingly, his first essay at research arose from problems encountered in his teaching. He noted later: "Although I had never done any [physics], nor worked at the Cavendish except for a couple of terms after I had taken my degree, it was supposed by the electors that I would probably pick up enough as I went along to perform my duties at the Adelaide University."[12]

But Bragg grossly overstated his ignorance. In June 1884 he had taken Parts I and II of the Cambridge Mathematical Tripos, for which he was coached by Edward Routh, emerging as Third Wrangler. These exams included not only major areas of basic mathematics but also such topics as statics, dynamics, the early sections of Newton's *Principia,* hydrostatics, optics, and astronomy.[13] The Mathematical Tripos thus covered "mixed mathe-

[9] Jenkin, "Appointment of Bragg to Adelaide" (cit. n. 6), pp. 92–93.

[10] J. J. Thomson, *Recollections and Reflections* (London: Bell, 1936), p. 118.

[11] Threlfall made this remark in the context of his not being part of the discovery of the electron; it is in Sir Harold Hartley, "Sir Richard Threlfall, GBE, FRS," p. 3, typescript in Richard Threlfall Papers, University of Sydney Archives. For Bragg's comment see Bragg, autobiographical notes (cit. n. 8), p. 31.

[12] Bragg, autobiographical notes, p. 30. On the wider Australian context see Home, "Problem of Intellectual Isolation in Scientific Life" (cit. n. 6); see also Archibald Liversidge and Robert Etheridge, eds., *Report of the First Meeting of the Australasian Association for the Advancement of Science, Sydney, 1888* (Sydney: AAAS, 1889).

[13] Bragg's progress through his Cambridge studies can be followed in the pages of the *Cambridge University Reporter,* 1880–1885; the regulations for his Mathematical Tripos examinations are given in *The Cambridge University Calendar for the Year 1884* (available in the Cambridge University Library), pp. 27–35.

matics," with a heavy emphasis on applied mathematics, much of which might also be called mathematical physics.

For Part III of the Tripos, as in his subsequent brief time in the Cavendish Laboratory, Bragg worked under the guidance of Richard Glazebrook, who was responsible for Group C of the four alternative groups of studies for Part III. Bragg thus missed Group D, which contained the electricity and magnetism (E&M) that was only slowly seeping into the Tripos program. As a result, he was obliged to devote a good deal of time to this area in his early years in Adelaide, for E&M formed an important part of all three years of the undergraduate physics course that his predecessor, Horace Lamb, had set up and was also beginning to have great practical importance.[14] Threlfall, on the other hand, had studied E&M in preparing for the Natural Sciences Tripos; it subsequently became a major part of his research and publication program, which involved both precision measurements of fundamental parameters and practical investigations regarding the installation of an electricity supply system in suburban Sydney and elsewhere. Threlfall's presidential address for Section A at the second meeting of the AAAS, held in Melbourne in January 1890, was entitled "The Present State of Electrical Knowledge."[15]

Threlfall therefore offered a very ready point of reference in relation to E&M, which Bragg quickly took up. Soon after the 1890 AAAS meeting Bragg began a large foolscap notebook into which he entered a long series of notes on electromagnetism, and in June 1890 he began a series of letters to Threlfall, seeking his advice regarding the subject:

> I have been very interested just lately in deducing the elementary electrostatic theorems from the "elastic medium" theory of Maxwell, of which Oliver Lodge gives the mechanical analogy. . . . The advantages of the method, as a teaching one, are that it gives clear mental pictures, but it also puts some things in a truer way than usual. . . . I haven't seen the ideas mathematically expressed, so if you haven't seen them either I might make a bit of a paper for the Association [AAAS] out of them.

Bragg did, indeed, deliver such a paper at the January 1891 meeting of the AAAS, held in Christchurch, New Zealand. Following advice from Lodge, who was professor of physics at University College, Liverpool, that he not publish the paper in the *Electrical Review,* Bragg sent it instead to the *Philosophical Magazine;* its importance was later noted by Edmund Whittaker in his two-volume *History of the Theories of Aether and Electricity.*[16]

[14] Although appointed to the University of Adelaide in 1875 to teach pure and applied mathematics, Horace Lamb also voluntarily instituted a full course in physics; see J. G. Jenkin and R. W. Home, "Horace Lamb and Early Physics Teaching in Australia," *Hist. Rec. Aust. Sci.,* 1995, *10:*349–380. For details of syllabi for both Lamb and Bragg see the annual *Adelaide University Calendar,* later *Calendar of the University of Adelaide* (available in the Melbourne University Library).

[15] Richard Threlfall, "The Present State of Electrical Knowledge: Presidential Address in Section A (Astronomy, Mathematics, Physics, and Mechanics)," in *Report of the Second Meeting of the Australasian Association for the Advancement of Science, Melbourne, 1890,* ed. W. B. Spencer (Melbourne: AAAS, 1890), pp. 27–54. On the Natural Sciences Tripos see D. B. Wilson, "Experimentalists among the Mathematicians: Physics in the Cambridge Natural Sciences Tripos, 1851–1900," *Historical Studies in the Physical Sciences,* 1982, *12:*325–371.

[16] For the new notebook treating electromagnetism see W. H. Bragg, notebook, untitled, Bragg Papers, 38/12. Bragg's letters to Threllfall are in the Bragg Papers, 6C; apparently the Threfall-to-Bragg half of this correspondence has not survived. See W. H. Bragg to Richard Threlfall, 10 June 1890, Bragg Papers, 6C/18 and 19; he is referring to Oliver Lodge, *Modern Views of Electricity* (London: Macmillan, 1889). The paper first appeared as Bragg, "The 'Elastic Medium' Method of Treating Electrostatic Theorems," in *Report of the Third Meeting of the Australasian Association for the Advancement of Science, Christchurch, 1891,* ed. Sir James Hector (Wellington: AAAS, 1891), pp. 57–71. For Lodge's advice see Oliver Lodge to Bragg, 5 Mar. 1891, Bragg Papers, 4A/25. The paper appeared in England as Bragg, "The 'Elastic Medium' Method of Treating Electrostatic Theorems," *Philosophical Magazine,* 1892, *34:*18–35; it was noted in Sir Edmund Whittaker, *A History of the Theories of Aether and Electricity,* 2nd ed., 2 vols. (London: Nelson, 1951), Vol. 1, p. 272.

Further correspondence with Threlfall followed. Having assumed the presidency of Section A for the January 1892 Hobart meeting of the AAAS, Bragg confidently presented his new understanding of electromagnetism by drawing wide-ranging theoretical analogies between electrostatics, current electricity, magnetism, heat, hydrokinetics, and mechanics (twist and spin). "I believe it is most important that every physical student should examine this analogy," he wrote, "because . . . we shall be rewarded for our pains by finding ourselves able to make a fresh start—a further advance into regions as yet unknown."[17]

Of particular interest are Bragg's several forays into experimental work, as outlined in his E&M notebook. Marking the start of his career as an experimental physicist, they are entitled "To find the specific resistance of some mica belonging to the Brush Co.," "Comparison of EMF of Latimer-Clark [cell] with copper deposit [cell]," and "Determination of capacity of condenser by Wheatstone's bridge." The first experiment, in June 1892, arose from the fact that Bragg's brother-in-law, Hedley Todd, had recently become the local agent for the London-based Brush Electrical Engineering Company, at a time when Adelaide was contemplating the introduction of an electricity supply network.

Although Bragg was a little behind the latest developments of electromagnetism in Europe, it was in fact a confused area of study. His work was a scholarly inquiry for the benefit of himself, his students, and his Australian colleagues. As his daughter later observed, these early events "illustrate one of his most striking characteristics; WHB could not rest until he had mastered some new idea completely, reduced it to a logical form which satisfied him, and expressed it in the simplest possible way."[18] Research, prompted by other factors as well, was clearly on Bragg's mind from 1890 onward.

Toward the end of 1890, the University of Adelaide received notification that some of the income from the investment of funds remaining from the Great Exhibition of 1851 was to be used to establish a scheme of Science Research Scholarships. These awards were intended "not to facilitate attendance on ordinary collegiate studies, but to enable students who have passed through a college curriculum and have given distinct evidence of capacity for original research, to continue the prosecution of science with the view of aiding its advance, or its application to the industries of the country." The Adelaide University Council considered the offer, then instructed the registrar "to write and accept the Scholarship for 1892 and to say that the University was taking steps to give effect to their offer."[19]

The requirement that candidates should have demonstrated a capacity for original work placed something of an obligation on Adelaide's science professors to begin or enhance a research program. When Bragg wrote to the Commissioners for the Exhibition of 1851 in 1892, recommending Bernard Allen for Adelaide's first award, he had to suggest, perhaps

[17] W. H. Bragg, "Mathematical Analogies between Various Branches of Physics," in *Report of the Fourth Meeting of the Australasian Association for the Advancement of Science, Hobart, 1892,* ed. Alexander Morton (Hobart: AAAS, 1893), pp. 31–47. He had earlier tried out his ideas in Bragg to Threlfall, 20 Dec. 1891, Bragg Papers, 6C/23; a brief abstract of the paper appeared in *Nature,* 1892, *45:*423.

[18] Caroe, *William Henry Bragg* (cit. n. 6), p. 31. See also Fabio Bevilacqua, "The Principle of Conservation of Energy and the History of Classical Electromagnetic Theory (1845–1903)" (Ph.D. diss., Univ. Cambridge, 1983).

[19] News of the new scholarships is in Agent General for South Australia, London, to Registrar, University of Adelaide, 22 Aug. 1890, University of Adelaide Archives, Series 200, docket 13/1890 (items in the university archives are hereafter cited as **Univ. Adelaide Archives,** with the series [S] number and item number). Describing the purpose of the awards see, e.g., *Record of the Science Research Scholars of the Royal Commission for the Exhibition of 1851, 1891–1960* (London: Commissioners, 1961), pp. 99–101. The Adelaide University Council response appears in Univ. Adelaide Archives, S18, Council Minutes (26 Sept. 1890), Vol. 5, p. 29.

with some embarrassment, that "although [Allen] has not, during his undergraduate course, done any original work of consequence, he has done a considerable amount of practical work in Physics; and he indicates high promise of capacity for advancing science by original research."[20] The commissioners accepted this recommendation, and Allen went to Sydney to work with Threlfall on precision measurements of the electrical properties of sulfur.

The year 1892 also saw more general agitation for scientific research in the Australian universities. The *South Australian Register* newspaper in Adelaide interviewed Anderson Stuart, professor of physiology at the University of Sydney, on his return from a trip to Europe and published a long leading editorial. The paper, regularly critical of universities in general and Adelaide's in particular, quoted Stuart's observation that "more original research must come from the Australian Universities" and added its own characteristic observation that "it is a very serious and only too well-founded reproach against the Universities of Australasia that up to the present time they have contributed very little indeed to the sum total of human knowledge." When Edward Rennie, the Angas Professor of Chemistry in Adelaide, prepared his graduation address late the same year, he included remarks on utilitarianism and research that the *Register* reported at length:

> Professor Rennie's oration was in part a protest against the purely utilitarian and materialistic view of the function of the teacher of science. . . . It may safely be asserted that there is no more insidious enemy to the happiness of mankind than the same spirit of opposition to everything which has not an immediate money-making result. . . . There is for many reasons much cogency in Professor Rennie's appeal to students to apply themselves to original researches.[21]

William Henry Bragg could not have missed the rhetoric regarding the desirability of research.

### WIRELESS TELEGRAPHY, RÖNTGEN RAYS, AND "STUDY LEAVE"

News of the possibility and then the practicality of wireless communication excited Bragg, as it did others. When the University of Adelaide reintroduced a program of public or "extension" lectures in 1895, Bragg offered six lectures on the broad topic of "Radiation," and in his last lecture in August he included a brief discussion and demonstration of "electric waves, their production and detection," including "the coherer." Indeed, it was at this time that the young Ernest Rutherford, on his way to Cambridge from New Zealand as J. J. Thomson's first "B.A. by research" student, stopped at Adelaide; A. S. Eve records that "he called Bragg from a dark-room where he was trying to get a Hertz oscillator to work and enthusiastically showed him the magnetic detector that he was taking to England." (See Figure 1.) It was the start for Bragg of a pivotal lifelong friendship. Bragg went on to develop his radio facilities and presented a number of lectures and demonstrations during 1897 that attracted wide public interest. Although it would be some years before radio became a practical reality, Bragg is credited with being the first in Australia convincingly to demonstrate radio transmission over a significant distance.[22]

[20] Bragg to Commissioners, 28 Mar. 1892, Archives of the Royal Commission for the Exhibition of 1851, Imperial College, London, J. B. Allen File (no. 31).

