V. William Henry Bragg

"Research is an act of faith in the immensity of things... . It is not a religion, but it is the act of one. It is our duty and our gain to explore... . It is the task of the researcher to describe what he observes so faithfully that his hearers also see the vision."[92]

William Henry Bragg was born near Wigton, West Cumberland, England on July 2nd, 1862. He was the eldest son of blond, hazel-eyed, gentle Robert John Bragg (1830–1885). When Robert was only ten years old, his father, in business at Workington, was lost at sea in the North Channel; rather young, Robert became an apprentice seaman. In 1852 it took the *Nereides* four months to reach Calcutta; on the return trip, it shipwrecked, and Robert Bragg, its chief mate, was fortunate to be among the five survivors. When he retired from the sea he bought a farm, Stoneraise Place, by Carlisle, near Wigton, in the quiet green meadowland that extends from the Lake hills to the Solway Firth. Six years later (1861), he married Mary Wood (1833–1869), the stately, husky-voiced daughter of the vicar of Westward. Mary Bragg augmented her contribution to the family by selling her butter and eggs at the local covered market. William Henry was their first child; they also had Jack (1864–1885) and James (1866–1938).[92]

As a child, William Henry enjoyed the close attention of his elderly maternal grandparents: many years later he still remembered his cherry-cheeked, petite grandmother, Ruth (Hayton) Wood (1804–?), wearing a white cap and still retaining signs of her former beauty. He remembered also his dedicated grandfather, the Reverend Robert Wood (1796–1883), who used to walk five miles from his vicarage at Church Hill for a second service on Sundays at Rosley.[92]

Young William Henry was taught to read by his mother at home and started school early. He walked through the meadow, crossed the Wisa beck, and climbed a hill where the Westward school, church, and graveyard were. From the top of that hill, he could see the Firth. His mother, who had cranked the barrel organ at her father's church, was said to have a "good mathematical head": it must have inspired her son's interest.[80] In 1869, at age 36, she died unexpectedly. William Henry's care was then entrusted to his uncle, William Bragg Bragg (1828–1898), a widower established as a pharmacist (chemist) at Market Harborough (Leicestershire); he placed the seven-year-old boy in grammar school. William Henry's paternal grandmother, Lucy (Brown) Bragg (1798–1875), took care of his religious indoctrination while his other uncle, James Brown Bragg (1838–1898 +), a grocer, provided distractions and pony rides. Uncle William's sister, Mary McCleary (Bragg) Addison (1832–1895), and her two children, Fanny and Willie Addison, were also in his household. William Henry respected Uncle William, enjoyed the companionship of Uncle James and of Aunt Mary; he got along well with Cousin Fanny but not so with Cousin Willie. He spent his vacations in Cumberland with his father and brothers and shared in the harvest chores (he injured a finger in a turnip chopping machine).

William Henry was a quiet child, content if left alone with books; in 1873 he passed the Oxford Junior locala at Leicester, failing in the subjects of Church History and Greek. Uncle William was a stern taskmaster, not very well liked even by members of his own family; in 1875 he had registered his nephew at Shrewsbury, a "public" (preparatory) boarding school. At that point, Robert Bragg, perhaps fearing to lose his son, reclaimed him and insisted that he be registered at King William's College on the Isle of Man. Uncle William continued to exercise a dominant influence on him; their years together fostered a genuine lasting affection between them. After the first year in college, during which the bullying was rather unpleasant, William Henry was happy enough in the school.[14] The youngster proved to be a good student, favoring mathematics and holding a high place in his class. He showed no taste for the common bucolic distractions but played hockey and in general was fond of ball games. In his senior year, a storm of religious emotionalism and fright of eternal damnation swept through the school: it all but destroyed his own faith. ("*For*

Fig. V-1. Professor William H. Bragg, University of Adelaide (1890).

many years, the Bible was a repelling book which I shrank from reading.")[92]

William Henry Bragg was awarded an Exhibition Scholarship to Trinity College at Cambridge which he exercised in 1881.* One year later, he was able to exchange it for a Senior Scholarship, conferring considerable standing in College, with rights to wear the strawberry and cream blazer, to sit in the scholar's pew, and to join the Trinity Tennis Club. "*I was in fact very much shut in on myself, unadventuresome, shy and ignorant*"—wrote Bragg later—"*and yet I enjoyed my life at Cambridge tremendously.*"[92] He now played tennis with, among others, young Professor Joseph John Thomson (1856–1940). In 1884 he took the mathematical tripos (final examinations) for a B.A. with honors and ranked Third Wrangler (he later won a first class in Part III). Among many others, he was congratulated by Alfred North Whitehead (1861–1947), the previous year's Fourth Wrangler, who was to achieve fame at Harvard as coauthor of *Principia Mathematica* and as one of the founders of mathematical logic. William Henry's father, who had retired to live in Ramsey on the Isle of Man and had renewed his interest in boats, died suddenly in 1885. His younger brother, Jack, a good student who suffered from painful gastric difficulties, also died suddenly that year.

Walking along King's Parade one morning (1885) to attend a lecture at The Cavendish, Bragg met the lecturer himself, Professor Thomson, who casually inquired if one of his classmates, the Senior Wrangler, was applying for the professorship of physics and mathematics in Adelaide. Bragg had seen the notices of the academic offer in Australia, but it was only during this conversation that he realized he himself was eligible. After the lecture, he telegraphed his application on the last day of entry; a few days later, he was among the three who were interviewed. A visiting dignitary from Australia, Sir Charles Todd (1826–1910), advised the decision in his favor (he was to become his father-in-law). Notified of his appointment, Bragg made haste to bring the telegram to his uncle at Market Harborough: he was surprised to see his old mentor break down under emotion. After three weeks of hasty preparations and farewells, 24-year-old Professor Bragg was off on the *Rome* from Tilbury toward his great adventure. Thanks to the Suez canal, it took only six weeks to reach Glenelg; Bragg used a great deal of this time to study physics. "*I had been lucky enough in England*"—wrote Bragg—"*but going to Australia was like sunshine and fresh invigorating air.*" (Fig. V-1.)

In 1886 Adelaide University, just over a decade old, was vigorous but largely undeveloped. The physics department was small, lacking in equipment: it was just as well, for the new professor, versed in mathematics, had a lot of physics to learn. To produce tools for his laboratory demonstrations, Bragg apprenticed himself to a firm of instrument makers. An unimpressive lecturer at first he gradually acquired the art. Having had no laboratory training, he carried on experiments only for demonstrations. Teaching and administration became his strength and he saw the challenge of educational reform. Having no contact with research, he limited himself to reading the exciting developments harvested by others and published abroad. His autodidactic efforts led him gradually to ideas of his own that he was careful to present in letters to his friendly colleagues: thus, he substituted for the lack of immediate academic stimulus.

