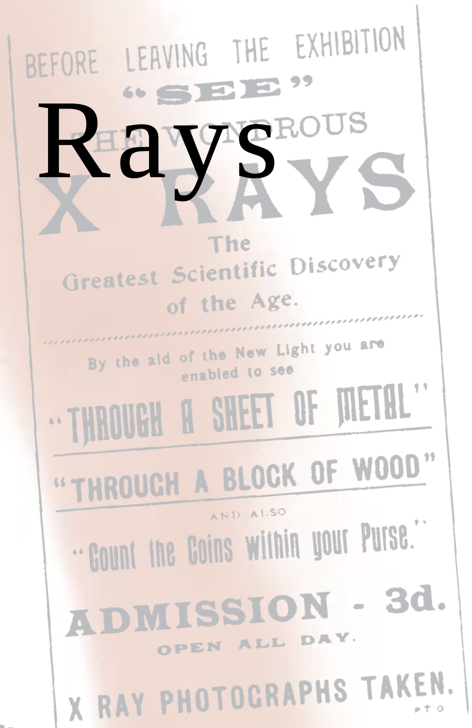
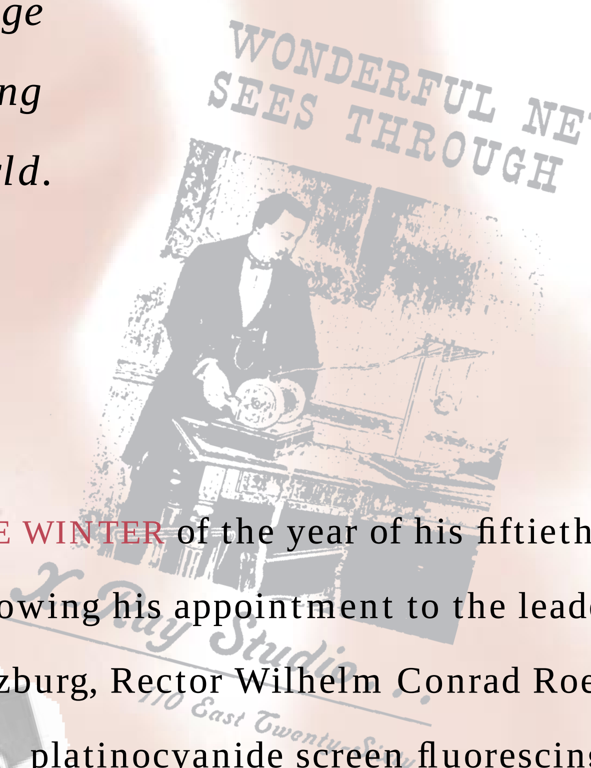
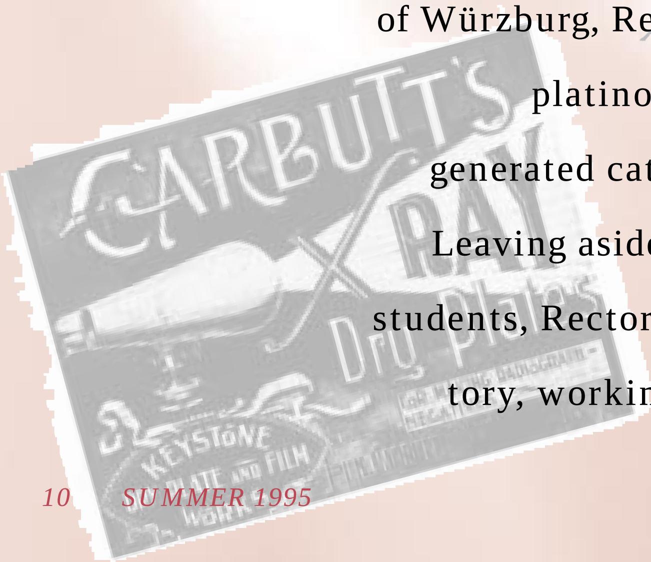
Early History of X Rays

by ALEXI ASSMUS



The discovery of X rays in 1895 was the beginning of a revolutionary change in our understanding of the physical world.





IN THE WINTER of the year of his fiftieth birthday, and the year following his appointment to the leadership of the University of Würzburg, Rector Wilhelm Conrad Roentgen noticed a barium platinocyanide screen fluorescing in his laboratory as he generated cathode rays in a Crookes tube some distance away. Leaving aside for a time his duties to the university and to his students, Rector Roentgen spent the next six weeks in his laboratory, working alone, and sharing nothing with his colleagues.

Wilhelm Conrad Roentgen (1845–1923). (Courtesy of AIP Emilio Segré Visual Archives)

Three days before Christmas he brought his wife into his laboratory, and they emerged with a photograph of the bones in her hand and of the ring on her finger. The Würzburg Physico-Medical Society was the first to hear of the new rays that could penetrate the body and photograph its bones. Roentgen delivered the news on the 28th of December 1895. Emil Warburg relayed it to the Berlin Physical Society on the 4th of January. The next day the *Wiener Press* carried the news, and the day following word of Roentgen's discovery began to spread by telegraph around the world.

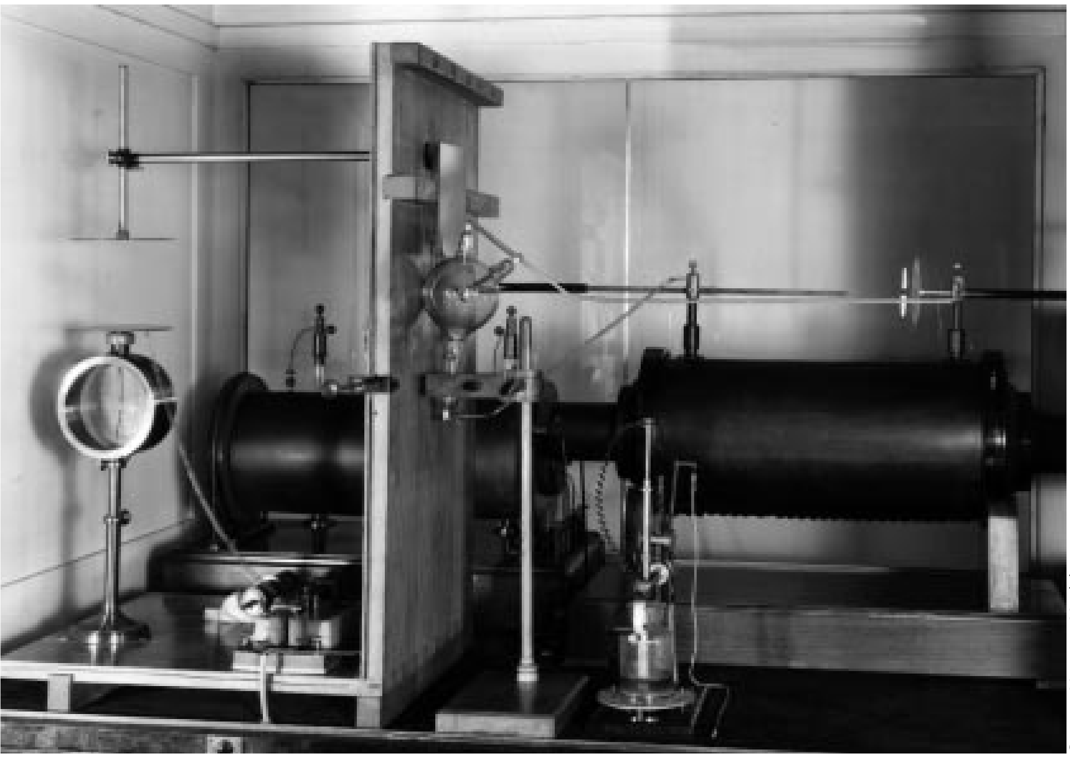
On the 13th of January, Roentgen presented himself to the Kaiser and was awarded the Prussian Order of the Crown, Second Class. And on the 16th of January the *The New-York Times* announced the discovery as a new form of photography, which revealed hidden solids, penetrated wood, paper, and flesh, and exposed the bones of the human frame. "Men of science in this city are awaiting with the utmost impatience the arrival of English technical journals which will give them the full particulars of Professor Roentgen's discovery of a method of photographing opaque bodies," *The New-York Times* began, and it concluded by predicting the "transformation of modern surgery by enabling the surgeon to detect the presence of foreign bodies." (Jan. 16, 1896, p. 9)