[21] *South Australian Register,* 23 Mar. 1892, p. 4, 15 Dec. 1892, p. 4.

[22] "Syllabus of Lectures on 'Radiation' by Professor Bragg," program of "University Extension Lectures, 1895," Univ. Adelaide Archives, S10 (see also *South Australian Register,* 8 Aug. 1895, p. 7); A. S. Eve, *Rutherford* (Cambridge: Cambridge Univ. Press, 1939), p. 13; and J. F. Ross, *A History of Radio in South Australia, 1897–1977* (Adelaide: J. F. Ross, 1978), Ch. 1.

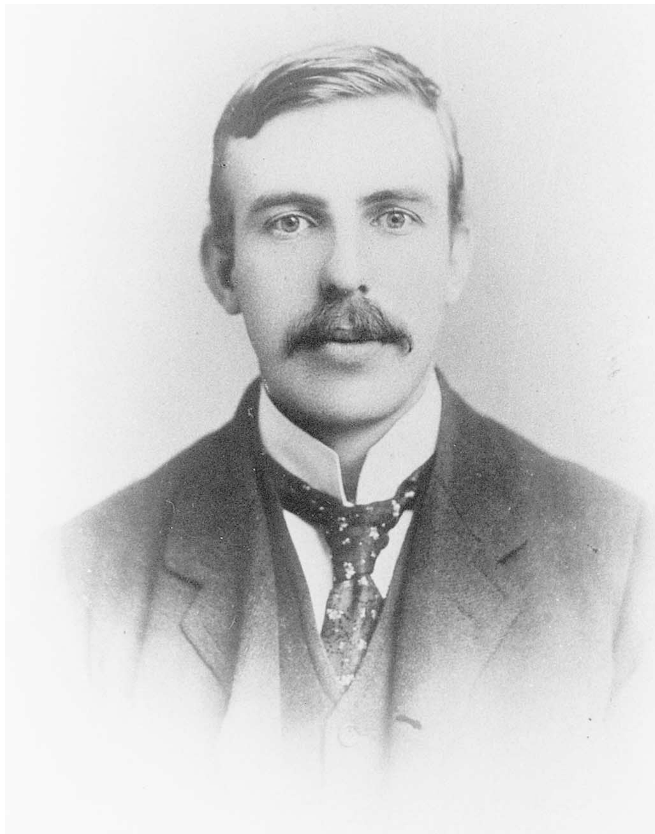

***Figure 1.*** *Ernest Rutherford, soon after his arrival in Cambridge. Photograph courtesy of John Campbell, Christchurch, New Zealand.*

Bragg's university work was again interrupted late in 1895, when Wilhelm Röntgen discovered X-rays; Bragg began to experiment with them immediately following the initial announcements. After early failures, he borrowed a suitable high-voltage induction coil, pooled his resources with an Adelaide chemist, and, with his expert mechanic, Arthur Rogers, produced good X-ray photographs. Bragg's name became a household word around Adelaide, as his lectures and demonstrations of X-rays—to the governor's family, public audiences, teachers, and the local branch of the British Medical Association—attracted unprecedented attention.[23] Bragg had further widened his experience and confidence in experimental physics—and in a way that brought him progressively closer to a major program of original research.

By 1897 Bragg had been in Adelaide for eleven years, and both physics and his own life had changed substantially: "the science of Physics has made great strides," he noted in a letter to the University Council, "and I feel that . . . I should study in England the advances both of the subject itself and the methods of teaching it." Adelaide had introduced the concept of "study leave" into Australian academic life some years earlier, after a

[23] Jenkin, *Bragg Family in Adelaide* (cit. n. 6), pp. 20–21, 26–27.

significant battle with Bragg's predecessor, Horace Lamb. The outcome was the provision of up to one year's leave of absence, provided the incumbent could find a substitute acceptable to the council. Bragg satisfied this requirement by increasing the workload of his existing academic assistant, lecturer Robert Chapman, and hiring his former student Bernard Allen.[24]

The Bragg family arrived in England in April 1898. Here Bragg had a number of projects and engagements. Charles Todd had asked him to obtain astronomical information, and so he paid personal visits to Herbert Turner at the Oxford Observatory and Sir William Huggins at his private observatory at Tulse Hill, London. To discuss wireless telegraphy he visited Sir William Preece at "Gothic Lodge," Wimbledon, and was Preece's guest at a Royal Society dinner in London.[25]

Bragg also carried with him a commission from the local government to inquire into educational matters, with particular reference to teacher education and technical education. The report that he produced on his return to Adelaide has not survived, but major changes and improvements in education followed, both at the university and the South Australian School of Mines and Industries and in the training of schoolteachers, in all of which Bragg played a major role. September brought Bragg to the sixty-eighth meeting of the British Association for the Advancement of Science at Bristol, where he had a long discussion with William Crooks and enjoyed many other personal contacts.[26]

The later weeks in England were spent in Cambridge. Here Bragg purchased equipment from the Engineering School for Adelaide's new engineering initiative and for his physical laboratory.[27] But the major legacy of the year lay in the discussions Bragg had with old friends and new acquaintances, not least in Cambridge, concerning recent advances in physics. Bragg and Thomson had been close during Bragg's undergraduate years and Thomson's early tenure at the Cavendish Laboratory, which had now assumed a leading worldwide role in the discipline.

Although we have no information on the content of these discussions, a surviving letter is very revealing of Bragg's state of mind eight months after his return to Adelaide. It is a lengthy, controlled but passionate request to the university for more financial and moral support for teaching and research in physics. Having described the extraordinary lecturing loads both he and Chapman carried, he pleaded for laboratory assistance:

> There is another way of adding to the efficiency of the laboratory teaching to which I ask leave to call your attention; viz. the employment of our own students, who have just taken their degrees and are suitable as junior demonstrators at a nominal salary. This plan is commonly adopted in laboratories and has many advantages. To begin with, such an assistant is of great use in the conduct of the practical classes. . . . The position would be of value to the aspiring

[24] Bragg to University Council, 30 July 1897, Univ. Adelaide Archives, S200, docket 422/1897; and Jenkin, "Appointment of Bragg to Adelaide" (cit. n. 6), pp. 77–78.

[25] Charles Todd to W. H. Preece, 2 Nov. 1898, and Todd to Bragg, 10 Nov. 1898, Todd Letter Book, Vol. 4, State Library of South Australia, Adelaide, GRG 31/1/4; William Huggins to Bragg, 29 Dec. 1898, Bragg Papers, 3C/52; and *South Australian Register,* 23 Jan. 1899, p. 6.

[26] Regarding the education commission see *South Australian Register,* 7 Mar. 1899, p. 5. On the subject of Bragg's role in educational changes I am relying on Caroe, *William Henry Bragg* (cit. n. 6), and a variety of Adelaide sources, but Bragg's significant contribution to many aspects of education in South Australia remains to be investigated adequately. On the meeting of the British association see *Report of the Sixty-eighth Meeting of the British Association for the Advancement of Science, Bristol, September 1898* (London: Murray, 1899); and *South Australian Register,* 7 Mar. 1899, p. 5.

[27] Bragg to Finance Committee, 27 Apr. 1899, 29 June 1899, Univ. Adelaide Archives, S200, dockets 381/1899, 538/1899.

> student . . . it would give opportunities for further study, and for doing original work. . . . We should have much more chance than we have at present of finding students fit to fulfil the conditions of the 1851 Exhibition scholarships and bursaries. Moreover, a young graduate . . . would stand a better chance of employment in the schools. Again, it would add greatly to the tone of the laboratory if there were always one or more students doing original, or post-graduate work in it. We ought to do all we can to gather about us students asking for the highest instruction. . . . In fact, I think the advantages of employing our own students in this way are so great that I recommend that the experiment be tried as soon as a suitable opportunity arises.

In November 1899 the University Council agreed to the recommendation of its Education Committee to appoint a demonstrator in the Physical Laboratory, and the way was opened for Bragg to obtain the services not only of a demonstrator but also of research students and assistants.[28]

## BREAKTHROUGH

On Bragg's return to Australia in March 1899, many tasks awaited him. He built a permanent home in Adelaide, he significantly modified and extended his own university teaching, and he lobbied for other important educational changes. He continued as a member of the University Council, the Council of the School of Mines and Industries, and the Board of Governors of the Public Library, Museum, and Art Gallery.[29]

The final trigger for Bragg to take up the research that he had long contemplated and for which he had been preparing was his agreement to give the presidential address for Section A at the January 1904 Dunedin, New Zealand, meeting of the AAAS. He began preparation during the long summer vacation of 1902/1903, when he opened a new foolscap notebook: a literature review, in his characteristically neat and economical handwriting, that he continued throughout 1903. He scanned the major English journals taken by the university library, particularly *Nature,* the *Philosophical Magazine,* the *Proceedings* and the *Philosophical Transactions of the Royal Society of London,* and the *Electrician.* The library also took major European journals such as the *Comptes Rendus,* the *Physikalische Zeitschrift,* and the *Annalen der Physik,* but since Bragg had no formal training in German and only occasionally translated from French, he largely relied on the regular abstracts, summaries, and translations in the *Electrician* for the important European material.[30]

The notebook contains about two hundred separate references to contemporary articles, almost all of which are from these eight journals. From the earliest pages it is clear that Bragg had already determined the general area of his interest: he would work on the new physics of X-rays, radioactivity, the electron, positive ions, and the ionization of gases, rather than topics from classical physics. His own investigations and his extensive discus-

[28] Bragg to Education Committee, 21 Nov. 1899, Univ. Adelaide Archives, S200, docket 936/1899; and Univ. Adelaide Archives, S18, Council Minutes (24 Nov. 1899), Vol. 6, p. 311. We may assume that, in writing of "students doing original, or post-graduate work," Bragg was contemplating some assistance with his own research program.

[29] Jenkin, *Bragg Family in Adelaide* (cit. n. 6).

[30] For the new notebook for literature reviews see W. H. Bragg, notebook, untitled, Bragg Papers, 12/1. There are records of Bragg's education at Market Harborough Grammar School and King William's College among the Bragg papers in the care of Lady Adrian, Cambridge, and his university subjects have been discussed above. The study of French appears widely in his school records, but there is no evidence for any study of German. For the presidential address see Bragg, "On Some Recent Advances in the Theory of the Ionization of Gases," in *Report of the Tenth Meeting of the Australasian Association for the Advancement of Science, Dunedin, 1904,* ed. G. M. Thomson (Dunedin: AAAS, 1905), pp. 47–77. The central importance of this address was acknowledged by Bragg himself in Bragg, *Studies in Radioactivity* (London: Macmillan, 1912), p. 1.

sions with Australasian and British colleagues had convinced him that the future of both physics and his own career lay in the new realm. The first article that caught his close attention was a 1903 paper by Rutherford, now at McGill University in Canada. As became his practice, Bragg summarized the content of the papers on the right-hand pages of the notebook and then entered his own observations on the left. He paid particular attention to articles by Rutherford, sometimes with Frederick Soddy, and by John Townsend, but the range of authors and topics was large.

An early, brief note headed "Curies' report in Vol. III of Paris Congress" is given a far more extensive elaboration later in the notebook, under the heading "Rapports au Congrès." This concerns the paper of Pierre and Marie Curie published in the proceedings of the 1900 Paris international congress on physics. From his earlier reading Bragg was aware that, while the behavior of the beta rays from radioactive substances had been examined in some detail, the alpha rays behaved differently and were far less studied. In the notebook he now entered his own observations far more expansively than before:

> The α-rays of polonium show marked diminution at a certain distance [from the radioactive source], and the absorption by a plate is greater the further it is away from the source. [Remarks on β-ray behavior, including their exponential decrease in intensity, due to scattering from atomic electrons.] The α-rays will have more complicated effects. Active electronic collision will occur 1000 times as often as for the β-ray, but we could hardly expect actual deflexion to occur in such a case, so perhaps the α-ray will go on. If so α-rays would rather tend to stop when their energy ran out, and so stop rather suddenly, as in Curie's experiments. On [the] other hand, though the α constellation of electrons might pass through the molecule constellation, yet perhaps a certain fraction of them will be quite deflected even when actual electronic collisions have not much to do with it.[31]

The nature of the alpha particle was an even greater mystery than its behavior, and investigation of these questions might also shed light on the structure of the atoms from which the rays originated. Here surely was a field to which a new researcher might contribute.