On the first day after his arrival in Adelaide, Bragg was a guest for supper at the Observatory on West Terrace and met the Todd family. Sent by the Greenwich Observatory to be government astronomer at Adelaide, Sir Charles Todd had installed the new electric telegraph in Australia; he was also the Postmaster General and was greatly esteemed in the colony. Bragg became a frequent visitor of the Observatory and a friend of the numerous Todds. Gwen Todd was only 16 when he first met her, but one year later, he was sending her flowers; in 1888 while vacationing in Tasmania and with the consent of her parents, they were formally engaged, and on June 1st, 1889 they were married.* They had two sons, William Lawrence (1890–1970), Robert Charles (1891–1915), and a daughter, Gwendolen Mary (1907–). A most congenial wife, Mrs. Bragg was a gracious, friendly, kindhearted, compassionate, and rather candid woman, free from affectation.

In 1891 Bragg wrote his first paper on an "elastic" theory to treat electrostatic theorems. He sent the paper to a prominent professor at Liverpool who commented that it was an instructive attempt, useful for students, and forwarded it to *The Electrician*. In the next decade, he wrote only two other papers. However, he had already started his life-long career as a successful lecturer. Whether his subject was photography, light, optics, or heat, his lay listeners were fascinated by his beguiling style and charmed by the simplicity of his presentation. In one of his lectures, he explained the experiments that he and Sir Charles Todd had carried out in wireless telegraphy. On the evening of Wednesday, January 8th, 1896, local notables and general public scrambled for seats at University Hall to hear him and to witness a demonstration of Röntgen's recent discovery of "a new kind of rays." During the lecture, a radiograph of Bragg's own hand was taken, showing a defect of his left little finger. He subsequently set up the apparatus (Crooke's tube, coil, and battery) in the basement of the Physics Laboratory for the benefit of physicians.

After a trip to England with a passing view of the Pyramids in 1897, the Braggs built a house for themselves in East Terrace, Adelaide and called it Catherwood House, after the home of Uncle William Bragg in Leicestershire. Summer holidays were spent at Port Elliot or at St. Vincent Gulf, where William Lawrence made a fine collection of shells, some of them rare. Bragg was a very good tennis and golf player, winning trophies in both; he was also an enthusiastic bicycler and captain of a team of lacrosse ("*...without doubt the finest all-round player we have.*") With his wife, he tried his hand at painting landscapes with, at least, technical success.

In 1904 Bragg delivered the presidential address of the Section of Mathematics and Physics of the Australasian Association for the Advancement of Science in Dunedin, New Zealand. Bragg chose the subject of radioactivity for his presentation; he would be talking to Rutherford's friends and kindred in the land of his origin. For his own edification, he read extensively the published works on the subject. He was particularly interested in the papers of Marie and Pierre Curie, who had just received the Nobel Prize for their study of radioactivity. His attention was attracted to the various considerations in the interaction of radiations and matter, their absorption and scattering; gradually, his efforts turned to a highly critical review of the field, and he started to query the accepted hypotheses. He found unjustifiable the assumption that the absorption of alpha and beta rays was analogous to the exponential decrease in intensity of a wave passing through an absorbing medium. "*The exponential law*"—he said—"*is not applicable to this kind of radiation.*"[73] In addition he felt the analogy confused particle flux and energy flux; if it appeared to hold, it was only because of a superposition of factors. He pointed out that alpha radiations, of necessity, had to pass *through* the atoms they met in their journey; thus, he concluded, there must be a moment when the alpha particle and the atom crossed occupy the same space.

Within weeks of his return to Adelaide, Bragg, at age 42, began his first research work: thanks to a benefactor of the university, he obtained a small quantity of radium bromide and, assisted by R. D. Kleeman (1878–1932), started his experimental work. "*After that*"—said Bragg—"*research was part of my daily life.*" It had been assumed that alpha rays traveled the same distance, regardless of their origin; he was to make a rather thorough and ingenious analysis of this fact. He found that alpha particles emitted by his source fell into four groups with different *ranges* corresponding to various radioactive materials mixed in it (radium, radon, radium A, radium C). He followed the suggestion of visiting professor Frederick Soddy (1877–1956) of dissolving his radium bromide in water in order to separate it from impurities that were also radioactive. His first surprise was to find that the pure radium emitted the alpha particles with the shortest range. The experiments on secondary electrons expelled by gamma rays established that the velocity of beta rays depended not upon the *intensity* but on the *quality* of the gamma rays, increasing with the penetrating power of the latter.

In August 1904 Bragg sent a paper to the *Philosophical Magazine*,[74] and he asked Professor J. J. Thomson to put in a word for him with the editor. He was anxious to know what Rutherford thought of his work and wrote him a detailed account of his views: "*the whole matter may be explained by supposing that alpha rays are not liable to deflection as the beta rays are...both lose energy by spending it in ionization, but in the case of alpha rays, this is the only cause of their being absorbed.*" Pointing to the fact that on the one aspect of the law of absorption, he found himself in contradiction with Rutherford, he added: "*The rays are, of course, not waves of energy but particles. I know, of course, that this is rather contrary to your theories.*"[92] It took nearly four months for Rutherford's answer to come from Montreal ("My dear Bragge"); he

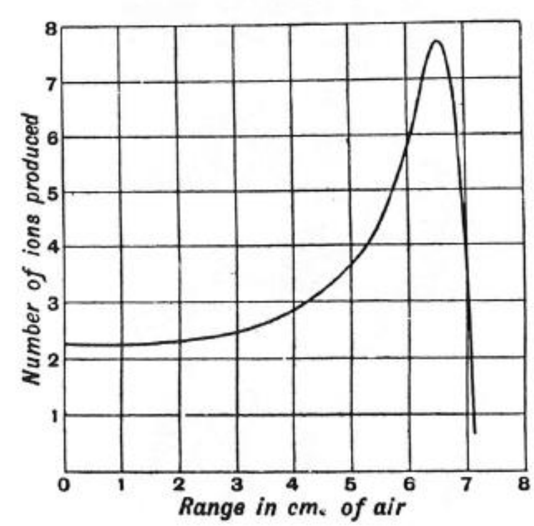

Fig. V-2. Ionization curve showing the "Bragg Peak."[77]

had done similar experiments and observations. He agreed that Bragg had the right explanation and urged him to publish his work in the *Philosophical Magazine* as Bragg had already intended. Thereafter, they corresponded abundantly and frequently. Bragg became adept at writing papers on his research works that were published at frequent intervals.

An important consequence of Bragg's work was his discovery of the fact that the specific ionization, or the number of ions, produced by alpha particles is greatest as they slow down towards the end of their path. The phenomenon is referred to as *Bragg peak*. (Fig. V-2.) It has acquired recent renewed importance because of the acceleration of monoenergetic charged particles, resulting in a narrow zone of high dose and high LET (linear energy transfer).

In the intensive studies hurriedly carried out by Röntgen in the weeks after his discovery, the apparent inability of the new rays to be reflected, refracted, or deflected was established: these findings set them apart from known electromagnetic radiations (light, ultraviolet). Röntgen suggested that x rays be abscribed to longitudinal rather than transverse vibrations in the ether. In 1897, Emil Weichert (1861–1928) in Königsberg[396] and George Gabriel Stokes (1819–1903) in Cambridge[382] independently suggested that roentgen rays should be considered as transverse electromagnetic waves. Cavendish's Professor J. J. Thomson accepted the idea of pulses and further suggested that roentgen rays should be considered as "tremors of tightly stretched Faraday tubes."[383]

Fig. V-3. Professor W. H. Bragg, University of Leeds (1910).