The public was enthralled by this new form of photography and curious to know the nature of the new rays. Physicians put it to immediate use. Physicists sat up and took notice. The discovery of X rays was the first in a series of three discoveries that jolted the *fin-de-siècle* discipline out of its mood of finality, of closing down the books with ever more precise measurements, of losing itself in debates over statistical mechanics, or of trying to ground all physical phenomena in mathematically precise fluctuations of the ether. All three discoveries, X rays, uranium rays, and the electron, followed from one of the major experimental traditions in the second half of the nineteenth century, the study of the discharge of electricity in gases. All three contributed to a profound transformation of physics. In the 20th century, the discipline has been grounded in the study of elementary particles.

As with the invention of incandescent light bulbs, the study of electrical discharge through gases was made possible by the development of improved vacuum technology in the 1850s. Early on, English scientists were investigating the patterns of light and dark that appeared in sealed lead-glass tubes. The patterns in

Forms of tube used by Roentgen in 1895–1896 for the production of X rays.

German Museum, Munich


German Museum, Munich

Roentgen's apparatus for studying the ionization of air by X rays, 1906.

these partially evacuated tubes were stimulated by a voltage drop between a cathode and an anode: typically there was a dark space, called Crookes' dark space; then a glow, called negative light; then another dark space, this one called Faraday's; and a final glow of positive light. If the air in the tube was exhausted until the first dark space expanded to fill the entire tube and all glows disappeared, then the rays emitted from the cathode could be investigated. The rays cast shadows, and were deflected by magnetic fields, but appeared to be immune to the effects of static electric forces.

As was to be characteristic of the new ray physics to come—the physics of cathode rays, X rays, alpha rays, beta rays, gamma rays, and N rays—the nature of the cathode rays was in dispute, the British favoring a stream of particles, those on the Continent preferring to think of them as some sort of disturbance of the ether. (The British position, and the research program developed by J.J. Thomson at the Cavendish Laboratory to study ionization in gases, would result in the discovery of the electron. But our story does not take us that way).

A strong reason for believing that the cathode rays were particles was the observation that they would not pass through matter that was transparent to ultra-violet light. When Heinrich Hertz found that he could pass the rays through metal foil, a fellow German scientist, Philip Lenard, began to study them more carefully. Lenard designed a tube with a thin aluminum window through which the rays could emerge, and he measured how far they could travel and still induce fluorescence. Defined in this way, the range of the cathode rays was six to eight centimeters. Lenard's experiments inspired Roentgen to wonder if the rays in an attenuated form really traveled farther, and he planned experiments to see if a sensitive electroscope would measure a discharge at four times the distance Lenard had identified.

This line of work was outside Roentgen's usual research pursuits, which had by this time gained him great stature in German science. Son of a cloth manufacturer and merchant from the Rhine province, Roentgen was not a particularly diligent student in his youth. He eventually made his way to the Polytechnic in Zurich, where he obtained a diploma in mechanical engineering in 1868 and a doctorate one year later. In Zurich he became an assistant to August Kundt and moved along with him to the University of Würzburg, and then on to the Physical Institute at Strasbourg. His first move on his own was to the chair of physics at Giessen in Hesse in 1879, from which he received many offers to go elsewhere. The path upward in the German university system was to follow calls to universities of higher and higher stature, and finally to obtain an institute of one's own. Roentgen

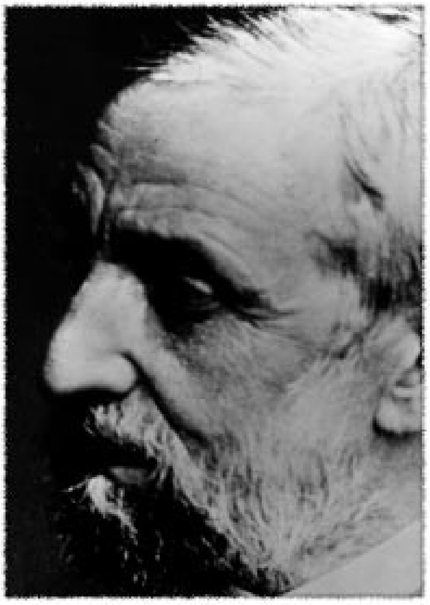
Sir Joseph John Thomson, 1856–1940. (Courtesy of the AIP Niels Bohr Library) refused the calls until the University of Würzburg offered him the Directorship of their Physical Institute. In 1894 he was elected Rector at Würzburg. In his inaugural address, given the year before his discovery of X rays, Roentgen stated that the "university is a nursery of scientific research and mental education" and cautioned that "pride in one's profession is demanded, but not professional conceit, snobbery, or academic arrogance, all of which grow from false egoism."*

Roentgen's pride could rest in the over forty papers he had published from Strasbourg, Giessen, and Würzburg. These early interests ranged widely—crystals, pyroelectrical and piezoelectrical phenomena, and the effects of pressure on liquids and solids—but did not yet include electrical discharges in gases. He had taken his turn at measuring the specific heat ratios of gases using a sensitive thermometer of his own making. He was an exact experimenter who often made his own apparatus—a skill learned during his training as an engineer in Zurich—and he was able to measure extremely small effects, surpassing even Faraday's measurement of the rotation of polarized light in gases.

Roentgen turned to a new interest in October of 1895: the study of cathode rays. In the course of repeating the experiments of Hertz and Lenard, he happened to notice a glowing fluorescent screen set off quite some distance from the Crookes' tube he was operating. The screen sat much farther away than the six to eight centimeters that Lenard had found to be the maximum distance for which cathode rays maintain their power to induce fluorescence. Roentgen recognized the effect as worthy of his undivided attention and devoted the next six weeks to its uninterrupted study.

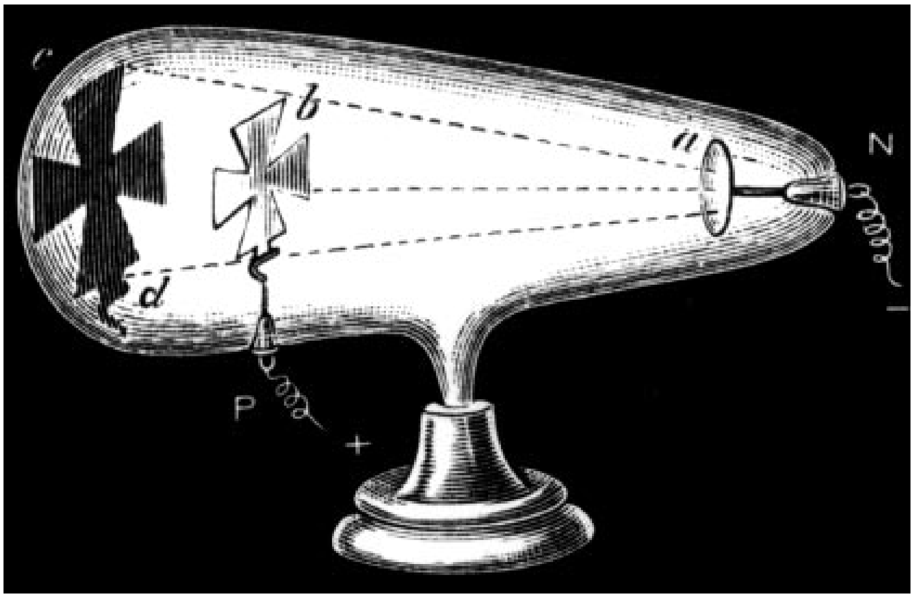
Historians have speculated about why Roentgen was the first to recognize the significance of this effect. The equipment, a cathode ray tube and a fluorescing screen, had been in use for decades. In 1894 J.J. Thomson had seen fluorescence in German-glass tubing several feet from the discharge tube. Others had noted fogged photographic plates. But before Lenard's work, the object of study was always the effects inside the tube itself, and stray ultra-ultraviolet light could be used to explain the fogging of photographic plates. Lenard's great interest was in proving, in contradiction to the British, the ethereal nature of cathode rays, and he was the first to study the

*Quoted in "Wilhelm Conrad Roentgen," *Dictionary of Scientific Biography* (New York: Scribner's, 1975), p. 531.