Bragg's Dunedin address drew on all aspects of his literature review and was entitled "On Some Recent Advances in the Theory of the Ionization of Gases," for, as he pointed out, "the phenomenon itself furnishes one of the principal methods by which the strange new properties of radio-active substances are made manifest and studied." There followed, in thirty dense pages of the conference report, discussion of ionization, the nature of the positive and negative ions produced by radioactivity, X-rays and the photoelectric effect, and the stopping behavior of fast electrons, with particular emphasis on Henri Becquerel's experiments with radium beta rays. Not until the last four pages do we meet: "it is very interesting to compare the penetrating and ionizing powers of the α and γ rays with those of the β ray." There followed a summary of the known properties of the alpha particle, including the observation that the "α ray penetrates more than a thousand times as much as this ['the free path of an air-molecule'] and yet moves in a straight line . . . at the high speed which it possesses when it leaves the parent body it breaks down the defence of any molecule it encounters and passes through."[32]

[31] Bragg notebook, untitled, Bragg Papers, 12/1, pp. 67, 127–131, 127–128 (quotation). For the Curies' paper see Pierre Curie and Mme. Curie, "Les nouvelles substances radioactives et les rayons qu'elles emettent," in *Rapports présentes au Congrès International de Physique, Paris, 1900,* ed. C. E. Guillaume and Henri Poincaré, 4 vols. (Paris: Gauthier-Villars, 1900), Vol. 3, pp. 79–114; the section "Pouvoir pénétrant des rayons non déviables," due to Marie alone, is especially relevant (pp. 101–103).

[32] Bragg, "Recent Advances in the Theory of the Ionization of Gases" (cit. n. 30), pp. 47, 74.

That the gradual stopping of the alpha particles "through expenditure of energy must be a more important cause" than scattering was confirmed by "two curious results," Bragg contended, the major one being due to the Curies. This material was elaborated in Marie's doctoral thesis. The basic apparatus she used was common to many experiments at this time. The two plates of a condenser, acting as an ionization chamber, were arranged so that the lower plate admitted rays from a radioactive source, whose distance from the chamber could be varied incrementally, and so that any charge accumulated by ionization (and hence the number of particles reaching the chamber) could be measured using an electrometer. In addition to the air, thin sheets of various absorbing materials could also be placed between the radioactive source and the ionization chamber. Marie Curie showed that, while the radiations from most radioactive substances were very complex, polonium, which she had isolated, emitted only one group of alpha particles. "I found the absorbability of the rays to increase with increase of thickness of the matter traversed . . . contrary to that known for other kinds of radiation," she recorded. Similarly, the alpha particles all traveled a similar distance "by rectilinear propagation" and, as Rutherford had suggested, appeared positively charged. Much else had "not been studied in detail."[33]

### EXPERIMENTS AND "ADVOCATES"

Bragg had now come to the tentative conclusions that "the $\alpha$ particle should pursue a perfectly rectilinear course, passing without deflection through all the atoms it [meets]"; that "the number of $\alpha$ particles penetrating a given distance does not alter much . . . until a certain critical value is passed, after which there is a rapid fall"; and that "the energy of the $\alpha$ particles . . . gradually decreases . . . and dies out at the same critical value."[34]

These were matters he had decided to test in a new research program, and, in preparation, he had written to W. G. Pye & Company in Cambridge in December 1903, before departing for the AAAS meeting in New Zealand:

> My dear Mr Pye
>
> I wrote to you last week about a Dolezalek electrometer. I hope the letter reached you safely. My next want is some radioactive material. I had a little present the other day, and I think I can spare £20, which should be enough to procure an amount sufficient for many forms of experiment. I have no idea . . . as to where and how radium compounds are obtained. But I gather that it is on the market. . . . I am sure Professor Thomson or Mr Searle would be good enough to advise. . . . I will ask our Registrar to forward a request to the Agent General that he will advance about £25 on your request: £20 for the radium material and £5 for the electrometer, at a guess.
>
> Sincerely yours, W. H. Bragg

The "little present" had been supplied "through the generosity of a constant friend of the University of Adelaide, Mr R. Barr Smith." Robert Barr Smith had come to South Australia from Scotland in 1855, had made a fortune through astute pastoral development, and had become a major philanthropist, not least to the university. Bragg had met Barr Smith and his wife very early in his time in Adelaide, when he participated in some theatricals in the

[33] *Ibid.,* p. 75. Marie Curie's dissertation was published as *Recherches sur les substances radioactives* (Paris: Gauthier-Villars, 1903), which appeared in English translation as "Radio-active Substances," *Chemical News,* 1903, *88,* nos. 2282–2291, and as *Radioactive Substances* (New York: Philosophical Library, 1961; Westport, Conn.: Greenwood, 1971), pp. 50, 51, 55, 57.

[34] Bragg, *Studies in Radioactivity* (cit. n. 30), p. 4.

magnificent theater they had built as part of their mansion in the Adelaide foothills.[35] "Three tubes of 5mgms each Radium bromide pur. cryst." were shipped from Cambridge by registered post on 12 May 1904 and arrived in Adelaide on 14 June, just in time for Bragg to incorporate them in demonstrations for his series of extension lectures entitled "The Electron and the Atom."[36]

On Saturday, 30 July 1904, William Bragg opened his first research notebook and began his first experiment on the alpha particles from radium. He was assisted from the beginning by his first research student, Richard Kleeman. Kleeman, the eldest of nine children of a German farming family, had left school at age thirteen and entered the coopering trade in the local wine industry, but he had also read mathematics and physics privately with the help of his Lutheran pastor. In 1897 he began sending short papers to Bragg, who arranged for his special admission to the university. Kleeman obtained his B.S. in 1903 and then undertook the honors degree in physics while lecturing and demonstrating in the subject and helping Bragg with his new research. Thereafter he enjoyed a productive period at the Cavendish Laboratory; in 1914, when his German heritage seemed likely to cause him difficulties after the outbreak of war, he moved to Union College in Schenectady, New York.[37]

The very day after he began his research, on Sunday, 31 July 1904, a chance encounter—akin to that involving Bragg and Rutherford nine years before—took place. This too was to have profound implications for the future of Bragg's research. Frederick Soddy visited Adelaide for just a few hours and, he later recalled, "was met by Professor Bragg and taken off to dinner at his home with Mrs. Bragg and some of the Adelaide University folk." (See Figure 2.) Soddy had completed his pivotal research in radioactivity with Rutherford in Canada and his important studies with William Ramsay at University College London, and he had not yet taken up his lectureship at Glasgow. He was able to accept an invitation to visit Western Australia to give several series of lectures on "electricity," interpreting the topic broadly. After this strenuous task was completed, Soddy returned to Britain via the Pacific and the Atlantic, stopping at ports along the way, including Adelaide. There he learned of Bragg's plans, the success of which he was to assist substantially in the next few years.[38]

[35] For the letter to Pye see Agent General for South Australia in London to Registrar, University of Adelaide, 13 May 1904, enclosing account for radium and copies of correspondence between Bragg and W. G. Pye, Univ. Adelaide Archives, S200, docket AG9/1904. On the source of the present see Bragg, *Studies in Radioactivity,* p. 5; on Barr Smith see Jenkin, *Bragg Family in Adelaide* (cit. n. 6), pp. 14–15.

[36] Pye to Bragg, 12 May 1904, in Agent General for South Australia in London to Registrar, University of Adelaide, 13 May 1904. In a public lecture that evening Bragg announced that the radium had arrived that day: *South Australian Register,* 15 June 1904, p. 6. For a survey of Bragg's many public lectures throughout his time in Adelaide see John Jenkin, "W. H. Bragg and the Public Image of Science in Australia," *Search (Australia),* 1987, *18:*34–37.

[37] Jenkin, *Bragg Family in Adelaide* (cit. n. 6), p. 44, taken from W. H. Bragg, first Adelaide Laboratory Research Notebook, Bragg Papers, 38/1. In his first international paper on this work, Bragg pointed out that radium was the only radioactive source available to him, although he would have preferred to use polonium for reasons of simplicity: W. H. Bragg, "On the Absorption of α Rays, and on the Classification of the α Rays of Radium," *Transactions of the Royal Society of South Australia,* 1904, *28:*298–299, *Phil. Mag.,* 1904, *8:*719–725, on p. 723. In fact, Bragg thereby opened up—luckily and at once—a more interesting and fruitful research project. On Kleeman see John Jenkin and R. W. Home, "Kleeman, Richard Daniel (1875–1932), Physicist," in *Australian Dictionary of Biography Supplement,* ed. Christopher Cunneen (Melbourne: Melbourne Univ. Press, forthcoming).

[38] Soddy's recollection is quoted in Muriel Howorth, *Pioneer Research on the Atom: The Life Story of Frederick Soddy* (London: New World, 1958), p. 137. See also John Jenkin, "Frederick Soddy's 1904 Visit to Australia and the Subsequent Soddy–Bragg Correspondence: Isolation from Without and Within," *Hist. Rec. Aust. Sci.,* 1985, *6:*153–169.

***Figure 2.*** *Frederick Soddy, about the time of his visit to Australia. Photograph courtesy of* British Journal of Radiology.

Bragg subsequently wrote an extensive and elegant account of his Adelaide research in which he outlined the historical development of his work.[39] For my purposes here, however, it is important to look at the people who accompanied him on the journey and to investigate the byways as well as the highway he traveled.

His first experiments were undertaken with simple apparatus. (See Figure 3.) It was an improvement on Curie's equipment because it defined a narrow pencil of alpha radiation that would wholly enter the ionization chamber and be detected (provided it was not stopped earlier), regardless of the chamber's distance from the radiation source. Curves of the variation in ionization in the chamber, measured by an electrometer, with changing distance from the source were plotted and then analyzed in terms that accounted for the fact that many of the alpha particles initially lost energy in escaping from the thick radium source used. A second set of experiments was conducted with a spherical ionization chamber and a much thinner and weaker source, and the meaning of the results then became clearer. The most important of these were that when radium decayed it passed through several changes, four of which (as suggested by Rutherford and Soddy) appeared to expel an alpha particle, with all the particles of any one change having the same energy and with the first change producing alpha particles of the lowest energy; that the alpha particles

[39] Bragg, *Studies in Radioactivity* (cit. n. 30), Chs. 1–10.

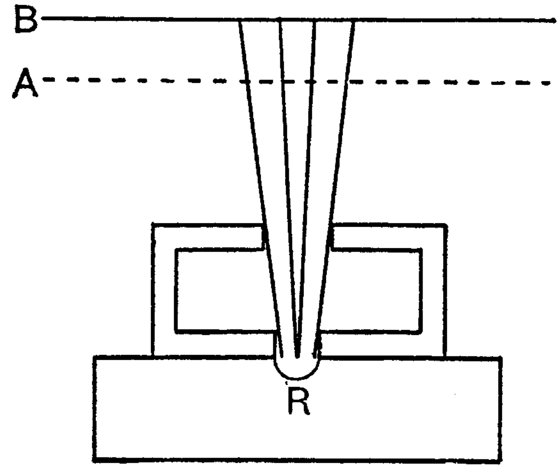


FIG. 2.—*A B* is the ionisation chamber ; the upper wall of metal, the lower of metal gauze. The $\alpha$ rays stream up from the radium at *R*.

***Figure 3.*** *The basic elements of Bragg's initial alpha-particle apparatus. From W. H. Bragg,* Studies in Radioactivity *(London: Macmillan, 1912), page 5.*

passed through the matter they traversed without appreciable deviation and lost their extraordinary energy by ionization along a straight trajectory; and—a new and important finding—that alpha particles were much more efficient in ionizing the material through which they passed near the end of their course, when their energy was much reduced.[40]

Progress had been very rapid. Bragg first presented these results to a regular meeting of the Royal Society of South Australia on 6 September 1904. They left Adelaide two days later in a letter to Frederick Soddy, who responded at once. These were the first items in an ongoing correspondence between the two men, only the Soddy-to-Bragg half of which apparently survives. Soddy's letter included the following:

> I got your long & interesting letter this morning & write at once to congratulate you on the extremely successful turn your work has taken. I need hardly say that I shall study the papers . . . with great interest; indeed, I await their appearance that I may be able to quote them to my own (theoretical) ends. To this end I have written the Phil. Mag. people asking them to get them out quickly if possible.
>
> I was chagrined to read that lack of space prevented Nature publishing your full letter & was on the point of writing the Editor to that effect, but now . . . I think on the whole it is best that it was not published in the unsatisfactory form of a short letter.