Charles Glover Barkla (1877–1944),† a native of Widnes, Lancashire, England, received his Master of Science degree in Liverpool; in 1899, as Rutherford and Bragg before him, he was awarded an Exhibition Scholarship to Trinity College, Cambridge.[207] Barkla did his first research work at Cavendish Laboratories measuring the velocity of transmission of electromagnetic waves along wires; he then began investigation of secondary radiations emitted by various substances placed in the path of roentgen rays. A gifted musician and a remarkable basso, he left Trinity for King's College (Cambridge) in order to join its famous choir. Later, he continued his work at Liverpool, where he received his D.Sc. and where he became lecturer and Oliver Lodge Fellow. In 1903 Barkla showed that the "absorbability" (average wave length) of secondary radiations emitted by gases was the same as that of the primary beam.[19] Moreover, Barkla emphasized, the scattering was proportional to the mass of the atom, giving further support to the view that the number of electrons in an atom was proportional to its atomic weight.[20] This led him to devise a test for the polarization of roentgen rays. By scattering roentgen rays first from one and then from a second block of carbon, Barkla succeeded where many had failed and produced elegant evidence that the rays could be polarized. He considered this to be a powerful argument in favor of the electromagnetic theory of radiations.[21]

In the spring of 1907, Bragg presented a paper to the Royal Society of South Australia heralding a reorientation of his interest.[75] The quick succession of his works within three years had rapidly established him as an original investigator throughout the world of physics. Earlier he had expressed doubts of the identity of gamma and roentgen rays; now assuming them to be of the same nature, he declared the ether pulse theory to be "overrated," incapable of accounting for the retained energy and momentum in spite of traveled distance. His main purpose was to present arguments supporting his view that radiations were of a *material* nature, specifically consisting of an electron and an alpha particle: *a neutral pair* ("*... an electron which has assumed a cloak of darkness in the form of suffcient positive electricity to neutralize its charge.*") Being electrically neutral, the pair would have high penetrating power and would not be deflected by magnetic fields. Thus, he anticipated by one year Rutherford's and Geiger's discovery of the doubly charged alpha particle.[208] Moreover, he drew the inference that the ionization produced by the passage of radiations through matter was not a result of direct action by the rays but consequence of the transformation of a neutral pair, leaving free a negative electron after removal of its neutralizing positive mate. Without being aware of Einstein's views, Bragg became the first and remained the foremost advocate of the quantal properties of the roentgen rays. In December 1907 Bragg wrote to Rutherford: "*I have got the decisive proof that gamma rays are not pulses but corpuscular.*"[92]

† See Biographical Notes on page 171

Bragg attempted to construe in his hypothesis all known facts on the roentgen rays, including Barkla's "*peculiar polarization effect.*" In October 1907 Barkla wrote a letter to the editor of *Nature*,[23] he emphasized that when roentgen rays hit a substance of low atomic weight, such as carbon, the intensity of secondary radiations was at a minimum in perpendicular direction to that of the primary beam and at a maximum in, or opposite to, that direction. Barkla took the "waist" in the distribution of scattered radiations as "strong confirmation" of the electromagnetic pulse theory. Bragg found evidence that secondary radiations possessed momentum in the direction of the primary, and he took this as evidence that they were "material."[384] It is possible that their differences were partially explained by the fact that Bragg experimented with radium and Barkla with low-voltage roentgen rays. A letter of rebuttal from Bragg[76] started a controversy, with variations on the same theme, that lasted until the editor of *Nature* decided to put an end to it three years later.[92] Bragg found the wave theory adequately suited to explain various factors (Kirchhoff's law, relation to temperature, etc.), but he felt that there was something missing that made it almost abortive: to him nothing else could so easily express the central idea of radiation as the neutral pair theory, "*even if it was deficient where the other succeeds.*"[92] The Bragg–Barkla controversy resulted in definite stress for both men. Bragg retreated from his original position while Barkla proved less capable of yielding; Bragg outclassed his inflexible opponent as a theorist, as an experimenter, and as a strategist in controversy.[208] The sustained feud may have sharpened their wits, for both men were to achieve subsequent distinction by unquestionable originality.[207]

In 1907 Bragg was elected Fellow of the Royal Society. Rutherford was moving to Manchester, and Bragg was offered the new Chair of Theoretical Physics at McGill University. Simultaneously, Bragg was also offered the vacant Chair of Physics at the University of Leeds. He was giving favorable consideration to the first when a disastrous fire crippled McGill University, and the tentative offer was withdrawn. He then accepted the invitation of Leeds to become the Cavendish Professor of Physics.

"*It would be a terrible wrench to move from here*"—said Bragg of leaving Adelaide—"*There was never a kinder lot of people nor a nicer little city.*" It must have been particularly difficult for the Braggs to leave Sir Charles Todd. They left in January 1909 with their three children, Willie (18), Bob (17), and Gwendy, just a toddler; the *S. S. Waratah*, going around Cape Town, reached Plymouth in March.* The Leeds people were nice, but Mrs. Bragg was appalled by the dirt and by the rows of poor smoky houses; Bragg was irked by the contrasting opulence of some and the squalor of many. At the University, he had to conform to a syllabus and fit into a hierarchy. The laboratories were vastly inadequate; the students stomped their feet impudently during lectures.[92] Eventually, the family found a pleasant home, Rosehurst, in the outskirts of Leeds and later, a delightful country cottage, Deerstones, in Wharfedale. Mrs. Bragg went back to painting and found use for her emerald green that had been little used in Australia. Bragg played old simple tunes to himself on his flute. (Fig. V-3.)

In Leeds Bragg was fortunately close to Rutherford; he visited the Manchester laboratories, met Hans Wilhelm Geiger (1882–1945), was impressed by the 250 mg of radium and the radon extraction plant. Rutherford, richly boisterous, and Bragg, gentle and quiet, enjoyed a mutual stimulation; during the Bragg–Barkla controversy, aggravated by the circumstances of Leeds, their friendship became a great comfort to Bragg. Rutherford wrote of his admiration for the Wilson cloud chamber and of the photographs of "the trail," the visible demonstration of things previously seen only in the imagination; he also complimented his older colleague for the "luminous" address he had made to the British Association for the Advancement of Science. Frequently bringing a note of humor into their interchange, Rutherford called attention to an issue of the *Philosophical Magazine* that was "highly radioactive" and to which both he and Bragg had contributed "materially"; another time he commented that Barkla did not appear philosophically endowed. Returning from the Solvay Conference in Brussels, Rutherford reported that continental physicists did not appear interested in trying to form a physical idea on the basis of Planck's theory. "*Where there are electrons in motion*"—wrote Bragg to Rutherford—"*there will necessarily be an accompaniment of quanta balancing them,*" and he went on for ten pages. After careful reading, Rutherford returned, as requested, the manuscript-letter of his friend. A paper on scattering by James Arnold Crowther (1883–1950) appeared[132]: Rutherford objected to the manner in which the author made his views fit those of J. J. Thomson. Bragg agreed that Crowther "unctuously" brought around a number of facts to fit the theory backed by a great name. He felt that Thomson as well as Barkla objected to the neutral pair theory because of their desire to connect roentgen rays with light. In the spring of 1912, the Rutherfords and the Braggs took a vacation and drove through southern France and the Pyrenees. The adventurous experience of the two couples was long remembered by them for its humor.