Phillip Lenard, 1862–1947. (Courtesy of Ullstein Bilderdienst and the AIP Niels Bohr Library)

Demonstration by Crookes that cathode rays travel in straight lines: a) cathode; b) aluminum cross and anode; d) dark shadow; c) fluorescent image.



Heinrich Rudolf Hertz, 1857–1894. (Courtesy of Deutsches Museum and AIP Emilio Segrè Visual Archives)

O, Röntgen, then the news is true,
And not a trick of idle rumour,
That bids us each beware of you,
And of your grim and graveyard humour.

We do not want, like Dr. Swift,
To take our flesh off and to pose in
Our bones, or show each little rift
And joint for you to poke your nose in.

We only crave to contemplate
Each other's usual full-dress photo;
Your worse than "altogether" state
Of portraiture we bar in toto!

The fondest swain would scarcely prize
A picture of his lady's framework;
To gaze on this with yearning eyes
Would probably be voted tame work!

No, keep them for your epitaph,
these tombstone-souvenirs unpleasant;
Or go away and photograph
Mahatmas, spooks, and Mrs. B-s-nt!

—Punch, *January 25, 1896*

effects of the rays in air or in a second glass tube into which he directed them.

Roentgen, a meticulous and observant experimenter, made the obvious tests on the new X rays: Were they propagated in straight lines? Were they refracted? Were they reflected? Were they distinct from cathode rays? What were they? Like the cathode rays, they moved in straight lines. Roentgen was unable to refract them with water and carbon bisulphide in mica prisms. Nor could he concentrate the rays with ebonite or glass lenses. With ebonite and aluminum prisms he noted the possibility of refracted rays on a photographic plate but could not observe this effect on a fluorescent screen. Testing further, he found that X rays could pass freely through thick layers of finely powdered rock salt, electrolytic salt powder, and zinc dust, unlike visible light which, because of refraction and reflection, is hardly passed at all. He concluded that X rays were not susceptible to regular refraction or reflection.

Roentgen found that the X rays originate from the bright fluorescence on the tube where the cathode rays strike the glass and spread out. The point of origin of the X rays moves as the cathode rays are moved by a magnetic field, but the X rays themselves are insensitive to the magnet. Roentgen concluded that they are distinct from cathode rays, since Lenard's work had shown that cathode rays passing through the tube maintained their direction but were susceptible to magnetic deflection.

Roentgen justified calling the new phenomena rays because of the shadowy pictures they produce: bones in a hand, a wire wrapped around a bobbin, weights in a box, a compass card and needle hidden away in a metal case, the inhomogeneity of a metal. The ability of the new rays to produce photographs gave them great popular appeal and brought Roentgen fame. Many articles appeared in photography journals, and *The New-York Times* indexed the new discovery under photography. Since the rays exposed photographic plate, the public assumed they were some form of light. The physicist Roentgen concurred. Accepting Lenard's claim that cathode rays were vibrations of the ether, Roentgen compared the new rays to them and forwarded the opinion that the two were ethereal, although different from visible, infra-red and ultra-violet light in that they did not reflect or refract. He suggested that cathode rays and X rays were longitudinal vibrations of the ether rather than transverse ones.

Now that their existence was established, it was easy enough to experiment with the new X rays. Roentgen himself published only three papers on the subject, but others jumped quickly into the field. And not just physicists. Thomas Edison used modified incandescent light bulbs to produce the new rays. He boasted to reporters that anyone could make photographs of skeleton hands; that was mere child's play. Within a month of Roentgen's announcement doctors were using the X rays to locate bullets in human flesh and photograph broken bones. Dr. Henry W. Cattell, Demonstrator of Morbid Anatomy at the University of Pennsylvania, confirmed their

Henri Poincaré, 1854–1912. (Courtesy of AIP Emilio Segrè Visual Archives)

importance for the diagnosis of kidney stones and cirrhotic livers and commented that "The surgical imagination can pleasurably lose itself in devising endless applications of this wonderful process." (*The New-York Times*, Feb. 15, 1896, p. 9). In the first six months after their discovery Viennese mummies were undressed, doctors claimed to have photographed their own brains, and the human heart was uncovered. By 1897 the rays' dangerous side began to be reported: examples included loss of hair and skin burns of varying severity.

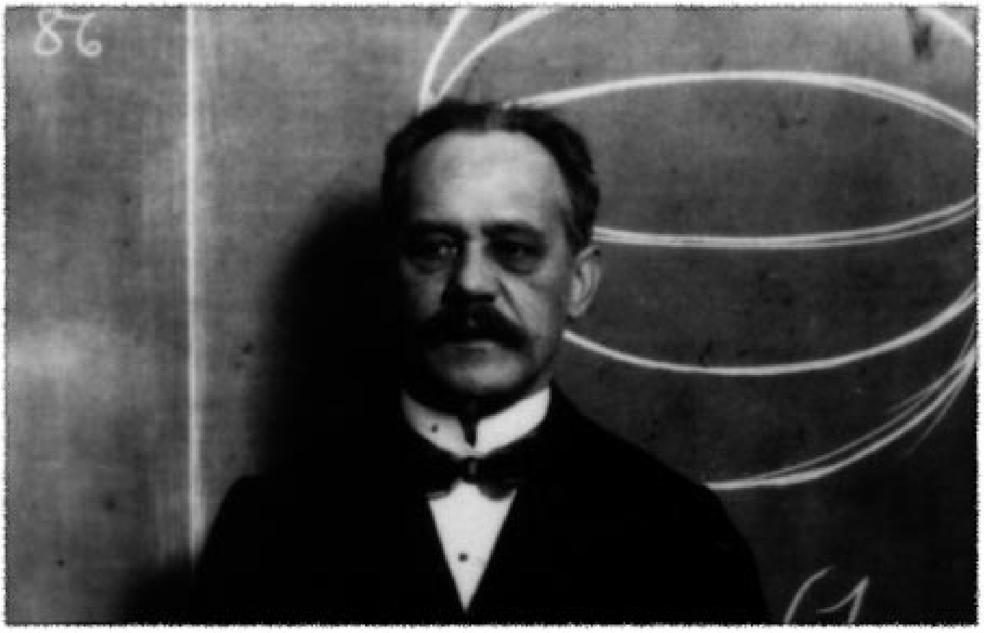
Electricians and physicists speculated on the nature of these X rays. Albert Michelson thought they might be vortices in the ether. Thomas Edison and Oliver Lodge suggested acoustical or gravitational waves. But the rays ability to photograph was decisive, and serious thinkers settled on three possibilities, all of them of electromagnetic origin: the waves were very high frequency light; they were longitudinal waves (Roentgen's initial suggestion); or they were transverse, discontinuous impulses of the ether.