[40] Bragg, "On the Absorption of $\alpha$ Rays" (cit. n. 37) (a popular account of this early work was given later in Bragg, "Days of My Youth" [cit. n. 6]); and Bragg and R. D. Kleeman, "On the Ionization Curve for Radium," *Trans. Roy. Soc. South Aust.,* 1904, *28:*726–738.

From the beginning Soddy provided encouragement and crucial support in speeding Bragg's papers through the publication process, not least because, when the editor of the *Philosophical Magazine* replied to Soddy, agreeing to get Bragg's papers out quickly, he also stated that he would send proofs and any technical queries to Soddy, thus avoiding the long round trip by sea required for questions addressed to the author.[41]

Just two days after his first letter, when Soddy was in London to conclude his association with University College, he wrote again with two pieces of news that must have made Bragg's heart jump for joy:

> Excuse this scrawl, but I just want to catch the mail with a small tube of a milligram or so of my pure Radium Bromide. I had a little over at Uni. Coll. & you mention in your letter that you have had difficulty in getting effects powerful enough for your Electrometer & I thought this small qty. might prove useful. I wrote Stark, the Editor of the Jahrbuch der Radioaktivitat, that he should get you to write an article on your work & I understand he has done so.[42]

The radium sample was superior in both strength and purity to what Bragg had used thus far and would be most important in his next round of experiments. The invitation from Johannes Stark would be central in alerting German scientists to Bragg's research work.

Stark wrote to Bragg on 22 October 1904:

> I am informed by Prof. Soddy that you are conducting important investigations of α-rays. New results on these insufficiently-studied rays seem highly desirable, and I wish to ask you to write a brief report of your work for the Radioactivity Yearbook. In view of the great distance between us, on the one hand, and the desirability of an early publication of your results on the other, I should be glad to receive your reply by return mail.

Bragg prepared a new account of his research that left Adelaide in November and arrived in Germany on 31 December 1904. It was translated into German and appeared in the 1905 *Jahrbuch der Radioaktivität und Elektronik.*[43] I have given the name "advocate" to the pivotal role Soddy had now assumed on Bragg's behalf.

Having apparently received one or more letters from Bragg, Soddy wrote again in January 1905, assuring him that the radium he had sent could be used "in any way you think will help you at all." He also said that he had had to make only a very minor correction to Bragg's papers, which by this point had appeared in the *Philosophical Magazine,* and he provided a long report of his own views on the nature of radioactive change. Nor was Soddy the only influential scientist to receive an account of Bragg's new results. As early as 10 August 1904, Bragg wrote excitedly to Thomson, discussing the contrasting behaviors of beta and alpha rays, outlining his two forthcoming papers, and adding, "I am sending home a good mathematician this year, and have ventured to give him a letter to you. His name is Wilton."[44]

[41] Soddy to Bragg, 18 Oct. 1904, 2 Nov. 1904, Bragg Papers, 6A/23, 6A/25. Regarding their inability to publish Bragg's letter see *Nature,* 1904, *70:*445.

[42] Soddy to Bragg, 20 Oct. 1904, Bragg Papers, 6A/24.

[43] Johannes Stark to Bragg, 22 Oct. 1904, Bragg Papers, 6B/8; and W. H. Bragg, "Die α-Strahlen des Radiums," *Jahrbuch der Radioaktivität und Elektronik,* 1905, *2:*4–18.

[44] Soddy to Bragg, 12 Jan. 1905, Bragg Papers, 6A/26; and Bragg to J. J. Thomson, 10 Aug. 1904, J. J. Thomson Papers, Cambridge University Library, Add MS 7654, B70. Bragg later described Raymond Wilton as "having had the greatest natural genius for mathematics among any of his students": quoted in R. B. Potts, "Wilton, John Raymond (1884–1944)," *Australian Dictionary of Biography,* ed. John Ritchie (Melbourne: Melbourne Univ. Press, 1990), Vol. 12, pp. 533–534.

Bragg also sent accounts of his research to an increasing number of his Australian colleagues, but from the beginning—apart from Soddy—his most important correspondent was Ernest Rutherford. In another letter written in August 1904 Bragg had presented his new results and emphasized his belief that the stopping of alpha particles was not exponential: "I know of course that this is rather contrary to your theories," he wrote, "and yet I think you will be pleased with what I want to tell you because my results are so beautifully explained on your theory of radioactive change"; and, finally, "I have read of you so often since you went through Adelaide many years ago that I seem to have never lost touch with you entirely. But let me take this opportunity to congratulate you on your magnificent work."[45] These congratulations were not gratuitous, since Bragg was nearly ten years older than Rutherford; but Rutherford would remain the senior partner in scientific terms during most of their long and friendly relationship. He would become Bragg's second influential "advocate."

Rutherford responded generously, supporting Bragg's conclusions, encouraging early publication, and reporting some of his own recent work. Furthermore, he conceded that "I am all the more interested [in your work] in that I was independently attacking the question . . . but had not your data" and then added, "I shall of course keep away from the subject until you are through." In November of the same year Rutherford wrote again, saying that he was preparing a second edition of his *Radio-Activity* text and inviting Bragg to forward the results of his work, "as I would like to include it in the new edition." Bragg responded, thanking Rutherford for the copy of his forthcoming Bakerian Lecture at the Royal Society of London, reporting recent thoughts on his research, and regretting that Rutherford was visiting New Zealand but could not get to Adelaide.[46] During the last six months of 1904 Bragg had enjoyed a breathtaking beginning to his new research program, further evidence that he had prepared for it meticulously.

On 19 January 1905 Bragg wrote to Rutherford, attaching a twenty-four-page handwritten copy of his AAAS address, together with ten pages of additional notes, and concluding: "I hope this letter is in time [to catch the overseas mail]. I am rather afraid that yours was delayed; it was marked 'Too Late.'" This illustrates Bragg's ever-present worry: that distance—from Europe in general and England in particular—would so delay his letters and manuscripts that he would be out of touch with the latest scientific developments and his priority would be jeopardized. In midyear he again wrote to Rutherford, now in New Zealand, pleading with him to visit Adelaide: "I should be delighted if you could spend a little time with me; I have house room. It would be a keen pleasure to me to have your society for as long as you can give me; and the chance of hearing your opinion on some of the radioactive problems."[47] Personal contacts were perhaps the greatest of the losses felt by the distant colonial scientist.

In February Rutherford had written to the journal *Nature* to report experiments that "undoubtedly show that the α particles do carry a positive charge"; this was followed a week later by a letter from Soddy that quoted Bragg in suggesting that the alpha particles were emitted uncharged but immediately became positive on losing an electron.[48] It would

[45] Bragg to Ernest Rutherford, 31 Aug. 1904, Ernest Rutherford Correspondence, Cambridge University Library, Add MS 7653, B354 (hereafter cited as **Rutherford Correspondence,** with the item number).

[46] Rutherford to Bragg, 23 Oct. 1904, 14 Nov. 1904, Bragg Papers, 26A/1, 26A/2; and Bragg to Rutherford, 18 Dec. 1904, Rutherford Correspondence, B355. The text in question is Ernest Rutherford, *Radio-Activity,* 2nd ed. (Cambridge: Cambridge Univ. Press, 1905).

[47] Bragg to Rutherford, 19 Jan. 1905, 7 June 1905, Rutherford Correspondence, B356, B357.

[48] Ernest Rutherford, "Charge Carried by the α Rays from Radium," *Nature,* 1905, *71:*413–414; and Frederick Soddy, "Charge on the α Particles of Polonium and Radium," *ibid.,* pp. 438–439.

be 1908 before Rutherford and his collaborators could settle the argument: the alpha particle was a helium ion/atom carrying two positive charges.

By June 1905 Bragg was ready to report to the Royal Society of South Australia and to his advocates and other correspondents on the next phase of his research. In summarizing his previous work, he explicitly used the term "range" for the first time: "each [alpha] particle possesses a definite range in a given medium, the length of which depends on the initial velocity of the particle and the nature of the medium," and "all the particles of any one group have the same initial velocity and the same range."[49] He gave precise results for the ranges in air of the four groups of alpha particles from radium in radioactive equilibrium; indicated that all the particles spent their energy at a rate approximately proportional to the inverse square root of their speed (a suggestion he later changed); and concluded that the loss of range of alpha particles was nearly proportional to the square root of the atomic weight of the atoms they traversed or, in the case of molecules, to the sum of the square roots of the atomic weights of the constituent atoms.

The paper and diagrams that followed in the *Philosophical Magazine* were, from the outset, channeled through his advocate Frederick Soddy, who was pleased to "see them through the Phil. Mag. as you request." The paper gave details of the major improvements that had been made both to the apparatus, thanks to the expertise and dedication of Arthur Rogers, and to the experiment, thanks to the use of Soddy's radium bromide sample. The results were therefore "much more accurate, and supply much more information."[50] Bragg and Kleeman were able to argue convincingly that, for the absorption of alpha particles, there was no absorption coefficient nor any approach to an exponential law. Similarly, having studied the passage of alpha particles through thin foils of six different metals (from aluminum to gold) and through seven different gases (from hydrogen to ether), they were able to conclude that a material's ability (referred to air as a standard) to reduce the range of alpha particles, or the energy spent in passing through it, or its relative "stopping power," was described by the atomic weight relationship given above.

Bragg apparently arrived at the atomic weight relationship empirically; more recent work has shown it to be fortuitous and restricted to a low energy range. Similarly, his conclusions that "the $\alpha$ particle makes the same number of ions during its course no matter what the gas which it traverses" and that "the energy required to make a pair of ions is always the same"—justifiable at the time—also imply that the atomic weight relationship could only be an approximate, if useful, one. Soddy had written to Bragg twice in June 1905, urging him to "push on with the absorption experiments," for "I think you are probably on the eve of something pretty fundamental. . . . With your theoretical insight I shall expect a great elucidation." He had also volunteered to assist Bragg in obtaining the best possible metal foils to replace the poor-quality samples he had been using and sent two pieces of his own platinum foil as an interim measure.[51]

[49] W. H. Bragg and R. D. Kleeman, "On the Alpha Particles of Radium, and Their Loss of Range in Passing through Various Atoms and Molecules," *Trans. Roy. Soc. South Aust.,* 1905, *29:*132–133. Spectacular visual verification of these conclusions regarding range came in 1912 with Wilson's cloud-chamber pictures; see Clinton Chaloner, "The Most Wonderful Experiment in the World: A History of the Cloud Chamber," *British Journal for the History of Science,* 1997, *30:*372–373.

[50] Soddy to Bragg, 30 July 1905, Bragg Papers, 6A/29; and W. H. Bragg and R. D. Kleeman, "On the $\alpha$ Particles of Radium, and Their Loss of Range in Passing through Various Atoms and Molecules," *Phil. Mag.,* 1905, *10:*318–340, on p. 325.

[51] Bragg and Kleeman, "On the $\alpha$ Particles of Radium," p. 339; and Soddy to Bragg, 1 June 1905, 14 June 1905, Bragg Papers, 6A/27, 6A/28. For later work on the atomic weight correlation see R. D. Evans, *The Atomic Nucleus* (New York: McGraw-Hill, 1955), pp. 652–653.

These papers embodied what became known as the "Bragg ionization curve" for alpha particles. Figure 4 depicts the two forms of the curve presented by Bragg in his 1912 account of his Adelaide work: Figure 4*a* shows Bragg's own method of presentation, with range along the vertical axis and ionization along the horizontal axis; while Figure 4*b,* attributable to Hans Geiger, became the conventional illustration. The name lives on in a wider context, as in the modern medical procedure called "Bragg peak therapy."[52]

Rutherford wrote to Bragg from New Zealand in July 1905, regretting that there was no hope of a side trip to Adelaide and promising, "I will keep my men as clear as possible of the line of work you wish to take if you let me know in time—as I know it is a drawback for publication living in Australia." Included in the letter, as well, was notification of a significant problem that is best expressed in a letter from Soddy the same month:

> Going on to the last part of [your] paper I am, of course, stopped dead by the great difference between your views on the energy remaining to the α particle after it loses its power of ionising and those in Rutherford's last paper. You 'assume that when it ceases to have this power the energy has fallen to an amount which is very small compared to its initial energy.' R[utherford] deduces that at this point the velocity is still 60% & the energy 40% of the initial.