In the course of his experiments with secondary radiations, Bragg was led to the view that the ionizing effects are indirectly due to secondary electrons released by the primary beam: he was the first to insist on this fact.[86] In 1912 he wrote his first book, *Studies on Radioactivity*,[77] in which be brought together methods and results of investigations of interaction of radiations and matter.

As early as 1907, Barkla had attempted to determine the relative atomic weight of nickel through the dependence of properties of secondary radiation upon

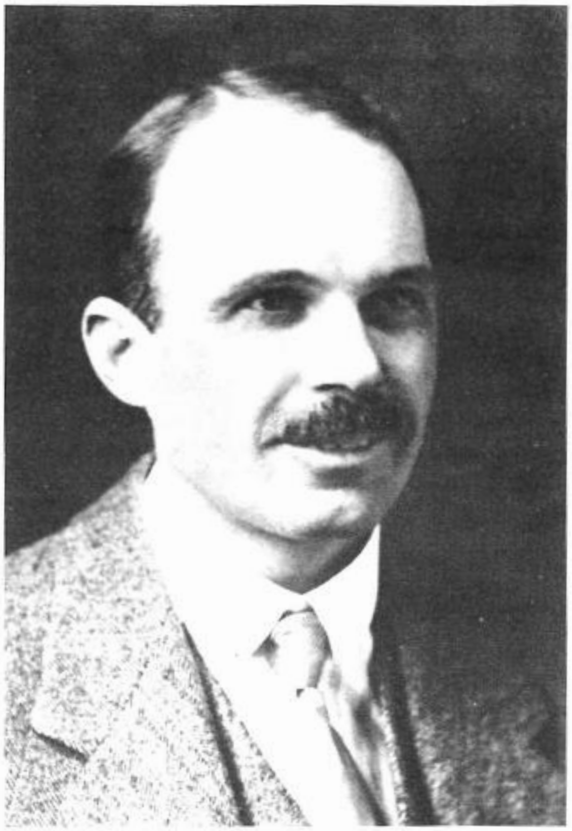

Fig. V-4. William Lawrence Bragg, author of the Bragg Law, Nobel Prize winner (1915). (Courtesy of the Niels Bohr Library.)

atomic weight,[22] he was beginning to fasten upon the hardness of the secondary ("fluorescent") radiations as *characteristic* of the element. In 1909 Barkla was appointed Wheatstone Professor of Physics at King's College in London. He and Charles A. Sadler (?–1920) discovered (1909) that two groups of remarkably homogeneous secondary radiations (eventually labeled *L* and *K*) were emitted from irradiated heavy elements, provided the elements were exposed to harder radiations than their own characteristic radiations. The demonstrable characteristic spectral lines caused this work to be recognized as of the utmost importance.[24] Barkla remained persistently inflexible towards quantum ideas.

In 1912 Max Theodor Felix von Laue (1879–1960),† studying the diffraction of light waves in ordinary and in crossed gratings, was led to ponder if shorter wavelength roentgen rays would give rise to interference in space lattices such as crystals. The distance between the regularly layered adjacent atoms in crystals had been estimated at ten-millionth of a millimeter: this distance was of the right order to produce interference phenomena with rays of the assumed wavelength of roentgen rays. Thus, von Laue suggested experiments that proved exceptionally successful and important. The experiments were carried out by Walter Friedrich (1883–1971) and Paul Knipping (1883–1935) in the Physics Laboratories of the University of Munich, of which Röntgen was director. Using copper sulphate crystals and a narrow beam of rays, a photographic plate showed a blackened dot where the direct beam struck and a number of irregularly distributed spots. Proper orientation of the crystal made the spots appear in geometric distribution: a manifest result of interference by the crystal. More importantly, the experiment proved that roentgen rays were of the same wave nature as light. Max von Laue received the 1914 Nobel Prize of Physics for this work that Poincaré is said to have considered of the greatest importance.

William Lawrence Bragg (1890–1970) was William Henry Bragg's eldest son; he was born in Adelaide, where he received a degree with high honors in mathematics before his departure with his family to continue his studies in England. He was a shy youngster who admitted to finding *things* easier than *people*.[92] At 19 he entered Trinity College, Cambridge and within a year earned a scholarship to study physics at Cavendish Laboratories. He wrote his parents of his encounter with a visiting Dane who "was awfully sound... and most interesting" and had a name "like Böhr or something that sounds like it." (Fig. V-4.)

In July–August 1912, while vacationing with friends in Yorkshire, the Braggs (father and son) read a reprint of von Laue's work and discussed its implications. William Lawrence suggested an "avenue" theory and set up an experiment to test it in his father's laboratory at Leeds; he had no results. Upon his return to Cavendish, William Lawrence restudied von Laue's results; working with mica and a photographic plate moving together, he aimed to find out if the rays shot down an avenue when it became parallel to the beam. The explanation of the spots offered by von Laue was somewhat elaborate; William Lawrence Bragg gave a simpler interpretation by considering the reflection of waves from parallel layers of atoms or diffracting points, each set of planes acting as a reflecting surface of radiations. The spots were explained as a result of diffraction by face-centered cubic lattice (October 1912), a clear demonstration of the wave character of the rays. From these observations, he derived an equation now known as the *Bragg Law*,[87] a fundamental law of physics:

$$\lambda n = 2d \sin \theta$$

in which d is the distance between parallel crystal planes and θ is the glancing angle (complement of the angle of incidence). Since the diffraction pattern depended on wavelength, the stage was set for the spectrometric analysis of the rays' wavelength through the angle of diffraction (Fig. V-5).

In deference to his father, William Lawrence did not make reference to roentgen rays and titled his first paper "Diffraction of Short Electromagnetic Waves by a Crystal." The senior Bragg was still vacillating when he made a simultaneous report of this work in November 1912.[79] William Lawrence proceeded to show that roentgen rays were specularly reflected over a range of

† See Biographical Notes on page 171.

angles by the cleavage planes of mica.[79,88] "*My boy has been getting beautiful x-ray reflections from mica sheets*"—wrote Bragg to Rutherford—"*just as simple as the reflections of light in a mirror.*"[92] Convinced, William Henry Bragg worked with his son through the Christmas holidays (1912), and they wrote their first joint paper,[82] showing the great possibilties of spectrometry. Together, they investigated the structure of various crystals, including a classical study of diamonds[83]: "It was like looking for gold"—said William Lawrence Bragg—"and finding nuggets everywhere." These were happy times for both, and their work set the foundation for a new science of the greatest importance: the radioscopic analysis of crystal structure. "*It was a glorious time when we worked far into every night with new worlds unfolding before us*... ." At first William Henry Bragg favored detecting the reflecting rays with an ionization chamber (Fig. V-6) but later adopted the photographic method and went on to design the *x-ray spectrometer* (Figs. V-7 and V-8). This useful instrument facilitated the study of crystallography and brought to fruition his son's ideas; it determined the absolute values of lattice spacings and brought the crystal analysis to a standard procedure. "Although the description of this instrument was published in our joint names"—wrote William Lawrence—"I had no share in its design." Their work became the basis of fundamental advances in both inorganic and organic chemistry.