Quite early on the hypothesis that they were longitudinal waves was discarded, despite the support of Henri Poincaré and Lord Kelvin. The crux of the question was whether the waves were polarizable. If so they could not be longitudinal waves. Although the early experiments on polarization were negative or unclear, with the discovery of another ray, Henri Bequerel's uranium rays for which he claimed to have found polarization, those on the Continent set up a convincing typology. It went from lower to higher frequency transverse ethereal vibrations: light, uranium rays, X rays. Uranium rays were given off by certain minerals, and they needed no apparatus to produce them, but they shared certain properties with X rays. They exposed photographic plates and they caused gases to conduct electricity.

British physicists weighed in on the side that X rays were impulses in the ether rather than continuous waves. Lucasian Professor of Mathematics at Cambridge, Sir George Gabriel Stokes, and his colleague and director of the Cavendish Laboratory, J.J. Thomson, committed themselves to the impulse hypothesis in 1896. It was consistent with their conception of cathode rays as particles (Thomson was to announce the discovery of the corpuscle or electron one year later.) The abrupt stop of a charged particle would result, after a tiny delay, in the propagation outward of an electromagnetic pulse. With Thomson's exact measurement of the charge-to-mass ratio and H.A. Lorentz' successful theory of the electron, which explained many intriguing phenomena, Continental physicists began to accept, to Lenard's dismay, cathode rays as material particles and X rays as impulses in the ether.

Soon new results began to come in. Two Dutch physicists,

First X ray made in public. Hand of the famed anatomist, Albert von Kölliker, made during Roentgen's initial lecture before the Würzburg Physical Medical Society on January 23, 1896.



Arnold Johannes Wilhelm Sommerfeld, 1868–1951. (Courtesy of the AIP Niels Bohr Library)

WE WANT TO KNOW

If the Roentgen rays, that are way ahead,
Will show us in simple note,
How, when we ask our best girl to wed,
That lump will look in our throat.

If the cathode rays, that we hear all about,
When the burglar threatens to shoot,
Will they show us the picture without any doubt,
Of the heart that we feel in our boot.

If the new x-rays, that the papers do laud,
When the ghosts do walk at night,
Will show 'neath our hat to the world abroad
How our hair stands on end in our fright.

If the wonderful, new, electric rays,
Will do all the people have said,
And show us quite plainly, before many days,
Those wheels that we have in our head.

If the Roentgen, cathode, electric, x-light,
Invisible! Think of that!
Can ever be turned on the Congressman bright
And show him just where he is at.

Oh, if these rays should strike you and me,
Going through us without any pain,
Oh, what a fright they would give us to see
The mess which our stomachs contain!

—Homer C. Bennett,
American X-ray Journal, *1897*

Hermann Haga and Cornelius Werd, announced that X rays could be diffracted, and a Privatdozent at Göttingen named Arnold Sommerfeld carried out a mathematical analysis of diffraction to show that their results could be explained in terms of aperiodic impulses. In 1904, Charles Glover Barkla, a student of both Stokes and Thomson at Cambridge, showed that X rays were plane polarizable while experimenting with secondary and tertiary X rays. (These were produced by directing X rays against solids.)

As X rays began to show, more and more, the properties of light, uranium rays provided new mysteries. They themselves were composed of three sorts of distinct rays: α, β, and γ rays. What were these? Suddenly physics, which had seemed to some to be coming to a conclusion, was faced with unexplainable, qualitative discoveries. They were not "in the sixth place of the decimals," as Michelson had predicted. At the international congress on physics, staged in Paris in 1900 by the French Physical Society, fully nine percent of the papers delivered were on the new ray physics.

In 1899 Ernest Rutherford, another student of Thomson's and the man who would become his successor as director of the Cavendish Laboratory, had separated α rays, stoppable by metal foil or paper sheets, from the more penetrating β rays. In 1900, Rutherford had identified the βs as high-speed electrons: deflected in a magnetic field they showed the correct charge-to-mass ratio. A third component of the uranium rays, undeviable and highly penetrating, was discovered by Paul Villard at the Ecole Normale Superieur in Paris. Rutherford named these γ rays. In her 1903 thesis Marie Curie made these comparisons: γ rays to X rays; β rays to cathode rays; and α rays to canal rays. (Canal rays were streams of positively charged molecules.)

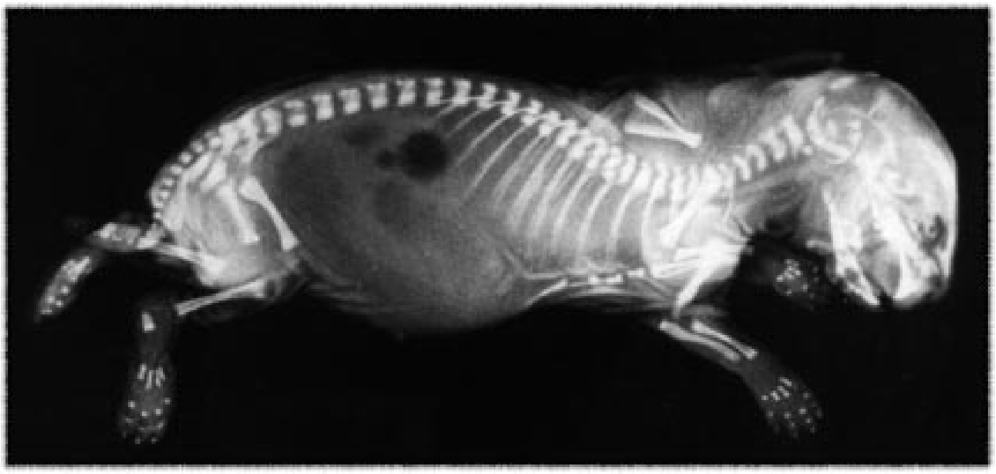
A few years later another story came out. The British scientist William Henry Bragg announced in 1907 that X rays and γ rays were not in fact ether waves, but rather particles, a neutral pair at that: electron plus positively charged particle. Bragg's serious research began at a late age, 41, after twenty pleasant years at the University of Adelaide, Australia, where he played golf and hobnobbed with government officials. He announced his new intellectual work in a Presidential Address to the Australian Association for the Advancement of Science during which he made a critical review of Rutherford's work, questioning the law of exponential decrease for the absorption of α rays. For two and a half years he published a paper every few months, work that led him to make the radical statement that X rays were particles. His idea was based on two facts: (i) X rays excite fewer gas molecules in their path than would be expected from a wave-like disturbance, and (ii) the velocity of the electrons excited by X rays is greater than could be given to them by a wave. By this time Bragg and his physicist son were back in England, and their theory caused great controversy even in the country where particles were in favor and where exotic modeling of physical phenomena was well tolerated. Their most vociferous opponent was Charles Barkla, who argued that the ionization of matter was a secondary effect not needing to be directly attributable to the wave-like nature of X rays. We will return later to the problem of the concentration of X-ray energy, unexplainable in terms of waves, as it bears on Louis de Broglie's insight into the wave nature of matter.

X RAYS AS A PROBE OF THE STRUCTURE OF MATTER

Before we turn to our final act in the almost thirty year drama to understand the nature of X rays, let us turn aside to follow another direction that the work on X rays took, a shift from the investigation of the *nature* of X rays to their *use* in probing the structure of crystals and of atoms. That story will take us back to Roentgen and the center for physics he built up at Munich. While at Würzberg, Roentgen had been agitating for an extra position in physics. He wanted a position for theoretical physics, a newly emerging specialty of German origin that followed by several decades the crystallization of physics itself in the mid-nineteenth century. (In 1871 James Clerk Maxwell hesitated in giving his support to the creation of a Physical Society in London. He wondered whether such a discipline distinct from chemistry existed!)