Bragg responded with a letter to the editor of the *Philosophical Magazine* pointing out corrections that should be made to his recent paper in view of these findings: namely, that

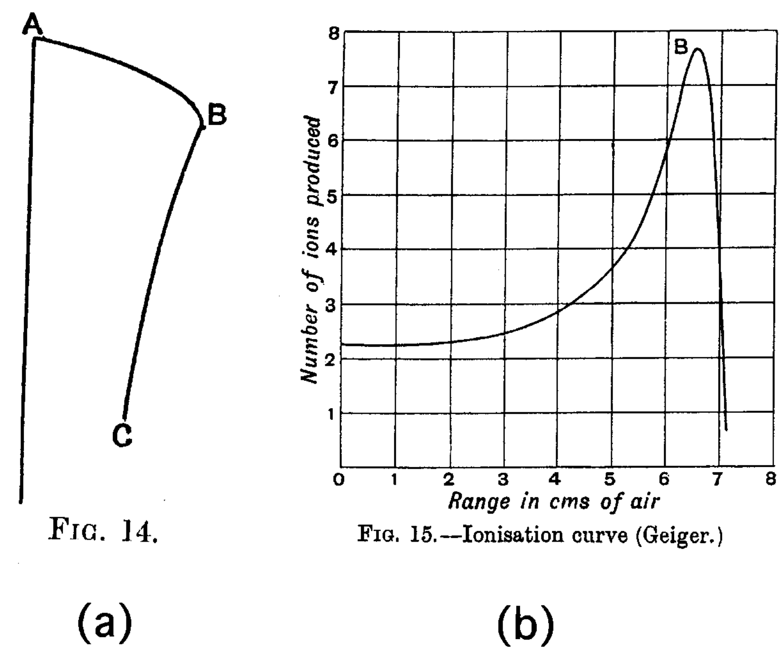


***Figure 4.*** *Two representations of the "Bragg ionization curve."* a, *Bragg's own style;* b, *The form that soon superseded it. From W. H. Bragg,* Studies in Radioactivity *(London: Macmillan, 1912), pages 29, 30.*

[52] Bragg, *Studies in Radioactivity* (cit. n. 30), pp. 29–30; for Bragg peak therapy see Michael Nitschke, "The Discrete Charm of Exotic Nuclei," *New Scientist,* 1989, *121:*58–59.

the proportionality of the stopping power of a substance to the square root of its atomic weight was unchanged, as was the supposition that the alpha particle stopped ionizing at the same speed in all gases; but that the latest results implied that the particles spent their energy at a rate proportional to the inverse square of their velocity, not the inverse square root.[53] Although Bragg appeared to accept Rutherford's view regarding the energy remaining in the alpha particle when it ceased to ionize, later events were to show that, privately, he was not convinced.

### CONSOLIDATION AND EXTENSION

Bragg was now a widely recognized worker in the field of radioactivity. It was he who had first observed that the alpha particle ionizes most strongly at lower speeds, near the end of its range. His research therefore turned to study the ionization process itself. He had ambitious plans: "My general idea is to attack the question of molecular and atomic structure by examining the absorption effects of the various atoms," he wrote to Rutherford.[54] In fact, the ionization process was to prove a complex study, but Bragg's vision regarding structure is arresting in view of his later achievements after he and his elder son invented X-ray crystallography.

As had now become his pattern, in September/October 1905 Bragg presented his latest results to the Royal Society of South Australia and then sent detailed letters to some of his Australian colleagues and to his advocates Soddy and Rutherford, including a draft paper for the *Philosophical Magazine.*[55] Noting that theory and experiment did not always agree with regard to the way ions, produced by the passage of an alpha particle through a solid or a gas, later recombined to neutralize the material ("general recombination"), Bragg and Kleeman suggested that there was also another, faster process involved. They speculated that some of the electrons very quickly recombined with their parent ion/atom, a process they christened "initial recombination," and they presented strong evidence to support the hypothesis.

A few months later, Bragg reported an extension of the work. Focusing on a wide range of gases and metals and on the two independent parameters $R$ and $I$—the range of a particular alpha-particle group and the ionization it produced in his apparatus—Bragg demonstrated that $R$ could be accurately measured and that the consequent stopping powers of the materials were closely proportional to the sum of the square roots of the atomic masses present. "It is much more difficult to measure I accurately," he then pointed out, and "there appears to be a more important difference in that the total ionization of a gas is not simply dependent on the weights of the atoms of which it is composed. Molecular structure counts for something."[56] How much future science was contained in these last five words! This was a time when even the structure of the atom was unknown, and it

[53] Rutherford to Bragg, 3 July 1905, Bragg Papers, 26A/3 (he did admit, however, that R. K. McClung at Montreal had repeated the Adelaide work and found it to be "completely corroborated"); Soddy to Bragg, 30 July 1905, Bragg Papers, 6A/29 (he is referring to Ernest Rutherford, "Some Properties of the α Rays from Radium," *Phil. Mag.,* 1905, *10:*163–176); and W. H. Bragg, "On the α Particles of Radium," *ibid.,* pp. 600–602.

[54] Bragg to Rutherford, 16 July 1905, Rutherford Correspondence, B358.

[55] W. H. Bragg and R. D. Kleeman, "On the Recombination of Ions in Air and Other Gases," *Trans. Roy. Soc. South Aust.,* 1905, *29:*187–206, *Phil. Mag.,* 1906, *11:*466–484; and Bragg to Rutherford, 8 Sept. 1905, Rutherford Correspondence, B359.

[56] W. H. Bragg, "On the Ionization of Various Gases by the α Particles of Radium," *Phil. Mag.,* 1906, *11:*617–632, on p. 622.

would be decades after the solution of that problem before the outer electronic structure of molecules and solids would shed light on the complexity of the problem Bragg was addressing.

Having provided invaluable support for Bragg in the earliest stages of his research, Richard Kleeman now left for Cambridge on an 1851 Science Research Scholarship, and Bragg began to acknowledge the work of two new research associates, J. P. V. Madsen and H. J. Priest. Following a brilliant undergraduate career at the University of Sydney, John Madsen had been appointed assistant lecturer in mathematics and demonstrator in physics at Adelaide in 1901; in 1902 he was appointed lecturer in electrical engineering and placed in charge of the new diploma course in that area. He now joined Bragg's research team and, after a short but productive research career, became one of the most powerful figures in Australian research administration. An Adelaide science graduate in 1902, Herbert Priest was a demonstrator and lecturer in physics while assisting Bragg's research. Temporarily Bragg's successor at Adelaide in 1909, and later a lecturer at the universities of Western Australia and Queensland, he died in 1930 after years of ill-health.[57] Bragg's earlier pleas for staff and research-student assistance had, at last, borne fruit. But although these men did experiments on closely related subjects, they did not collaborate on Bragg's own experiments. His research notebooks and published papers contain only one hand, his own.

In his September letter to Rutherford Bragg quoted work by Townsend in questioning Rutherford's suggestion that alpha particles cease ionizing at an early stage; he further doubted Rutherford's claim that he had used a very thin film of radium in one of his experiments. "If I may venture to say so," Bragg wrote, "it is in fine crystals of fairly uniform thickness . . . [of] many thousands of atoms." After receiving Rutherford's reply of 4 November, Bragg responded briefly and at once, thanking him for the copy of the second edition of *Radio-Activity* and saying, "I must thank you also for all your kindly references to my own work."[58]

Bragg wrote again near Christmas, from the balcony of his family's seaside holiday residence: "It is very jolly to have your comments on my paper; most reassuring and welcome. You see, I am a little out of the world here, and do not hear very much; and so I sometimes wonder whether those who understand the subject are approving of what I have done. You and Soddy have been most kind and have quite kept me going!" In acknowledging the complexity of the ionization/recombination process, Bragg then speculated about a process of "secondary ionization within the molecule" and also suggested that initial recombination might not always occur rapidly but that there might be a "suspended recombination" in which the two elements of an ionized atom would form a charge doublet that would not immediately recombine. The latter suggestion is interesting as a signpost to Bragg's later important hypothesis that X-rays and gamma rays were particulate and not wavelike, taking the form of a positive-negative particle pair.[59]

As is also apparent from the correspondence with Rutherford, Bragg had now clearly grown in confidence and stature to the point where his advice was being sought and his work was regarded as authoritative by the leaders in the field. Soddy had been including

[57] R. W. Home, "W. H. Bragg and J. P. V. Madsen: Collaboration and Correspondence, 1905–1911," *Hist. Rec. Aust. Sci.,* 1981, *5:*1–29; on Priest see *Advertiser* newspaper, Adelaide, 4 Dec. 1930, p. 12.

[58] Bragg to Rutherford, 8 Sept. 1905, Rutherford Correspondence, B359; Rutherford to Bragg, 4 Nov. 1905, Bragg Papers, 26A/4; and Bragg to Rutherford, 22 Nov. 1905, Rutherford Correspondence, B360.

[59] Bragg to Rutherford, 21 Dec. 1905, Rutherford Correspondence, B361; and Wheaton, *Tiger and the Shark* (cit. n. 7).

Bragg's work in his "Annual Progress Reports on Radioactivity to the Chemical Society" since their inception for 1904, and authors in addition to Rutherford were including Bragg's findings in their books on radioactivity.[60]

Two aspects of Bragg's research program now called for further attention: use of his method to examine the alpha particles of radioactive species other than radium, and further exploration of the complex process of ionization. Regarding the first, and in connection with his own wish to determine the amount of helium produced by uranium and thorium, Soddy had asked Bragg to determine the range of alpha particles from uranium and thorium. Bragg willingly acceded: "I am so much in his debt that I was glad to try to do what he asked."[61]

Because the best uranium and thorium sources he was able to obtain were much weaker than his radium source, Bragg was obliged to amend his experimental procedure; he had to accept a wide angular range, redesign the apparatus, and formulate a new mathematical model to interpret the results. His mathematical prowess stood him in good stead here, as it had done previously, but even so he found it desirable to make significant changes to the report of his experiment between its appearances in the *Transactions of the Royal Society of South Australia* and in the *Philosophical Magazine.* In addition, the approximations Bragg was required to make meant that the characteristics of the alpha particles were determined with less accuracy than he would have liked, and so, having satisfied Soddy's request, he did not return to these elements again. Soddy received Bragg's original draft of this paper and made the corrections before sending it on to the editor of the *Philosophical Magazine.* He also noted: "the sad news has just been received of the death of M. Curie, run over & killed in the streets of Paris"—once again providing valuable and time-saving editorial work for Bragg and supplying news that kept him in touch with current events in Europe.[62]

The ionization process now became the central focus of Bragg's attention. In a long paper read and published in both Adelaide and London, he began to grapple with the complexities he had noted earlier.[63] After determining the relative amounts of ionization produced in some eighteen different gases by the alpha particles of radium, Bragg concluded that the ionization ($\delta i$) produced by the energy expended ($\delta e$) by an alpha particle was given by $\delta i = k \cdot \mathrm{f}(v) \cdot \delta e$, where $k$ is the "specific ionization constant" for alpha particles for any given gas (relative to air) and $\mathrm{f}(v)$ is a function of the velocity of the alpha particle only. The constant $k$ was determined for each gas, but the form of the function $\mathrm{f}(v)$ was discussed only tentatively.

In a long letter penned to Bragg in February 1906, Rutherford reported that he had now determined that the alpha particle ionized down to 43 percent of its initial velocity but

[60] See Thaddeus J. Trenn, ed., *Radioactivity and Atomic Theory: Annual Progress Reports on Radioactivity, 1904–1920, to the Chemical Society by Frederick Soddy F.R.S.* (London: Taylor & Francis, 1975). See also, e.g., Walter Makower, *The Radioactive Substances* (London: Paul, Trench, Trübner, 1908), pp. 93–108; and Norman R. Campbell, *Modern Electrical Theory* (Cambridge: Cambridge Univ. Press, 1907), pp. 186–191.

[61] Soddy to Bragg, 6 Nov. 1905, Bragg Papers, 6A/32; and Bragg to Rutherford, 5 Apr. 1906, Rutherford Correspondence, B363.

[62] W. H. Bragg, "The $\alpha$ Particles of Uranium and Thorium," *Trans. Roy. Soc. South Aust.,* 1906, *30:*16–32, *Phil. Mag.,* 1906, *11:*754–768; and Soddy to Bragg, 20 Apr. 1906, Bragg Papers, 6A/35.

[63] W. H. Bragg, "On the Ionization of Various Gases by the $\alpha$ Particles of Radium: No. 2," *Trans. Roy. Soc. South Aust.,* 1906, *30:*166–187, *Phil. Mag.,* 1907, *13:*333–357 ("No. 1"—though it was not so designated—is the essay cited in note 56, above). The manuscript for the *Philosophical Magazine* was communicated to the editor by the Physical Society of London, where the paper was read on 22 February (*Proceedings of the Physical Society of London,* 1905–1907, *20:*523–550).

agreed that "we really know mighty little about ionization when we come down to it. . . . I think that the α particle is a helium molecule with *2* ionic charges," he continued, and then outlined his attempt to measure its charge-to-mass ratio. "Hahn is working out the 'Bragg' curves for radiothorium," he reported, and "by the way, Soddy seems to have rather broken loose from his scientific moorings to judge from his recent letters to Nature."[64] This was the beginning of the decline in Soddy's prestige in scientific circles, but he remained a generous advocate for Bragg.