No one accepted more readily the impact of von Laue's discovery on his own concept of the nature of roentgen rays than Bragg himself, although he never relinquished his aim to combine a wave–particle theory. "*If the experiment helps to prove x-rays and light to be of the same nature*"—wrote Bragg—"*then such a theory as that or neutral pair' is quite inadequate to bear the burden of explaining the facts of radiation.*" And he added: "*The problem then becomes...to find ...one theory which possesses the capacity of both.*[78] * With an optimist's enthusiasm, he became engulfed in the newly created activities. At the Solvay Conference in Brussels (1913), Bragg recorded full acknowledgement of his son as the originator of the idea. Participants at the conference sent William Lawrence a post

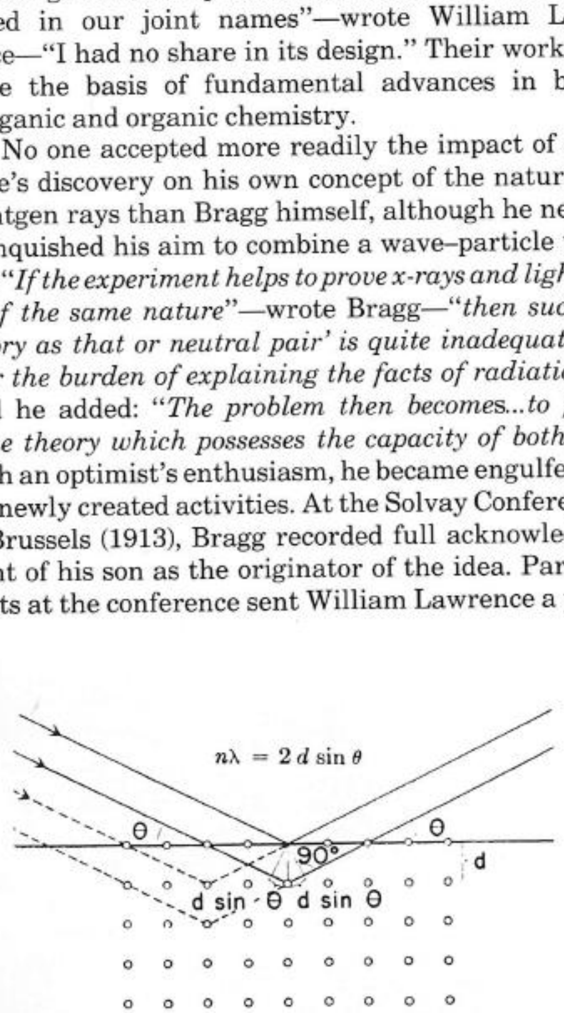

Fig. V-5. Reflection of roentgen rays from parallel atom planes in a crystal, Lawrence Bragg's equation permits finding of the wavelength by determination of the angle of reflection.

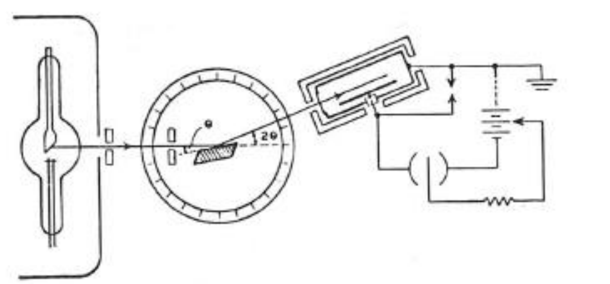

Fig. V-6. Early spectrometer using ionization chamber, designed by William Bragg.

card with congratulations for "advancing the course of natural science"; it was signed by Mme. Curie, Einstein, Rutherford, and Laue. However, the abstract of Bragg's report published abroad did not retain Bragg's reference to his son. Their joint success, as it often does, was to bring father and son an unanticipated measure of unhappiness and of lingering uneasiness in their relationship. The fact that William Lawrence Bragg made the earliest report[87] and that William Henry Bragg gave repeated credit to his son for his original idea did not compensate for the general tendency, at home and abroad, to give credit to the well known senior Bragg and to congratulate him for his luck in having such a bright collaborator in his son. Possibly, the son's modesty and filial deference combined with the father's ebullient enthusiasm for their joint achievements led most scientists to give undue credit to William Henry and unquestionable pain to William Lawrence; it lasted for years.[92] But for the fire at McGill, the Braggs, father and son, would have been separated, and the world might have been deprived of the fruits of their candid collaboration.

The senior Bragg retained his interest in other subjects and undertook, among others, studies of characteristic absorption of different radiations. Work done in collaboration with S. E. Peirce led to an equation, the *Bragg–Peirce Law*, according to which if one keeps the wavelength below the band or edge at which the absorption discontinuity takes place, the absorption coefficient per atom is proportional to the fourth power of the atomic number (z) and to the 2.5 power of the wavelength[85]:

$$\mu = K^1 Z^4 \lambda^{5/2}.$$

As World War I began, the two Bragg sons enlisted in a corps of colonial cavalry at the University. William Lawrence was sent to France to learn sound ranging of shells for the British forces. Early in the conflict, younger son Robert Charles Bragg, a Cambridge undergraduate, was killed in Gallipoli; Henry Gwynn-Jeffreys Moseley (1887–1915),† who had just done excellent research on atomic numbers, was also lost there.[327] In 1915 the Nobel Prize of Physics was awarded to William Henry and William Lawrence Bragg, for their research of the structure of crystal by means of roentgen rays; William Lawrence celebrated in the company of a village priest with whom he was billeted

* See Subject Notes on page 183.

† See Biographical Notes on page 171.