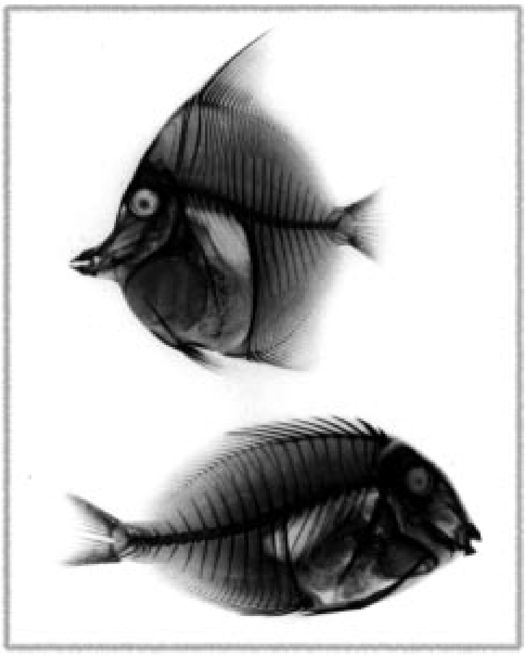
When in 1899 Roentgen was offered a position at Munich and the chance to build up physics there, he accepted. Five years later, in negotiations with the minister of education over another possible move, this time to the Reichsanstalt, Roentgen received, in return for a pledge to stay in Munich, a second institute, for theoretical physics, to complement his existing institute for experimental physics. When Emil Cohn and Emil Weichert successively declined the offer of a position, it was given to Privatdozent Sommerfeld, who joined Roentgen in Munich and shared his desire to build up physics there to the quality of the institutes in Göttingen, Berlin, and Leipzig. In the work on quantum theory of the next two decades, Munich would join Copenhagen and Göttingen as the main centers on the Continent.

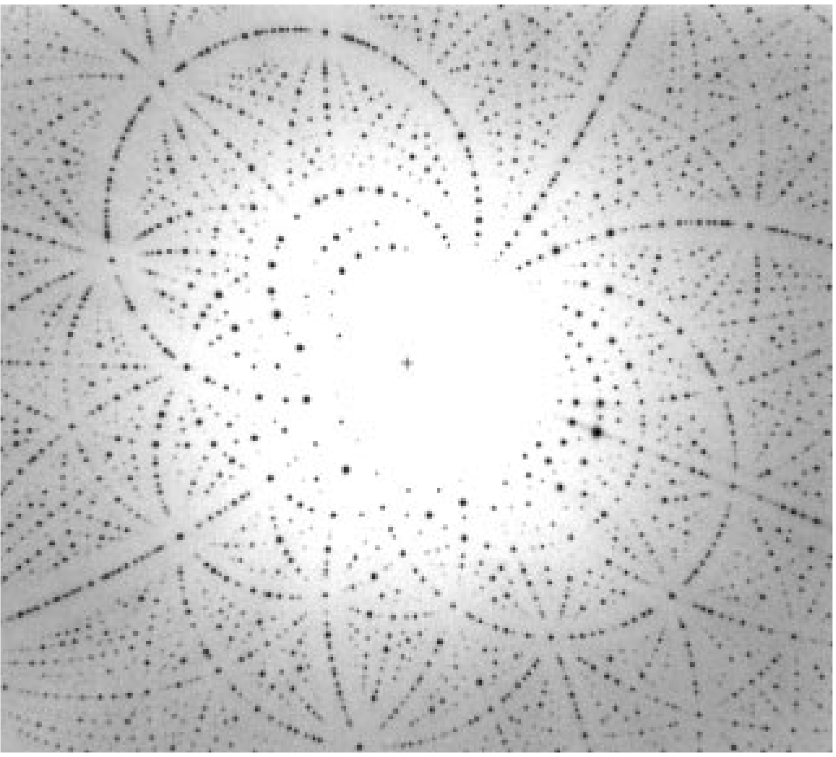
Sommerfeld was initially unenthusiastic about assistant Max von Laue's idea that regularly spaced atoms in a crystal might act as a diffraction grating for X rays, the fine distances between the atoms serving, as no hand- or machine-ruled grating could, to diffract ultra-high frequencies. If, of course, that is what one thought X rays were! Sommerfeld, pushing the impulse hypothesis, was



Roentgen picture of a newborn rabbit made by J. N. Eder and E. Valenta of Vienna, 1896. (Burndy Library, Dibner Institute, Cambridge, Massachusetts.)

Radiographs of tropical fish made by J.N. Eder and E. Valenta of Vienna, Jaunary 1896 and presented to Roentgen. (Burndy Library, Dibner Institute, Cambridge, Massachusetts.)





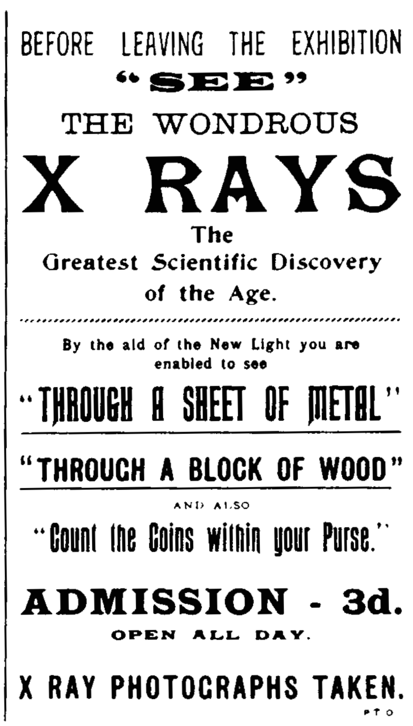
White radiation Laue diffraction pattern from the protein trimethylene dehydrogenase (an enzyme that catalyzes the conversion of trimethylamine to dimethylamine and formaldehyde) recorded on SSRL beam 10–2 with a 5 msec X-ray exposure. The photograph was taken by Scott Matthews and Scott White of Washington University, St. Louis, and Mike Soltis, Henry Bellamy, and Paul Phizackerly of SSRL/SLAC.

engaging in discussions with Johannes Stark over the quantum nature of X rays. Stark was one of the few physicists who in 1911 took seriously Einstein's suggestion that light comes in quanta of energy. Applying the notion to X rays, Stark was able to assign them a frequency *and* to explain the high velocity of electrons that had been excited by X rays, one of the phenomena that so exercised Bragg and Barkla.

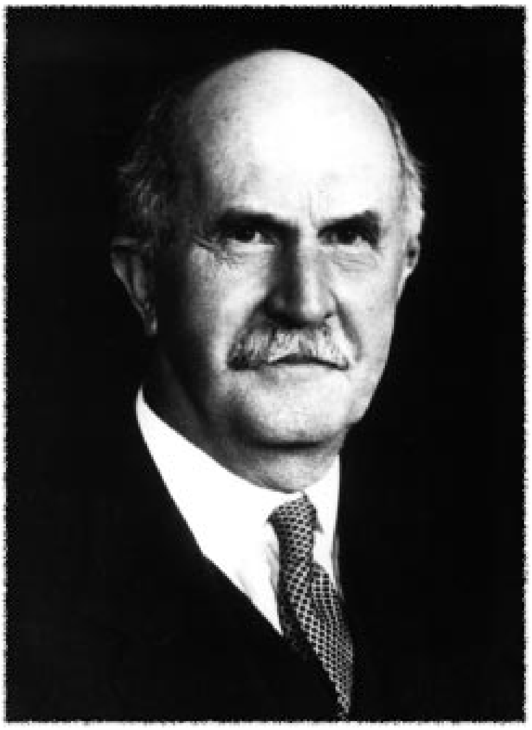
Laue persisted in asking that the experimentalists try out X rays on crystals. A student of Max Planck's (in fact, his favorite), Laue had worked on a theory of the interference of light in plane parallel plates. By 1912 his specialty had become the theory of relativity, but he was not averse to following Sommerfeld in working on a theory of diffraction. Laue's guess was that it would be only the secondary X rays, not the chaotic Bremsstrahlung identified with the initial deceleration of electrons, that would interfere constructively in the crystal. In April 1912 Walther Friedrich and Paul Knipping shone secondary X rays on copper sulfate and zinc sulfate surfaces and found that dark spots in successive circles appeared on photographic plates placed behind them. At this time both the nature of X rays and the structure of crystals was a puzzle. Laue's analysis of the situation was to identify five distinct wavelengths of incoming X rays between 1.27 and 4.83×10^{-9} cm. Later others would suggest that the crystal itself imposed structure on the incoming radiation. Laue published a rather long article on his theory of diffraction in the *Enzyklopadie der Mathematische Wissenschaften*, and much later (1941) he went on to publish a 350-page review of the subject, *Roentgenstrahlen-Interferenzen*, in which he included the effects of electron interference.