Soddy's letters in July 1906 observed that Bragg's method of studying alpha particles was now widespread and that the Bragg style of ionization curve "is filling the Phil. Mag. just now." Subsequent letters from Soddy buoyantly reported his engagement to Miss Winifred Beilby and loudly criticized J. J. Thomson's atom model and other "Cavendish Crudities"; arranged the purchase and shipment of a liquid air plant for Bragg's Adelaide laboratory (again donated by Robert Barr Smith); show that he continued to shepherd Bragg's papers through the publication process; and reported that Rutherford had been appointed to Manchester: "it will make a great difference having him over here."[65]

Turning next to the influence of the velocity of the alpha particle on the stopping power of metals, Bragg was hampered by the fact that his determination of stopping power was only a relative one: the ratio of the stopping power of a metal to that of air. The variation of the former with speed was therefore clouded by changes in the latter. Nevertheless, he was able to conclude that the relative stopping power was a changing function of particle speed, proportional to the square root of the atomic weight of the metal. So the relative stopping power of aluminum was almost independent of speed, while that of gold increased markedly with increasing speed. If this were so, then the order in which an alpha particle traversed a pair of dissimilar metals should be significant for the ionization produced in the two possible cases. This Bragg confirmed, despite the contrary findings of other workers. Similarly, the relative stopping power should decrease with increasing speed for a substance with an atomic weight less than that of air (nitrogen + oxygen). This too Bragg verified, using methane (carbon + hydrogen).[66]

While Bragg had told Rutherford that there was much more to be discovered about ionization, he also knew that it was mysterious, and he correctly concluded that his current studies had exhausted their productivity. He began to consider an alternative project—namely, the nature of X-rays and gamma rays—and this would take him into another realm. Indeed, in the issue of the *Philosophical Magazine* after the one that presented his paper on methane, Bragg speculated "on the properties and natures of various electric radiations."[67]

## RESEARCH FACILITIES

The facilities available to Bragg for his research were limited and followed closely the pattern suggested by Graeme Gooday's article on the working environments of Victorian

[64] Rutherford to Bragg, 24 Feb. 1906, Bragg Papers, 26A/5.

[65] Soddy to Bragg, 9 July 1906, 26 July 1906, 4 Sept. 1906, 27 Nov. 1906, 9 Dec. 1906, 10 Dec. 1906, 10 Jan. 1907, 16 Jan. 1907, Bragg Papers, 6A/36–43.

[66] W. H. Bragg, "The Influence of the Velocity of the α Particle upon the Stopping Power of the Substance through Which It Passes," *Phil. Mag.,* 1907, *13:*507–516; and Bragg and W. T. Cooke, "The Ionization Curve of Methane," *ibid.,* 1907, *14:*425–427. Cooke was a colleague in the Department of Chemistry. For others' contrary findings see Lawrence Badash, *Radioactivity in America: Growth and Decay of a Science* (Baltimore: Johns Hopkins Univ. Press, 1979), Ch. 15.

[67] W. H. Bragg, "On the Properties and Natures of Various Electric Radiations," *Phil. Mag.,* 1907, *14:* 429–449.

experimental science.[68] Bragg was allocated a small room in the basement of the single Adelaide University building—happily, close to Rogers's workshop—that contained two slate workbenches supported on solid brick piers but was otherwise devoid of sophisticated equipment. (See Figure 5.)

The important paper on ionization published in the *Philosophical Magazine* in 1907 is notable for its presentation, for the first time, of precise details of the apparatus Bragg had been using. (See Figure 6.) This apparatus had evolved continuously from the earliest days of Bragg's program, and presumably he waited until it reached a level of development that satisfied his demanding standards before undertaking a description. A comparison of Figures 3 and 6 indicates the very substantial development that had occurred. Problems of vacuum, pressure, leakage, temperature, and movement were ever present, however, and Bragg's papers testify to the very high level of experimental expertise he had acquired to overcome such difficulties.

On the matter of Bragg's experimental and presentation skills, honed and nurtured in

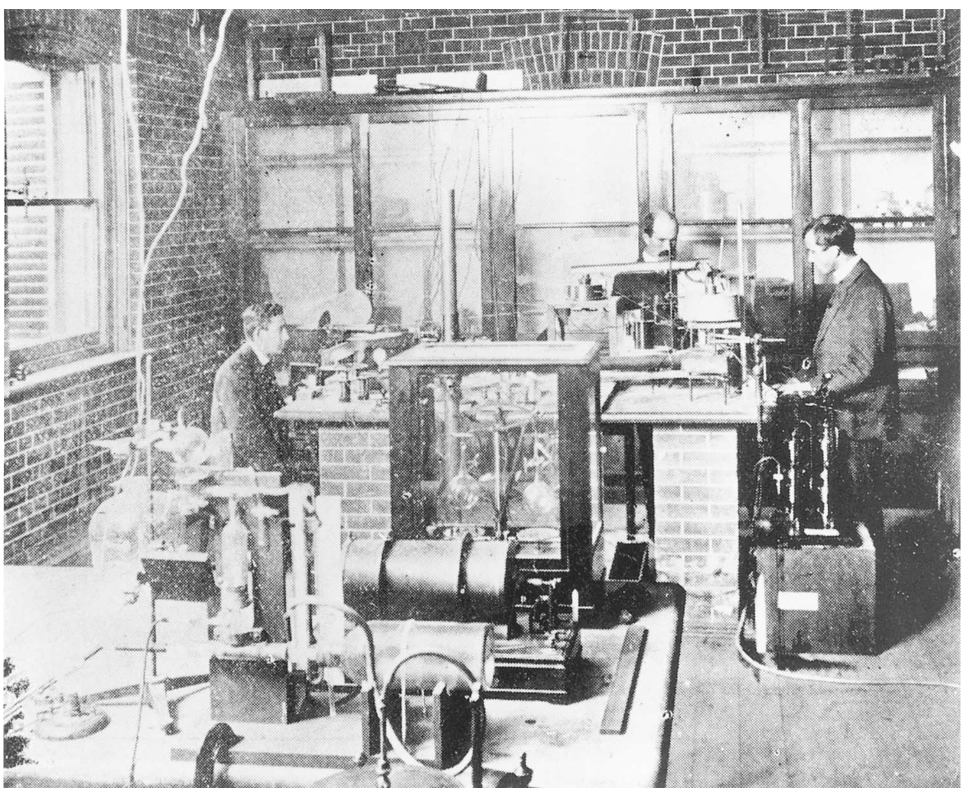

***Figure 5.*** *Bragg's research laboratory at the University of Adelaide. Bragg is in the center, Herbert Priest on the left, and John Madsen on the right. From* Supplement to "The Critic," *Adelaide, 11 July 1906.*

[68] G. J. N. Gooday, "Instrumentation and Interpretation: Managing and Representing the Working Environment of Victorian Experimental Science," in *Victorian Science in Context,* ed. Bernard Lightman (Chicago: Univ. Chicago Press, 1997), pp. 409–437, and references therein.

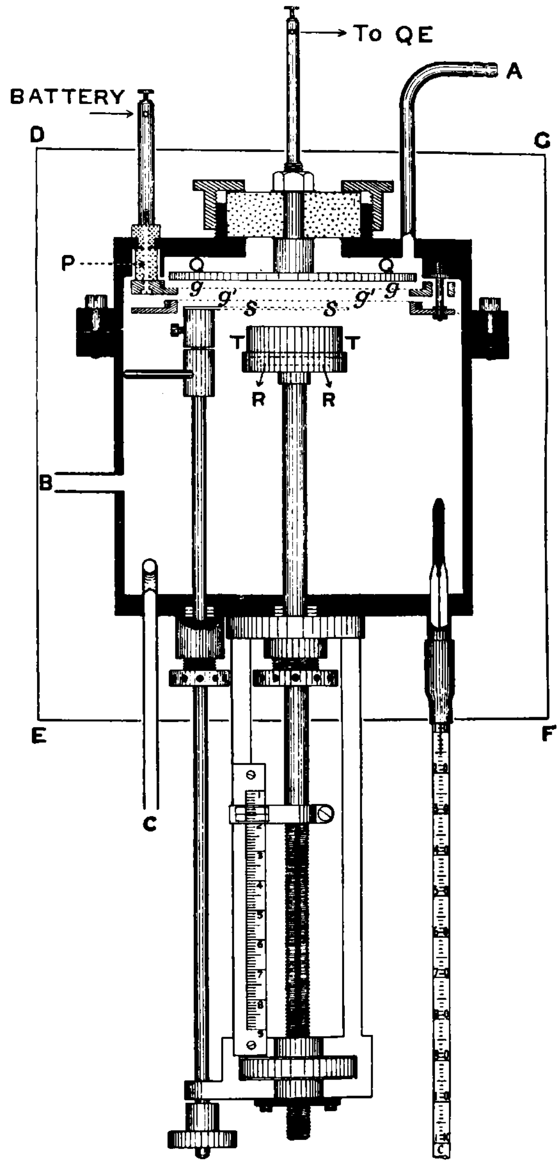


***Figure 6.*** *The final form of Bragg's alpha-particle apparatus. From* Philosophical Magazine, *1907,* 13:*333–357, Plate IX; compare Figure 3. Alpha particles from thin radium layer* R *were collimated by narrow tubes* T *and traveled toward ionization chamber* ggQQ, *shielded by earthed gauze* g'g' *and connected to quadrant electrometer* QE. SS *was a metal sheet that could be interposed between source and chamber. Tube* A *connected to a manometer to measure gas pressure, tubes* B *and* C *were gas-vacuum connections, and* CDEF *represented an electric oven to control the temperature of the gas under study.*

Adelaide, two later remarks by his elder son and scientific partner, W. Lawrence Bragg, are revealing:

> [1] Arriving in Adelaide . . . he arranged to get instruction from a firm of instrument makers, learned to use the lathe and made the apparatus for his classes. I always think this early training was reflected in the beautifully-designed apparatus which he used for his various researches.
> [2] He was unusual in two ways. He came to Physics as a mathematician and always looked at Physics from that point of view, with an almost Greek way of expressing his ideas in logical language. And in sharp contrast to this theoretical approach, he entirely escaped the "string and sealing wax" tradition. He had high ideals about good tools, good design, and good workmanship. . . . Much of Rutherford's early apparatus was markedly in the tin-can and sealing-wax tradition—my father's never. . . . His notebooks, and the curves he plotted, were always my envy and admiration. Points just fell on a smooth curve as if by magic when he read and plotted.[69]

On the matter of Bragg's apparatus and the nature of his experimental difficulties, the following note from someone who joined the Adelaide physics staff a few years after Bragg's departure is indicative:

> When I first started work as demonstrator in Physics, I was given a small room in the basement. The shelves supported some thousands of medicine bottles which had been decapitated to form small jars; each jar contained two small metal plates. I discovered from Rogers that . . . Bragg needed a source of very high e.m.f. He asked his students to collect all the medicine bottles they could lay their hands on. Rogers cut the tops off. Adding two dissimilar metals and acid to each jar and joining them up, Bragg had his source of high e.m.f. . . . The wooden shelving was stained dark brown from the effects of acid spills.[70]

The demand for experimental sophistication was generally much less severe in the new physics than in research in the old, classical style. Indeed, this was one of its attractions, for, as in most new areas of study, important progress could be made with less-expensive and less-complex equipment. Thus, while Bragg's requirements were modest, Threlfall went to extraordinary lengths in his new physical laboratory building in Sydney to provide solid floors, "slate working tables independent of the floors . . . a plentiful supply of gas, water, electricity, gas and electric light, air blast, steam, oxygen and vacuum pumps, . . . perfect darkening by shutters or blinds . . . large ventilation ports," and "the whole of the western half of the building . . . free from iron."[71]

## OUTCOMES AND AFTERMATH

During the three years (1904–1907) he had spent engaged in experiments on alpha particles and the ionization they induced, Bragg's star had risen to worldwide prominence, as illustrated by two developments of major significance: his election as a Fellow of the Royal Society of London, and offers of senior appointments at major laboratories elsewhere.