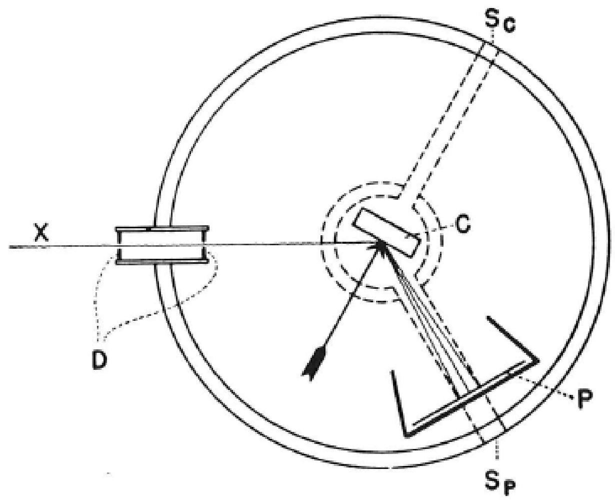

Fig. V-7. Schematic drawing of William Bragg's crystal x-ray spectrometer. *X* is the incident beam of rays. *D* is the diaphragm with appropriate slits. *C* is the reflecting crystal. *P* is the photographic plate. *Sc* is the scale giving the angle of the crystal. *Sp* is the scale giving the angle of the plate.

in France. The senior Bragg was offered a position as Quain Professor of Physics at University College in London; he liked the research facilities and liked being close to the Royal Society. He resigned his professorship and the Vice-Chancellorship at Leeds. However, he was not to stay long in London, for he was assigned as Director of the Admiralty Research on Hawkcraig Point near Rosyth at the Firth of Forth; the war had stopped spectrometric work. One dominant consideration at that time was the development of better hydrophones for the sound detection of submarines. Later, he was transferred to Parkeston Quay, Harwich, and the family settled at Dovercourt Bay. The richer facilities of the new station promoted better research. Bragg became enthusiastic about the detection and location of enemy submarines by the echoing of pulses, a method initiated by Paul Langevin (1872–1946) in France.[329] Originally called ASDICS (anti-submarine division) in England, to conceal its nature, the system is now called *sonar.*

In 1916 Bragg received the Rumford Medal, and in 1917 he was made a Commander of the Order of the British Empire. After the war, Bragg returned to University College in London; he gathered a group of young collaborators whose work he directed. In addition he resumed his own work at the spectrometer. He had worked with single crystals and now adopted the powder method; he satisfied his assumption that the benzene or naphthalene ring is an actual structure that preserves its general form from one compound to the other. This became the starting point of investigation in a series of organic compounds.

In 1919 Bragg was called to deliver the Christmas Lectures, initiated by Faraday at the Royal Institution. He delivered six lectures entitled "The World of Sound" in which he revealed his powers of observation, his persuasive teaching style, and his affection for young people. The attention his lectures drew had important consequences. In 1920 he was made an Honorary Fellow of Trinity College, and he and his wife became Sir William (K.B.E.) and Lady Bragg (Fig. V-9).

Upon the death of Sir James Dewar (1842–1923), the headship of the august Royal Institution of Great Britain* was offered to Bragg; the appointment implied additional titles. Having assured himself that he could retain his research grant of the Department of Scientific and Industrial Research (DSIR), he transferred with it some of his collaborators and accepted the position with a remarkably modest salary. Bragg used to say that he could not have taken this position except for his uncle William's legacy to him "to found a family."[92] In a variety of ways, he showed his pride in this honor that permitted him to follow in the footsteps of Faraday of whom he proved to be one of the most worthy successors. As Fullerian Professor of Chemistry and as Director of the Davy–Faraday Research Laboratories, adjacent to the Royal Institution, 20 Albemarle St., Picadilly, he attracted a number of capable researchers and started a series of original investigations on organic structures. Visitors to the Institution found themselves unexpectedly and genuinely welcomed by the Director himself.*

William Lawrence Bragg, who had been called to replace Rutherford in Manchester, married Alice G. J. Hopkinson (1899–?) in 1921 and settled down to pursuing the study of *inorganic* crystals. Meanwhile, the senior Bragg engaged in the study of *organic* structures; his investigations raised the moribund Davy–Faraday Laboratories to a world renowned center of research. In addition, he undertook the modernization of the facilities of the building and the equipment of the laboratories. The Braggs brought to the social life of the Institution renewed charm and elegance that was to rapidly win all hearts.[14] Special care was taken in the choosing of outstanding speakers for the Friday evening lectures, always accompanied by éclat. A favorite, frequently recurring lecturer was Rutherford: "he coughed and boomed, and his words exploded with enthusiasm as his lock of hair flapped and flopped down his forehead."[92] As one of his own tasks, Bragg

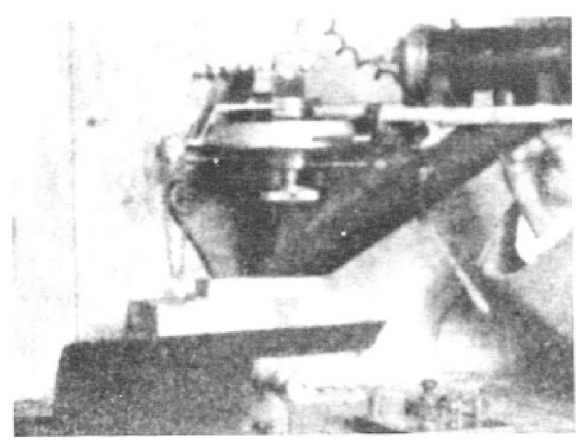

Fig. V-8. Bragg's spectrometer. (Courtesy of Mrs. Alban Caroe.)

* See Subject Notes on page 183.

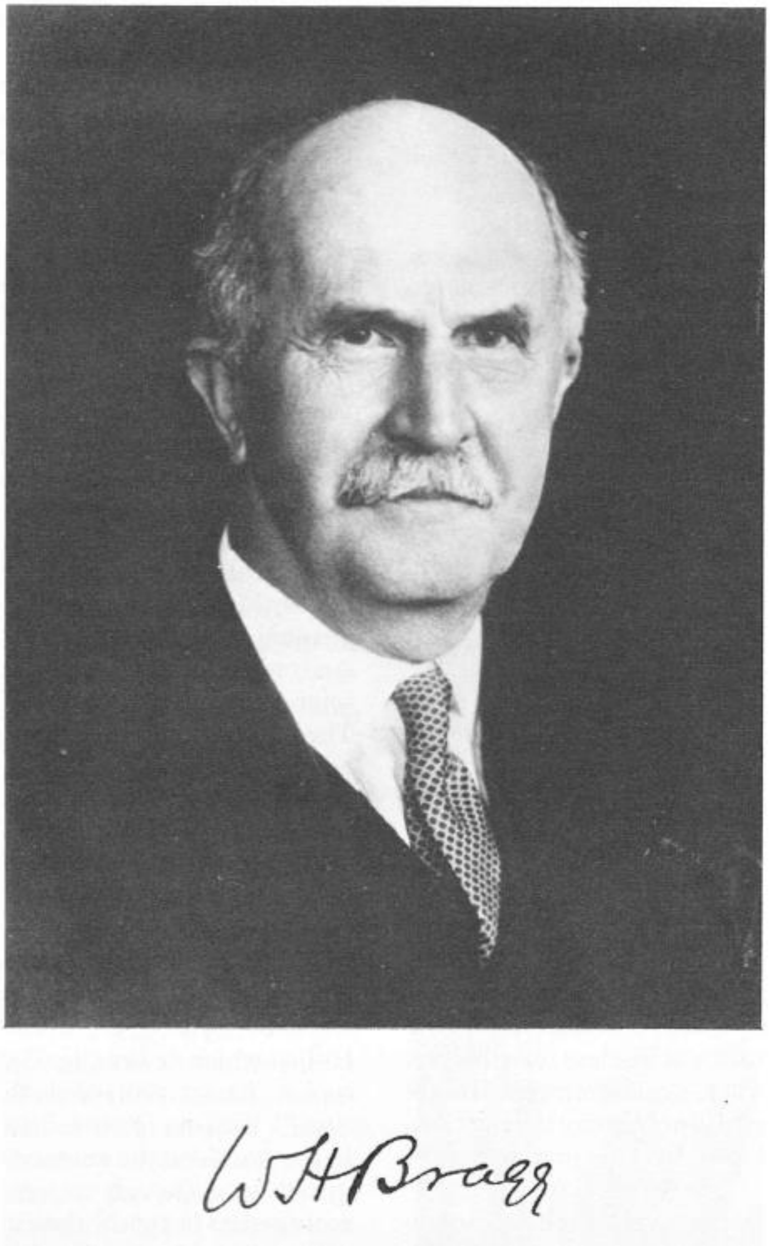

Fig. V-9. Sir William H. Bragg, O. M., Nobel Prize winner (1915). Signature.