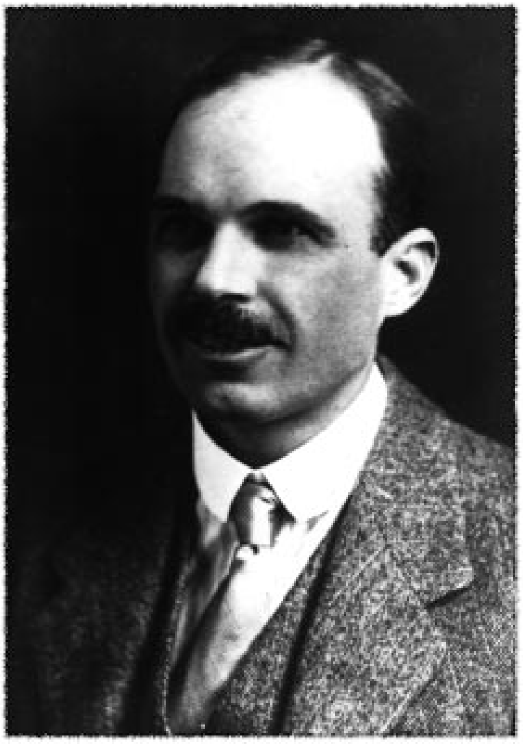
Perhaps as was fitting for an early proponent of relativity and a defender of Einstein throughout the Nazi period, Laue made little of quantum theory and remained skeptical of the Copenhagen interpretation throughout his life. He became director of the Kaiser Wilhelm Institute in the years before World War II, resigning his position in 1943, at which time the Institute was directed towards the building of an atomic bomb under the leadership of Werner Heisenberg. After the war Laue worked to rebuild German science. In the fall of 1946 he helped create the German Physical Society in the British Zone, and worked to revive the first of the national bureaus of standards, the Physikalische-Technische-Reichsanstalt. Towards the end of his life he assumed the directorship of the now one of several Kaiser Wilhelm Institutes, this one devoted to electrochemistry in Berlin-Dahlem. Laue died in an auto accident at the age of eighty-one.

Laue was representative of the German talent for institution building in the support of science and the German fascination for fundamental principles and theories. Those who would apply Laue's idea and build on Friedrich and Knipping's



Top right: Sir William Henry Bragg, 1862–1942. Lower right: Sir William Lawrence Bragg, 1890–1971. (Courtesy of the AIP Niels Bohr Library)





experimental demonstration were the British, specifically the Braggs and Henry Moseley. In view of the German results the Braggs had come to believe that X rays were of an electromagnetic nature, but they insisted that the rays must have some sort of dual existence as they were able to concentrate their energy. But the continuing puzzle as to their nature did not stop the Braggs from recognizing the practicability and importance of a new field of study, X-ray crystallography.

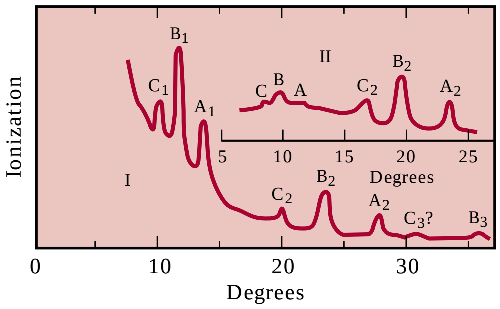
The new field was pioneered by the Braggs. They were inspired by the Cambridge theorists who argued that a diffraction grating imposes a structure on an inhomogeneous pulse of white light, picking out, as if in a Fourier transform, the wavelengths into which the beam can be decomposed. William Henry Bragg and his son, William Lawrence Bragg, argued by analogy that the crystal, by dint of the distance between planes of atoms, imposes a similar structure on an inhomogeneous pulse of X rays. When the X rays are reflected off two successive planes of atoms in the crystal, they interfere constructively if the difference in the distance traveled is equal to an integral number of wavelengths. Thus the famous Bragg condition

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

where d is the distance between planes and θ is the angle of reflection.

Using an X-ray tube and a collimating slit to produce the incoming rays; using various minerals, quartz, rock salt, iron, pyrite, zincblende, and calcite, as three-dimensional diffraction gratings; and using a photographic plate or an ionization chamber (depending on the strength of the incoming rays) as a detector—the Braggs proceeded with the first measurements in X-ray spectroscopy. By 1913, just a year after they had pioneered the method, crystal analysis with X rays had become a standard technique. The results not only gave insight into the structure of crystals but also into the nature of the anti-cathode that produced the rays.

The first person to notice that X rays can be characteristic of the substance that emits them was Charles Barkla, the opponent of the Braggs in the matter of X rays as neutral particles and a professor at the University of Edinburgh who spent over forty years examining the properties of secondary X rays. Between 1906 and 1908 he had noticed that elements emit secondary X rays with a penetrating power in aluminum that is distinct for each element. To distinguish between the hardness of the characteristic rays, he introduced the terminology K and L rays. It was for this discovery that he was awarded the Nobel Prize in 1917. (His subsequent work earned Barkla the reputation as something of a scientific crank.) What the Braggs noticed (see figure on next page) was that a pattern of multiple peaks with varying intensities was produced no matter what the crystal (shifted only by the varying distances between planes of atoms) as long as the element of the anti-cathode remained the same. In other words, the pattern was analogous to spectral lines emitted by gases in the optical frequencies. The person to explore this analogy to its fullest was Henry Moseley,



One of the earliest examples of X-ray spectroscopy. The Braggs made a seredipitous discovery: while studying the scattering of X rays off of crystals they noticed that a distinctive pattern of peaks appeared for each of the different anti-cathodes being used to produce the rays. What had initially started out as a study of the structure of crystals led to an investigation of the atomic structure of the anti-cathode elements. [Bragg and Bragg, PRS, 88A, 413 (1913).]

H. G. J. Moseley in Balliol-Trinity Laboratory, Oxford, circa 1910. (Courtesy of University of Oxford, Museum of the History of Science and the AIP Niels Bohr Library)

a young researcher working in Rutherford's Manchester laboratory during the time when Niels Bohr was visiting regularly.