Horace Lamb had been the foundation professor of mathematics at Adelaide, and he had followed Bragg's career with interest. As early as May 1906 he wrote:

[69] W. L. Bragg to Sir Cyril Hinshelwood, 26 Jan. 1965, and W. L. Bragg to Sir Mark Oliphant, Oct. 1966, Bragg Papers, 53A, 54A.

[70] W. H. Schneider, autobiographical notes (private communication from M. P. Schneider).

[71] Richard Threlfall, "On the New Physical Laboratory at the University of Sydney," in *Report of the First Meeting of the AAAS,* ed. Liversidge and Etheridge (cit. n. 12), pp. 95–105; see also Threlfall, *On Laboratory Arts* (London: Macmillan, 1898).

> Some of your scientific friends on this side the equator are of opinion that the time has come when you ought to be put in nomination for the Royal Society. If you do not object, will you kindly let me have a list of your papers, and a few details about your career. I will draw up the necessary certificate, and get some weighty signatures. The candidature will be warmly supported by J. J. Thomson, who will help in getting signatures in Cambridge and elsewhere.[72]

Three certificates were lodged before Christmas 1906: the first had been signed by R. J. Strutt, C. T. R. Wilson, Lodge, Townsend, and A. Schuster "from general knowledge" and by Lamb, Thomson, A. R. Forsyth, H. L. Callendar, A. E. H. Love, H. H. Turner, Threlfall, and Preece "from personal knowledge"; the second, from Australia, was signed by Ellery, D. O. Masson, E. C. Stirtling, W. B. Spencer, A. Liversidge, and W. A. Haswell "from personal knowledge"; and the third bore just one signature, "E. Rutherford."[73] It was a most impressive list of supporters.

Bragg's election was announced on 1 March 1907, and Lamb sent a telegram to "University Adelaide" the same day: "Bragg selected Royal." Rod Home, who has written extensively of the scientific network and patronage system embodied in the Royal Society of London, has pointed out that by the end of the nineteenth century the pressure on places had increased inexorably and that election was not assured even after several years of candidacy. "New candidates tended to find themselves joining something of a queue of fellow specialists, and only the most outstanding (for example, Bragg in 1907) managed to leap-frog those ahead of them." Bragg was certainly surprised when he was elected at the first opportunity.[74]

Local newspapers carried the story. There were letters from academic colleagues around the country and from former students in Australia and overseas; Robert Barr Smith, now an octogenarian, sent him a note in very shaky handwriting; and a fellow Adelaide professor, George Henderson, left a message on Bragg's desk proclaiming, "Hurrah, hurrah for Bragg and his University. Splendid. G.C.H."[75]

Rutherford's appointment to Manchester became known early in 1907. He would leave McGill in midyear, and Howard Barnes would be promoted to the Macdonald Chair; but Rutherford thought an additional person was needed "to give the Graduate School a good start and fill a gap in the mathematical teaching" and that Bragg was "exactly the man that is wanted at McGill." Accordingly, Rutherford wrote to Bragg in July:

> Now in regard to an important matter I want to talk to you about. . . . They are anxious, between ourselves, to get somebody to carry on my particular lines of work with vigour . . . and there is considerable need of a man to take the work in applied mathematics. . . . I have been asked to sound you out on the question. . . . Montreal is not so isolated as Adelaide & you can run down as often as you like to attend the meetings of the Amer. Phys. Soc. who are glad to welcome all good Canadians. Let me know what you think of it. Don't be seduced by second rate appointments in England, for I have heard rumours of such intentions.

[72] Horace Lamb to Bragg, 5 May 1906, Bragg Papers, 4A/2.

[73] Royal Society of London, *Certificates of Candidature,* 1848–1950, W. H. Bragg, nos. 240–242.

[74] Lamb to University Adelaide, 1 Mar. 1907 (cable), Bragg papers in the care of Lady Adrian, Cambridge; and R. W. Home, "A World-wide Scientific Network and Patronage System: Australian and Other 'Colonial' Fellows of the Royal Society of London," in *International Science and National Scientific Identity,* ed. Home and Kohlstedt (cit. n. 3), pp. 151–179, on p. 166. See also Home, "The Royal Society and the Empire: The Colonial and Commonwealth Fellowship," Pt. 1: "1731–1848," Pt. 2: "After 1847," *Notes and Records of the Royal Society of London,* 2002, *56:*307–332, 2003, *57:*47–84. For Bragg's surprise see, e.g., Bragg to Geoffrey Duffield, 4 Apr. 1907, Geoffrey Duffield Papers, Basser Library, Canberra, 4/7: "I scarcely like to think about it until I get letters. I have seen a list of the candidates, and am lost in amazement at my good fortune"; see also Bragg's letter of acceptance, 6 June 1907, Royal Society of London.

[75] Bragg papers in the care of Lady Adrian, Cambridge.

Soon after, Bragg wrote to Lamb:

> It is a very tempting offer, and I feel strongly inclined to accept it, when actually made. I am writing to tell you this, for . . . you have been so much my good genius that I feel I should like you to know. I seem to have got on to a certain line of research work which is worth pursuing. It has been possible to get on with it here during the last two or three years because I have made rather a big effort which I could hardly keep up; I have done it, so to speak, out of hours. . . . In any case I am rather cut off from others in the same line, intercourse with whom would help me very much, and might save me from many mistakes. . . . I believe Montreal is a healthy place, and it is only six days from England, where I hope that my boys will soon be at college. . . . It would be a terrible wrench to move from here; there never was a kinder lot of people nor a nicer little city, but perhaps it is good to be stirred up.[76]

Bragg's next letter to Rutherford enumerated "the reasons for and against a move from Adelaide to Montreal":

> That which attracts me most is the chance which seems offered me to do better work. I should be glad to be free from the ties of elementary classes and the burden of administration work which is unavoidable in a small but rather ambitious and enthusiastic university. . . . Here I am somewhat isolated, for though I have many good friends, there is none except William Sutherland of Melbourne whose work is on at all the same lines as mine. Moreover, . . . the number of advanced students is almost negligible; the courses in applied science are too attractive. The most serious difficulty is that of moving my household. We have built our own house and altogether have struck our roots very deep.

In the end, however, other events determined the outcome. University budgetary constraints at McGill, caused by the fires that destroyed the engineering building and the medical school, dictated that the offer eventually made to Bragg was much less attractive than might have been expected, and he had little difficulty in declining it.[77]

The "rumours" noted by Rutherford began very early in 1907, when William Stroud, the Cavendish Professor of Physics at the University of Leeds, intimated that he would take early retirement to enter into a business partnership, and when Soddy, hearing the news, wrote twice to Arthur Smithells, professor of chemistry and dean of the faculty of science at Leeds, to point out that Bragg's claims should not be overlooked.[78] The appointment process here was also prolonged, but the eventual offer was generous, and Bragg reluctantly accepted and moved to England with his family early in 1909. He could have had no inkling of just how dramatic the next few years of his life would be.

During the first half of 1907, the correspondence between Bragg and Soddy continued: they exchanged New Year greetings and portrait photographs; Soddy continued to guide Bragg's papers through the publication process; Bragg sent Soddy a well-received wedding present; and Soddy sent Bragg congratulations on the birth of his daughter.[79]

[76] Rutherford to Bragg, 12 Mar. 1907, 5 July 1907, Bragg Papers, 26A/8, 26/A10; and Bragg to Lamb, n.d. (draft), Bragg Papers, 10A/6. See also Lewis Pyenson, "The Incomplete Transition of a European Image: Physics at Greater Buenos Aires and Montreal, 1890–1920," *Proceedings of the American Philosophical Society,* 1978, *122:*92–114, on p. 108.

[77] Bragg to Rutherford, 21 Aug. 1907, Rutherford Correspondence, B368. On the outcome in this case see Pyenson, "Incomplete Transition of a European Image," p. 108; Bragg to Rutherford, 17 Dec. 1907, 22 Jan. 1908, Rutherford Correspondence, B369, B370; and Rutherford to Bragg, 24 Oct. 1907, Bragg Papers, 26A/12.

[78] P. H. J. H. Gosden and A. J. Taylor, eds., *Studies in the History of a University, 1874–1974* (Leeds: Arnold, 1975), pp. 20–23; and Soddy to Arthur Smithells, 24 Jan. 1907, 28 Jan. 1907, Bragg Papers, 10A/2, 10A/3.

[79] Soddy to Bragg, 5 Feb. 1907, 18 Apr. 1907, 21 Apr. 1907, 23 Apr. 1907, 23 July 1907, Bragg Papers, 6A/44–48.

The surviving correspondence ends abruptly here, however, except for a letter from Soddy to congratulate Bragg on his appointment to Leeds, and it seems likely that it ceased altogether when Bragg left Australia. Soddy was not sympathetic to Bragg's particle concept of radiation, Bragg's physics and Soddy's chemistry drifted apart, and when Bragg returned to England the principal *raison d'être* of the correspondence ceased. In the following years both men reached the high point in their careers, but there seems to be no evidence that they reactivated their earlier closeness. Indeed, toward the end of his life, sad and sometimes bitter, Soddy struck out at his old friend: "One often hears that nowadays physics and chemistry are one subject. God forbid! But even were it so, it does not give physicists any right to steal the work of chemists, or for that matter the Fullerian Professorship in Chemistry at the Royal Institution either!" The professor he was referring to was William Henry Bragg. His biographer, Muriel Howorth, then added: "Since the foregoing was written, another distinguished physicist has been appointed to the Fullerian Professorship of Chemistry at the Royal Institution." She was referring to William Lawrence Bragg.[80]

Little more need be said about the relationship between Bragg and Rutherford, since it is thoroughly discussed in all the major Rutherford biographies and elsewhere.[81] There were, for example, an ongoing and extensive correspondence; family holidays together; collaborative scientific work during World War I, including a joint patent; interaction regarding the division of X-ray research between Bragg in Leeds and "Harry" Moseley at Manchester; Lawrence Bragg's appointment as Rutherford's successor at Manchester; and numerous meetings together at the Royal Society and the Royal Institution in London.

Bragg's presidential address to the January 1909 AAAS meeting in Brisbane, also attended by his two sons, marked the conclusion of his Australian research program, the early stages of which have been the subject of this essay. It was a splendid summary of "the lessons of radio-activity" at this time and testimony to the position Bragg had come to occupy in Australasian science. He began with a survey of radiations of all kinds and pointed out that their study led to an understanding of the nature of the atoms and molecules producing the radiations as well as the nature of radiations themselves. He continued:

> It is clear that we are dealing with the most fundamental characteristics of atoms, with the building material and not with the structure; with the inner nature of the atom and not its outside show; and it is this which differentiates radio-activity from the older sciences. You will remember how Jules Verne . . . drives the submarine boat far down into the depths of the sea. The unrest of the surface . . . [is] soon left behind; the boat passes through the teeming life below, down into regions where only a few strange and lonely creatures can stand the enormous pressure; and, diving still, reaches the last black depths where there is a vast and awful simplicity. Here . . . the silent crew gazes on the huge cliffs which are the foundations and buttresses of the continents above. It is with the same feeling of awe that we examine the fundamental facts and lessons of the new science.

He then went on to examine these fundamental facts and lessons, including those associated with the alpha particle, where he stressed his own persistent astonishment that the fast-

[80] Soddy to Bragg, 25 May 1908, Bragg papers in the care of Lady Adrian, Cambridge; Jenkin, "Soddy's 1904 Visit to Australia and the Subsequent Soddy–Bragg Correspondence" (cit. n. 38), pp. 164–165; and Muriel Howorth, *Atomic Transmutation* (London: New World, 1953), p. 87.

[81] See, e.g., Eve, *Rutherford* (cit. n. 22); David Wilson, *Rutherford: Simple Genius* (London: Hodder & Stoughton, 1983); and John Campbell, *Rutherford: Scientist Supreme* (Christchurch, New Zealand: AAS Publications, 1999).

moving particles passed through, not around, the atoms they met and observed, prophetically, "All this amounts to saying that the atoms must be very empty things; something like solar systems in miniature, a few significant points or parts, and in between a relatively large amount of almost unmeaning space."[82]

**CONCLUSIONS**

Two matters, introduced at the beginning of this essay, now call for comment: the question of the effects of distance and isolation on the scientist and the prosecution of science; and the question of the relationship, in science, between the "home" country and its colonies. Bragg's colonial experience in Adelaide can hardly be regarded as typical—and, indeed, it is not clear that such a prototype exists—but these two matters have widespread relevance.