Fig. V-10. Sir William Bragg, O.M., Director of the Royal Institution. Drawing by Sir William Rothenstein (1934).

chose to prepare and to deliver several courses of Christmas Lectures; one of these series was entitled "*Concerning the Nature of Things.*" He thoroughly enjoyed and delighted his young audiences, for whom the lectures were intended, with a variety of subjects: Sound, Light, Trades, Science, Craftsmanship. His apparently effortless delivery did not betray the concern, the care and the skill that went into the preparation of his lectures (Fig. V-10).

With their living quarters "over the shop," an important part of the Bragg's family life was their old, romantic country cottage at Chiddingfold, Surrey, within reach of London; there they retired for relaxation, and they entertained his collaborators as part of the family. Bragg could retire to the "apple house" if he cared to work or could play billiards at his neighbor's.

In December 1927 two gas explosions on Albemarle Street caused damage to the Royal Institution; with Lady Bragg seriously ill, the family took temporary abode in a furnished house in Chelsea in order to allow for rebuilding. To face the expense of reconstruction, Bragg raised money by selling the Dorchester Papers, the correspondence of American headquarters staff, including letters by Washington during the War of Independence.[92] In 1929 after a period of considerable suffering, Lady Bragg died, and their daughter remained Bragg's closest companion. Gwendolen Bragg, an accomplished artist, contributed some of the illustrations for her father's publications. Together, they traveled to America. He spoke at the Franklin Institute in Philadelphia and at the Massachusetts Institute of Technology in Boston. To an audience of 400 physicists and chemists at Cornell University, he read fragments of the diary of Michael Faraday; he attended a luncheon of 200 at which he received Honorary Membership in the New York Meteorological Society. He also lectured in Toronto, Rio de Janeiro, and Buenos Aires. "We had grand times together," wrote Gwendolen.

In 1929 Bragg delivered the Huxley Lecture:"*On the Crystal Structure of Organic Substance in its Relation to Medicine*"[65]; he spoke of the range of structures found in the living body and of the roentgen rays as means of finding the accurate geometry of their long chain compounds. "Bragg saw, and saw more clearly with the passing of years"—said Astbury—"that the crowning glory of structure analysis would one day be in the realms of biology."[18] In 1930 Bragg received the Copley Medal of the Royal Society, and in 1931 he was granted the Order of Merit. "He had become"—wrote Andrade—"not only one of the great figures of English science but also something of a national figure."[18] Through all these distinctions, he retained a modest and unassuming manner. In 1932 Gwendolen Bragg married Alban D. R. Caroe (1904–); after 18 months, the newlyweds moved in to live at the Royal Institution, enlivening it with the sounds of children: Bragg loved his grandchildren and was said to be a splendid grandfather (Fig. V-11).

In 1931 Bragg worked intensely on the Faraday Centenary. Besides the profusion of exhibits at Albert Hall, there was a Commemorative meeting at Queen's Hall at which de Broglie, Marconi, and Elihu Thomson spoke; Bragg delivered the Commemorative Oration.[80] Writing for the *British Journal of Radiology*, Bragg heralded the entrance of roentgen rays as a tool in industry; though no eye could see it, he said, the roentgen rays reveal the curious spiral arrangement of the atoms of oxygen and silicon in the quartz crystal with 50 million turns to the inch.[66]

Attention has been called to Bragg's exceptional ability to take up a subject, adding something new to it and then, just as casually, laying it down again. An example of this was his interest in smectic crystals; in a discussion at the Faraday Society (1933), he made an elegant demonstration and explanation of their optic phenomena in terms of the cyclides of Dupin.[18] "Bragg showed that the static arrangement of a number of equidistant parallel layers without rigidity was a set of surfaces formed in successive layers around an ellipse, having as lines of discontinuity the ellipse itself and a hyperbola in a plane perpendicular to it, each plane passing through the focus of the other."[14] In short, he explained the phenomenon in terms of the cyclides of Charles Dupin (1784–1837), French mathematician and engineer famous for his theories of curved surfaces. He never seems to have been interested again in liquid crystals.

In 1935 Bragg delivered the 15th Mackenzie-Davidson Lecture,[67] the British Institute of Radiology's memorial in honor of the pioneer, Sir James Mackenzie-Davidson (1856–1919). He showed that the radiologic investigation of organic crystals is best displayed in the form of contour maps that show the distribution of electrons in the crystal, giving the organic chemist a remarkable insight and permitting him to see the individual atoms as so many electron groups, their relative positions and distance. That year he made a series of six lectures over the British radio network (BBC) on the subject of light, color, and waves. Thus, his articulate voice became familiar to thousands.

In 1935 Bragg was elected President of the Royal Society; his respect for tradition and his historical sense commended him to the older Fellows; his kindness and easy access reassured the younger ones.[68,69] "His fine presence, his dignity tempered with geniality, his wide knowledge and his ready sense of the right word made him a complete figure in the Chair."[14] As World War II approached, he was to be called upon for his scientific leadership and his respected ability to express the scientist's point of view to the general public. His voice was reassuring.*

Following the Munich crisis (August 1938), Bragg made a broadcast speech to his nation on international reconcilement and on the need for it to be fought *with all the devotion that a war would require*." Although he coined the phrase "moral rearmament," he was not a follower of the movement that adopted that name. Advances were made to the Royal Society by the Kaiser Wilhelm Gessellschaft for an exchange of visitors.[69] Bragg took them as a gesture of friendliness and accepted carrying on the exchange in the belief that it would promote understanding: his decision was not popular in a scientific community that included numerous German refugees. In January 1939, with 17 other British figures, he subscribed a proclamation in the German language calling on men of good will to cooperate towards the prevention of war.

In April 1939 Bragg delivered the Pilgrim Trust Lecture before the National Academy of Sciences in Washington, D.C. By then, the wheels were in surreptitious motion to achieve an atomic chain reaction. He chose to talk on the 300 years of accumulated history in the archives of the Royal Society[70] and used the occasion to emphasize his firm conviction that "*the spirit in which knowledge is sought and the manner in which it is used are more important than the knowledge itself.*"

The war brought Sir William new obligations. Pressured by the Royal Society, under Bragg's presidency, the British government set up a Scientific Advisory Committee to the War Cabinet; Bragg was one of its members. A carefully compiled list of some eight thousand scientists was made available to the Chief of Staff; within a short time, it proved greatly valuable. In addition Bragg became chairman of the Committee on Food Policy. At age 78, he wrote a remarkable and comprehensive article published by *The Times* on the subject of the nation's food. He was also a member of the Advisory Council of the Department of Scientific and Industrial Research. "*If we could and would reject the universal aid which science is giving us, our war effort would collapse.*" Everywhere he went he brought his courteous and optimistic attitude.