Moseley's two grandfathers had been fellows of the Royal Society, and his father had founded a school of zoology at Oxford. Mosely himself was perhaps the only important atomic physicist to be educated at Oxford. In the fall of 1910 he came to work as a demonstrator under Rutherford, his salary being paid by a Manchester industrialist. He was assigned a research problem to which everyone knew the answer: how many β particles are emitted in the radioactive disintegration of radium B (Pb^{214}) to radium C (Bi^{214}). On finding the answer everyone expected, one, he proved his competency as an experimentalist. However, his next experiments would not be so cut and dried, nor would they receive the ready approval of Rutherford. Like the Braggs, and quite independently of them, Moseley was stimulated by the photographs of Friedrich and Knipping, and felt that Laue had misinterpreted them as evidence of five homogeneous X rays. He teamed up with Charles G. Darwin, grandson of the famous evolutionist, and turned to, as he said, the "real meaning" of the German experiments. The Laue dots connoted the structure of the crystal, not the structure of the incoming rays. When presenting his results to a Friday physics colloquium which father Bragg attended, Moseley discovered the similarity in their understanding of the phenomena, and afterwards he wrote to his mother:

> *I have been lazy for a couple of days recouping after the lecture I gave on Friday on X rays. It was rather anxious work, as Bragg, the chief authority on the subject (Professor of Leeds) was present, and as I had to be cautious. However it proved quite successful and I managed to completely disguise my nervousness. I was talking chiefly about the new German experiments of passing rays through crystals. The men who did the work entirely failed to understand what it meant, and gave an explanation which was obviously wrong. After much hard work Darwin and I found the real meaning of the experiments.**

For a time the Braggs, Moseley, and Darwin continued on the same track, even though Rutherford presented difficulties which were finally overcome by Moseley's persistent enthusiasm and by Bragg's offer to Moseley of a visit to Leeds to teach him the techniques of X-ray spectroscopy. Some of the questions they pursued were the old ones about the nature of X rays. How to reconcile the corpuscular nature of the rays with their ability to interfere? Bragg had compared this conundrum in the electromagnetic theory of X rays to the physical impossibility of a spreading circle of water waves, caused by the fall of a rock, to excite another rock to jump the same distance the wave-producing rock had fallen.

The new questions concerned the elements. In July of 1913 Bohr paid a visit to Manchester and discussed atomic structure with Moseley, Darwin, and George Hevesey. The discussion revolved around the similarity, and possible differences,

*Nov. 4, 1912. Quoted in J.L. Heilbron, H.G.J. Moseley, p. 194.

Charles G. Darwin, L. M. Thomas, and Gregory Breit. (Courtesy of the Goudsmit Collection)

between the atomic weight of an element (A) and its nuclear charge (Z). Geiger's and Marsden's scattering experiments and Rutherford's theory had proposed that the newly discovered nucleus held a charge half that of the atomic weight. A Dutch lawyer and would-be interpreter of Mendeleev's table, Van de Broek, had suggested that the nuclear charge of an element set its place in the table. Now the frequency of characteristic K rays gave another quantity with which to mark the elements. What would the X-ray spectroscope have to say about those places in the table where the atomic weights did not follow in increasing order the serial numbers: between nickel and cobalt; between argon and potassium; and between iodine and tellurium? Would the hardness of the K rays order the elements by atomic weight or by nuclear charge?

Moseley used an ingenious device of G. W. C. Kaye's to examine the K rays from copper, nickel, cobalt, iron, manganese, chromium, and titanium. By putting the different elements which served as anticathodes on a magnetized truck and rail inside the evacuated chamber, Moseley was able to change anti-cathodes with an external magnet without disrupting the integrity of the chamber. After switching from detecting the K rays by ionization to detecting them by photography, his work went quickly, and in several weeks he showed that the ranking of elements by K rays followed their ranking by nuclear charge, Z. The relation was simple as well. The darker of the two primary K lines, K_α, fit the form

$$\nu_{K_\alpha} = \frac{3}{4}\nu_0 (Z-1)^2.$$

Moseley interpreted his formula as a vindication of Bohr's theory, which at the time was being published in three lengthy and famous papers "On the Constitution of Atoms." Moseley argued, not quite convincingly, that his results could be used to support the quantization of an electron's angular momentum. Frederick A. Lindeman, a fellow Englishman working with Walther Nernst on the Continent but with his eye on the same chair of physics as Moseley, Clifton's chair at Oxford, criticized both Bohr and Moseley. He was working out of an already successful tradition which applied the condition of quantized frequencies to the motion of atoms to predict specific heats in a solid and to the motions of molecules in a gas to predict the patterns of rotational and vibrational infrared spectra. (A quantum theory of molecular spectra preceded one of atomic spectra!)

More successful than Moseley's argument in favor of Bohr's atomic theory was his help to the chemists in sorting out the confusions of the rare earths. In November of 1913, Moseley moved to Oxford where he worked with equipment at the

X-ACTLY SO!

The Roentgen Rays, the Roentgen Rays,
What is this craze?
The town's ablaze
With the new phase
Of X-ray's ways.

I'm full of daze,
Shock and amaze;
For nowadays
I hear they'll gaze
Thro' cloak and gown—and even stays,
These naughty, naughty Roentgen Rays.

—*Wilhelma,* Electrical Review,
April 17, 1896

Arthur Holly Compton, 1892–1962. (Courtesy of the AIP Niels Bohr Library)

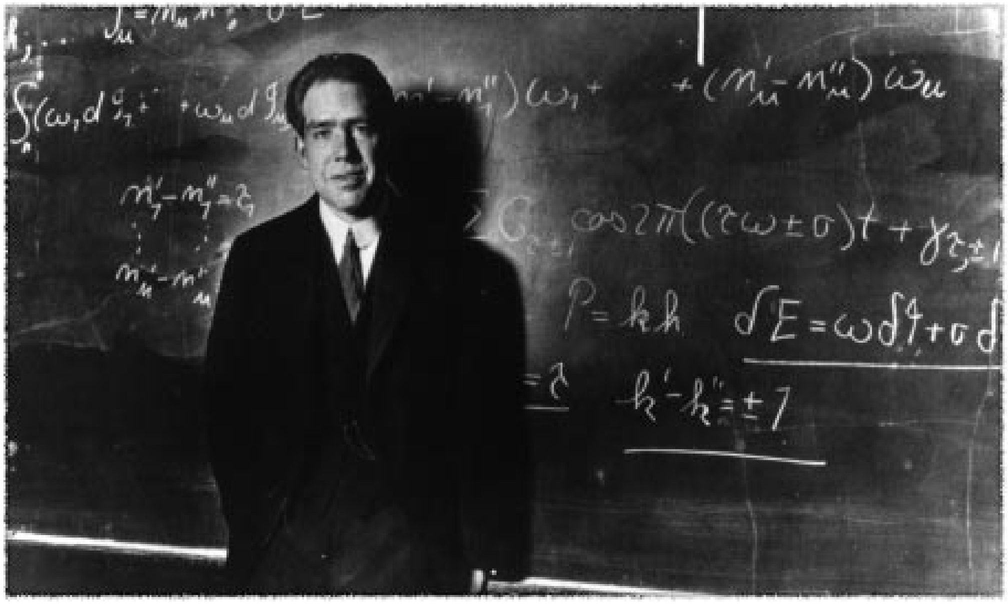
Electrical Laboratory but with no salary. Moseley began a thorough investigation of Mendeleev's table using X rays, and moving from calcium to zinc and then to the rare earths, lanthanum to erbium. George Urbain, a Professor of Chemistry in Paris at one of the Grands Ecoles had been engaged for years in fractionating the elemental rare earths in competition with Carl Auer von Welsback, who performed his fractionations in an Austrian castle. Urbain recognized the power of Moseley's technique and paid him a visit with precious samples of the last four rare earths, thulium, ytterbium, lutecium, and celtium. He was astounded at how quickly Moseley's X-ray spectrometer could determine that celtium was not his sought after new element, but was only a combination of lutecium and ytterbium!

The Braggs' work on crystals and that of Moseley's on elements was brought to a halt by the end of the World War I. The Braggs' work continued after the war. The elder Bragg revivified the Royal Institution, where Sir Humphry Davy and Michael Faraday had made their chemical and electrical discoveries, by establishing a research school for the analysis of organic crystals. This work would become central to the developing field of molecular biology. During the war the elder Bragg worked for the Navy board to evaluate inventions and to promote research with military applications. Like many British and U.S. scientists he eventually found himself working on problems of submarine detection. Moseley, with his Eton patriotism, practically forced himself upon the Royal Engineers along with his friend Henry Tizard. Tizard survived the Great War and subsequently led the minds of British scientists into World War II. Moseley, however, died at Gallipoli in the battle of Sari Bari.