The significance of distance has been widely discussed, and particularly so in Australia, where an important book by a local historian, Geoffrey Blainey, has long focused attention on the effect, on the country as a whole, of distance from London and, on the individual cities and states, of distance from each other around the long Australian coastline. On the other hand, Chambers has argued convincingly that distance did not, of itself, tyrannize science, for there were many other factors relevant to its development in Australia.[83]

I want to argue here, however, that whatever historians might say or agree about in historical terms, scientists of the period around 1900 believed that distance *was* a significant problem and impediment. That is, scientists working at outposts of the British empire thought they were disadvantaged, and this was one of many reasons why they returned to Britain when they had an opportunity to do so, to the benefit of science "at home" and the detriment of science in the colonies. The comments by Stark in Germany and Rutherford in Canada quoted earlier illustrate the problem that distance posed to rapid publication, and the following observations from Rutherford and Bragg are even more specific. Rutherford, writing about his anticipated move to Manchester, noted: "The Laboratory is a very good one and also the salary, so I expect to have a good time there. I shall be glad too to be nearer the scientific centre, as I always feel America as well as Canada is on the periphery of the circle." Bragg reported:

> I sent my results home for publication in the Philosophical Magazine. . . . I remember very well the suspense of waiting to hear whether my work was going to be approved in Europe; it took three months to get a reply to a letter. At the time when I thought I might hear something I was staying at Aldinga, a little township in South Australia; and each afternoon I used to wait for the sight of the mail coach as it appeared against the sky in a gap in the hill, and then go down to the postoffice to see if anything had arrived for me. At last there was a letter from Professor (now Lord) Rutherford, and I was very happy.[84]

It will be clear from the content of the present essay that Bragg was not, in fact, greatly disadvantaged by his distance from London, but it is also clear that he himself regarded it

[82] W. H. Bragg, "Inaugural Address: The Lessons of Radio-activity," in *Report of the Twelfth Meeting of the Australasian Association for the Advancement of Science, Brisbane, 1909,* ed. John Shirley (Brisbane: AAAS, 1910), pp. 1–30, on pp. 5–6.

[83] Geoffrey Blainey, *The Tyranny of Distance: How Distance Shaped Australia's History* (Melbourne: Sun, 1966); and Chambers, "Does Distance Tyrannize Science?" (cit. n. 4). See also, e.g., the works cited in note 4, above.

[84] Rutherford to Otto Hahn, 6 Jan. 1907, Rutherford Correspondence, H10; and W. H. Bragg, autobiographical notes, unpublished and untitled, part 2, n.d., Bragg Papers, 14F/1, p. 3.

as a major potential problem and that one of his several reasons for deciding to leave Adelaide was the opportunity to get much closer to Europe, to Britain, to London. The perception that distance was a problem and the behaviors it led to were very real indeed.

How Bragg was able to overcome this perceived difficulty is instructive. At the end of an experiment, he would present a draft paper to a meeting of the Royal Society of South Australia, which then printed it promptly in its *Transactions.* A copy, suitably amended if necessary, was sent on to Soddy, who would review it and send it on to the editor of the chosen journal. Letters and copies would also be sent to Bragg's Australian colleagues and to Rutherford and others overseas. Any changes resulting from this wide reading would then be communicated by Bragg to Soddy, who would incorporate them into the paper at the proof stage, without the paper having to undergo the fourteen-week sea-mail trip to Australia and back. The consequent reduction in publication time was a great comfort to Bragg, who was constantly worried that others might anticipate his work.

The question of isolation is manifestly related to distance, but it can also be considered separately; it is possible to be isolated even when one is close to any center. Bragg came to Adelaide far better prepared than he later admitted for the work that made him widely known. He was, however, very inexperienced when he arrived. He was also immature, having been deprived of a normal family-centered childhood and having spent all his secondary and tertiary education in male institutions: at school "I was a very quiet, almost unsociable boy, who did not mix well," while as an undergraduate "I was very much shut in on myself, unventuresome, shy and ignorant."[85] It was largely the Todd family, and especially the daughter he fell in love with and married, who gently and sympathetically gave him the personal confidence and security that became the bedrock of his emerging success.

Bragg was also fortunate during his slow maturation as a scientific researcher. Rod Home has written of the substantial support Bragg received from his academic colleagues during his early years in Australia.[86] Threlfall mentored him, and others supported and encouraged him. And when he outgrew their expertise, though not their support, he had the great good fortune to have met both Rutherford and Soddy, two of the founding fathers of the science of radioactivity, who had passed through Adelaide and were willing to provide the subject accreditation and procedural guidance that he needed. They were advocates of a very high order.

Of course, Bragg's own personal characteristics were of central importance to his success. Encouraged by the Adelaide community's fascination with X-rays and radio and its disquiet at the lack of local research, by the requirements of the 1851 Great Exhibition scholarship scheme, and by his crucial period of leave in Britain in 1898, Bragg embarked on his ambitious program from a very low base, with few facilities and no funds for research. A private benefactor helped financially, and his project could get under way with simple apparatus. From that point, his own skill, maturity, persistence, and intellectual capabilities triumphed, but only after a period of intense activity "out of hours."

In fact, Bragg's isolation was in one sense real, not merely perceived. Home has referred to "the isolation of the élite." Once at the forefront of his field, Bragg needed to talk personally to other leading figures, to hear their news and views; he needed to attend

[85] Bragg, autobiographical notes (cit. n. 8), pp. 14, 21.

[86] Home, "Problem of Intellectual Isolation in Scientific Life" (cit. n. 6). See also R. W. Home, "Volta's English Connection," in *Nuova Voltiana: Studies on Volta and His Times,* ed. Fabio Bevilacqua and Lucio Fregonese (Pavia: Univ. Pavia, 2000), Vol. 1, pp. 115–132.

conferences and meetings so as to be in touch with the latest developments before the papers reporting them appeared; he needed to be included. "I shall have constant opportunities in England of meeting men who are engaged on the same lines of investigation as myself," he wrote to the Adelaide University Council regarding the offer from Leeds. "I would be glad to go to England for many reasons; you must not mind me saying that one of these is to be near to people like yourself," he wrote to Rutherford.[87]

The benefits of this closeness became apparent soon after Bragg arrived in England. "I had a day with Rutherford in Manchester," he told Rogers, "and you can imagine it was very interesting! He showed me 250 mmg of Ra in solution in a pump. They draw off the emanation as wanted. . . . He does not like Pye's cells. . . . One of his research students, Geiger, says he knows where to get good cells in Germany, and is writing both for Rutherford and for me."[88] There was nothing chimerical about isolation.

Lewis Pyenson has written extensively and influentially about the history of European colonial science, with major studies of the exact sciences (including physics) in the imperial practice of Germany, Holland, and France. As a result, he developed a descriptive model, based on three orthogonal axes of imperial strategies, and he has suggested that Britain's strategy was equally strong in promoting research and in fostering commercial, technological activities.[89] He has also contended that "the British government sought to promote garrisons of imperial learning at colonial universities." I have disputed the first suggestion in relation to physics in Australia, and the histories of Australia's oldest universities do not support the latter proposition. For the case of Australia, I tend to agree more with Paolo Palladino and Michael Worboys, who concluded that "there is no evidence that physics or astronomy played any significant role in British imperial policy or colonial rule," although this may be too blunt a statement.[90]

The volume of *Osiris* published in 2000 was devoted to the question of science, empire, and colonialism. In his introduction Roy MacLeod observed: "Looking back, the diffusionist perspective, the center-periphery model, and even the 'strong program' of imperial science have proved insufficiently accommodating to the sources and discoveries of recent research. . . . Today, locality and place are now being constituted as legitimate 'centers' for historical reconstruction. But . . . for most of us the metropolis remains, after all, where the action is." The present case seems ideally suited to such an analysis and, in particular, to that offered by Chambers and Gillespie in the same collection:

> Within the "big picture" Europe was progressively "decentered" and, in a very real sense, science was also decentered; . . . modern science is better understood, both metaphorically and

[87] Home, "Problem of Intellectual Isolation in Scientific Life," p. 28; Bragg to University Council, 11 Apr. 1908, Univ. Adelaide Archives, S200, docket 341/1908; and Bragg to Rutherford, 22 Jan. 1908, Rutherford Correspondence, B371.

[88] Bragg to A. L. Rogers, 8 Apr. 1909, Bragg papers in the care of Lady Adrian, Cambridge.

[89] Lewis Pyenson, "Pure Learning and Political Economy: Science and European Expansion in the Age of Imperialism," in *New Trends in the History of Science,* ed. R. P. W. Visser, H. J. M. Bos, L. C. Palm, and H. A. M. Snelders (Amsterdam: Rodopi, 1989), pp. 209–278, esp. pp. 274–278. See also Pyenson and Sheets-Pyenson, *Servants of Nature* (cit. n. 3), and the references therein.

[90] Pyenson, "Incomplete Transition of a European Image" (cit. n. 76), p. 112; and John Jenkin, "British Influence on Australian Physics," *Berichte zur Wissenschaftsgeschichte,* 1990, *13:*93–100. I remain unconvinced by Pyenson's reply: Lewis Pyenson, "Typologie des strategies d'expansion en sciences exactes," in *Science and Empires,* ed. Petitjean *et al.* (cit. n. 3), pp. 211–217, on p. 215. On the Australian universities see Clifford Turney, Ursula Bygott, and Peter Chippendale, eds., *Australia First: A History of the University of Sydney,* Vol. 1: *1850–1939* (Sydney: Hale & Iremonger, 1991); Geoffrey Blainey, *A Centenary History of the University of Melbourne* (Melbourne: Melbourne Univ. Press, 1957); and W. G. K. Duncan and R. A. Leonard, *The University of Adelaide, 1874–1974* (Adelaide: Rigby, 1973). For the conclusion of Palladino and Worboys see Paolo Palladino and Michael Worboys, "Science and Imperialism," *Isis,* 1993, *84:*91–102, on p. 101.

> actually, as a polycentric communications network. . . . The local and the global are a dialectic pair and must remain so in our histories. . . . As the process of assemblage develops in a locality, vital connections and linkages are made both locally and internationally . . . with major and minor centers and close and distant peripheries defined not geographically but in terms of scientific authority and social power.[91]

In Australasia, Bragg's influence was profound but not immediately ongoing in all cases. The research ethic he helped create survived, although his Adelaide research school died on his departure and physics research was not strong there until after World War II. The reforms in education Bragg inspired in South Australia were pivotal and long lasting. He lifted the horizon, the enthusiasm, and the confidence of local scientists, who were proud to say that they had known him.[92] The local newspapers devoted much space to his departure.

In terms of scientific practice, Bragg in Adelaide clearly became a center and not a periphery in the evolving science of radioactivity, as were Rutherford in Montreal and Soddy in Glasgow. None of them was inferior or subservient to researchers in London (or Paris or Berlin), and all three would later win Nobel Prizes. Having returned to Britain, they looked back with pride and affection to their early, independent research achievements. For a time, Adelaide, Montreal, and Glasgow were centers of the global radioactive world.

However, these centers or localities were also connected into a global scientific network of communication, trade in scientific equipment, publication, accreditation, and reward; and for this group there was a "center of calculation": Britain, London. As MacLeod noted, while the local environment may have shaped the enterprise of the "transplanted Britons," they bore "mental knapsacks packed thousands of miles away." Bragg carried his English background, education, and ambition with him to Australia, he published primarily in British journals, and, when the rewards came, they were British: FRS, a chair at Leeds, and the best English education for his sons. Thus, Home concluded, "the Royal Society functioned as an organ of empire, the central element of an Empire-wide system of scientific recognition and reward that for the best part of two centuries tied colonial scientists firmly to the values of the metropolis."[93]

In summary, "less overtly than the Spanish and Portuguese, less systematically than the French, less methodically than the Germans, the British had nonetheless made science overseas an expression of British values."[94] This, too, Bragg personified.

[91] Roy MacLeod, "Introduction," in *Nature and Empire,* ed. MacLeod (cit. n. 3), pp. 1–13, on pp. 5, 10; and Chambers and Gillespie, "Locality in the History of Science" (cit. n. 4), pp. 223, 229, 231.

[92] C. C. Farr to Rutherford, incomplete letter [1908], Rutherford Correspondence, F15: "Bragg . . . is one of the finest fellows I know. He is as unassuming as he is brilliant . . . he more than any other man has helped to shift the centre of gravity of scientific research a little to the South."

[93] Latour, *Science in Action* (cit. n. 3), Ch. 6 ("center of calculation"); MacLeod, "Passages in Imperial Science" (cit. n. 5), p. 124; and Home, "Royal Society and the Empire," Pt. 2 (cit. n. 74), p. 66.

[94] MacLeod, "Passages in Imperial Science," p. 118.