In 1941 William Lawrence Bragg received the personal recognition that he so much deserved as he was made Knight Bachelor and became Sir Lawrence (Fig. V-4). Sir William was even happier than his son. "*Willie is knighted! Isn't that fine?*"—wrote Bragg—"*He will have to be Sir Lawrence: we can't have confusion worse than ever.*" He hoped that the honor would contribute towards alleviating the lingering uneasiness between them. (Fig. V-12.)

Fig. V-11. Grandfather Bragg and grandchildren at Watland. (Courtesy of Mrs. Alban Caroe.)

* See Subject Notes on page 183.

Fig. V-12. Sir Lawrence Bragg, Companion of Honor, in retirement (1968).

Bragg's early experience with literal interpretation of the Bible ("*Literal only means what the reader thinks that the writer means*") and his drastic rejection of it allowed for gradual return of his religious yearning. In Adelaide he embraced the churchgoing habits of his wife's family and became a churchwarden ("*We trust that this life is a preparation, not a final probation*").[92] In Leeds he endured his vicar's lack of understanding of the scientist's viewpoint. In London he attended the Early Service and avoided the interminable sermons. "*One man's creed*"—said Bragg—"*is another man's hypothesis... . The scientist becomes chary of prophecy and assertion, having found that his hypothesis can only be provisional.*"[71] At Wells, in a Diocesean Conference, he was disheartened by the theologian's attitude towards science.[92] In Washington, in answer to a reporter, Bragg said: "*Science is merely knowledge; it has no morality... . To the question of whether Eve should have eaten the apple of knowledge...the scientist can only answer yes.*

Great sayings speak to every man in the language that he understands, said Bragg. Love thy God...love thy neighbor: "*To the student of science*"—he said—"*the words mean that he is to put his whole heart into his work, believing that in some way he cannot fully comprehend, it is all worthwhile, that every straining to understand his surroundings is right and good...*"[64] In Newcastle-upon-Tyne (March 1941), he argued that scientists must draw temporary conclusions to find guidance in their effort of discovery; therefore, they make hypotheses that are always tentative. Hypothesis—Bragg held—is the essence of science and faith alike. "*Conviction of the truth of any faith*"—said he—"*is to be gained by practice... . Every man...has ever in front of him the hope that he will by doing his service play his part in binding the community together.*"[71]

A scientific researcher is by nature a doubter, geared to suspicions of his own beliefs and not consciously inclined to accept dogma. *Faith,* on the other hand, is the belief in what is not demonstrable in the evidence of things not seen, the substance of things hoped for. *Hope,* however, may be the anticipation of one's wishes, the expectation of the impossible. *Charity,* as Bragg pointed out, offers the greatest opportunity to seek the truth of one's faith.[71]

Few scientists have done as much as Bragg to develop a healthy partnership of science and industry. For this purpose, he repeatedly described the progress brought forth as a consequence of scientific research.[81] "*The mind of a nation*"—said Bragg—"*is so expressed because its craftsmanship, in its widest sense, represents its effort to live.*"[64] He maintained that the state of a nation's craftsmanship was an index to its health and that to hinder the growth of science was to prevent the growth of craftsmanship. "*No clear line can be drawn*"—he added—"*between pure science and applied science.*"[64]

Bragg's last paper, published posthumously, dealt with the extrareflections or diffuse spots of sylvine[72]; the subject aroused his perennial enthusiasm. He suffered from arteriosclerosis and could only walk short distances at a time. On March 12, 1942, after two days in bed, he expired. Seldom has the death of a scientist brought such a wide sense of personal loss to members of the scientific community everywhere and to the public at large.

William Lawrence Bragg possessed or developed in himself many of the same qualities that characterized his father: he was a remarkable and unselfishly dedicated teacher, an ingenious experimenter and a lecturer most capable of disrobing facts of their camouflaging vestments. He was also greatly admired by his students and very popular with lay audiences. In 1937–38 he left Manchester to become director of the National Physics Laboratory; then he went on to succeed Rutherford again, this time as Cavendish Professor of Experimental Physics at Cambridge. In 1954 he was appointed director of the Royal Institution, which had been revived by his father. Sir Lawrence founded three famous research schools for the study of silicates, metals, and alloys as well as protein crystals. He retired from active scientific work in 1965 and was planning a biography of his father in coauthorship with his sister. On his 80th birthday, a gathering of world radiation crystallographers hailed him rightly as the father of their science; contrastingly, as noted by his sister, they hardly mentioned the important role played by his father.[92] He died in Ipswich (Suffolk) on July 1st, 1971 (Fig. V-12).

In the foreword of a biography of their father that Sir Lawrence Bragg and Mrs. Alban Caroe were planning to achieve together, they asked: "What sort of man is a scientist? How does he come to make discoveries? What is his urge?" They went on to suggest: "Perhaps some kind of answer to those questions can be found by making casebooks of the lives and thoughts of scientists, each man's life providing his individual and partial answer."[92] One has to agree with them that the writings, works and thoughts of William Henry Bragg offer a coherent set of answers.

William Henry Bragg was a simple and sincere man with a seriousness of purpose that was balanced by a deep sense of humor. His was a simple but genuine piety. He had a natural desire to share his joy, his boyish glee[18]; he also had a talent for making friends and enjoyed friendliness, though he did not seem to require intimacy. In his laboratories, he was the compelling soul of everything: his associates frequently felt the impulse to "tell Bragg about it." He seemed to trust the best in everybody, and they gave their best to him in return. Although academically persuasive, he was reluctant to sway others by his wishes. If his advice was sought, he was usually hesitant; he balanced carefully his opinion and reasoned his advice. To use a phrase that he applied to very few: he was a dear man.

luctant to sway others by his wishes. If his advice was sought, he was usually hesitant; he balanced carefully his opinion and reasoned his advice. To use a phrase that he applied to very few: he was a dear man.

Bragg's work, like his personality, was simple yet profound; he neither wasted time on the trivial nor camouflaged difficulties under veils of mathematical vagueness. It is given to a few to excell in both pursuit and in exposition. As a writer and lecturer, Bragg was preeminent; he had the power of putting in simple language, with clarity and precision, the essence of a problem.

"That sense of the illimitable in its ordered magnificence, which covers the student like a worshiper's garment, is a gift no one may lightly decline"[31] —said Bragg. *"It is a fact that love of good work and delight in successful accomplishment are powerful motives and, when satisfied, are sources of real happiness. Of all the motives that sway the world, these are among the purest and best."*[64] *"Our effectiveness will depend upon the devotion, wisdom and goodwill that we bring to our task."*[70]