As Europe engaged itself in the Great War, interesting work on X rays began to come out of the United States. Following Robert Millikan's work on the photoelectric effect, William Duane at Harvard gave an exact law that related the energy of cathode ray electrons to the frequency of X rays emitted. By 1916, the Duane-Hunt law was the best way to determine *h*, Planck's constant, although neither Millikan nor Duane then subscribed to the view that energy came in discrete quantized units.

Arthur Holly Compton also initially interpreted his results on X-ray scattering from electrons as a cut-off relation that was governed in this case by Planck's constant rather than as proof of the quantum nature of radiation. Compton, who was later to run the Manhattan Project's Metallurgical Laboratory at Chicago during World War II, received his Ph.D. from Princeton just before the First World War for work on X-ray diffraction and scattering. After several years spent at Westinghouse Manufacturing Company working on fluorescent lamps, he spent a year at Cambridge's Cavendish Laboratory where he developed a friendship with J.J. Thomson and carried out an investigation into the orderly change of X-ray frequency with scattering angle as the X rays scattered from electrons. As a new professor at Washington University in St. Louis, Compton published a mass of data on the relation between X-ray frequency and scattering angle taken with a Bragg crystal spectrometer. In 1922, a year after he had taken the measurements, and along with Peter Debye in Germany who had seen his results in the *Bulletin of the National Research Council*, Compton accepted Einstein's light quantum and by extension the X-ray quantum. The explanation of the Compton-effect then became a simple scattering of two elastic particles.

Niels Bohr, 1885–1962. (Courtesy of the AIP Niels Bohr Library



Few physicists had taken Einstein seriously when he predicted the light quantum in 1905. Bohr had pooh-poohed the idea. But by 1921 evidence was mounting and so was Einstein's fame. The de Broglie brothers, Maurice and Louis, were two others who had learned from the studies of X rays of the dual nature of radiation, and Louis was inspired to suggest that matter too might have this dual nature. Maurice de Broglie's interest in the quantum had been sparked by his secretaryship of the first Solvay Conference called in 1911 by chemist Walther Nernst to introduce the quantum concept to physical scientists, and he decided to investigate the energies of electrons excited by K and L frequency X rays. He found the old problem over which Bragg and Barkla had argued: X rays can concentrate their entire energy and pass it on to electrons. And like Bragg he concluded that X rays act both as waves and as particles. His younger brother, Louis, in a spirit of unification, longed to treat light and matter as equals. Both could be understood as particles following waves, he proposed. A "mobile" of light or X rays or of matter followed along behind an "onde fictive."

So the discussion of X rays had come around full circle. They were discovered in Roentgen's laboratory as this newcomer to cathode rays was trying to puzzle out his countryman Lenard's challenge to the British. Lenard believed cathode rays to be ethereal. The British thought them particles. Soon X rays became the new mystery. Were they electromagnetic waves or were they neutral pairs of particles? By 1913 the interference of X rays had convinced most physicists that they were waves. The Braggs, not quite giving up, insisted that they had the properties of both waves and particles. By 1922 the startling explanation by Compton of his scattering experiments—X-ray energy was concentrated into particle points—helped convince the science community to take Einstein's notion of light quanta seriously. And finally the work on X rays by the de Broglies, and the younger brother's desire to put on an equal footing light and matter, gave Louis de Broglie the courage to suggest that even the good old electron (the cathode ray particles!) partook of wave qualities.

ADDENDUM

The early history of X rays follows another path that I have not covered here. As the physicists wondered about the nature of X rays and used them to probe the structure of crystals and atoms, medical doctors used them to probe the human body and to diagnose and treat disease. Roentgen by presenting an X-ray photograph of his wife's hand to the Würzburg Physical and Medical Society in January of 1896 began the practice of radiology. A month later a German doctor used an X ray to diagnose sarcoma of the tibia in the

Louis de Broglie, 1892–1987.
(Courtesy of the AIP Niels Bohr Library)

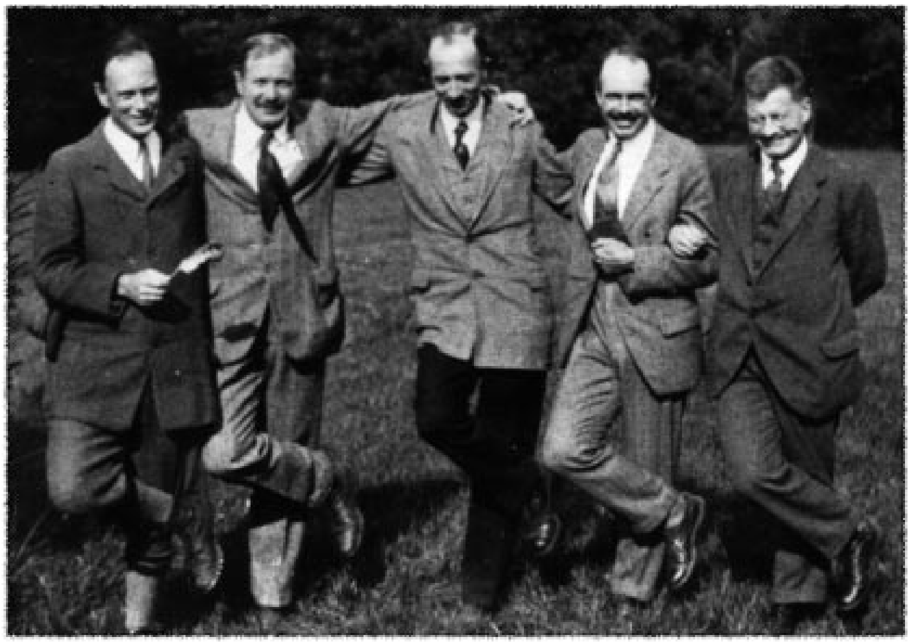
right leg of a young boy. The military first used X rays in Naples in May of 1896 to locate bullets in the forearms of two soldiers who had been wounded in Italy's Ethiopian campaign.

Radiology would be advanced by the strong tradition of medical research in France. Antoine Béclère set up the first X-ray machine in which a patient was strapped and moved around for complete X rays of the chest. For those taking pictures he introduced safety equipment, lead aprons and lead rubber gloves. He pioneered the first use of radiography of the stomach in 1906. The patient had first a meal of bismuth. Through the work of Béclère and others the practice of medical diagnosis changed significantly. Soon to follow was the use of X rays to treat cancer. The rays of the chemists and physicists seemed to inspire doctors: α, β, and γ rays were also beamed at cancerous tumors.

Two of the three discoveries that helped shake physics out of its *fin-de-siècle* malaise, X rays and radioactivity, would be taken up, almost immediately, by doctors in their medical practice. And as physicists began to require substantial funds to continue their quest to discover the smallest structures of matter, the link between physics and medicine would be pushed. Ernest Lawrence regularly raised money for his laboratory's cyclotrons by virtually promising cures for cancer: "It is almost unthinkable that the manifold new radiations and radioactive substances [produced by his cyclotrons] should not greatly extend the successful range of application of radiation therapy."*

**Quoted in J.L. Heilbron and Robert Seidel,* Lawrence and his Laboratory, *(Berkeley, University of California Press, 1989) p. 215.*

An informal moment at an informal conference called by Paul Ewald in 1925. From left: Paul P. Ewald, Charles G. Darwin, H. Ott, William L. Bragg, and R. W. James. (The Isidor Fankuchen Collection)



FOR FURTHER READING

John Heilbron, **H.G.J. Moseley: The Life and Letters of an English Physicist** (Berkeley, U.C. Press, 1974).
Bruce Wheaton, **The Tiger and the Shark: Empirical Roots of Wave-Particle Dualism** (Cambridge, Cambridge University Press, 1983)

One can also find good bibliographies in the numerous articles in the **Dictionary of Scientific Biography** under the individual scientists discussed above.