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(*b*. Widnes, Lancashire, England, 27 June 1877; *d*. Edinburgh, Scotland, 23 October 1944).

physics.

Barkla's father, John Martin Barkla, was secretary of the Atlas Chemical Company in Widnes; his mother, Sarah Glover, was of a local family of watch manufacturers. Barkla received his secondary education at the Liverpool Institute, and in October 1895, with scholarships, entered University College, Liverpool. He concentrated on mathematics and physics. After taking Honours in mathematics he specialized in experimental physics under Oliver Lodge and in 1898 was awarded First-Class Honours in the B. Sc. examination. He received the M. Sc. in 1899. While at Liverpool, Barkla served as first president of the University Physical Society and as occasional substitute for Lodge.

In the autumn of 1899, with an 1851 Exhibition scholarship, Barkla entered Trinity College, Cambridge, as an advanced student. He attended lectures, including those of George Stokes on optics and hydrodynamics (where he was on occasion the sole auditor), and began researches at the Cavendish Laboratory, for which he eventually received the Cambridge B.A. After eighteen months at Trinity, Barkla moved to King's College in order to sing in its famous chapel choir—the chapel was jammed for his baritone solos. In 1901 Barkla's two-year scholarship was exceptionally renewed for a third year. The following year, refusing the opportunity to remain at Cambridge on a choral scholarship, Barkla returned to the University of Liverpool as Oliver Lodge Fellow for three years. He received Liverpool's D. Sc. in 1904; between 1905 and 1909 he was, successively, demonstrator, assistant lecturer, and special lecturer. In 1909 Barkla succeeded H.A. Wilson as Wheatstone professor of physics at King's College, London, and in 1913, only ten years after the publication of his first paper on X rays, Barkla was appointed professor of natural philosophy in the University of Edinburgh, where he remained until his death. He was elected a fellow of the Royal Society in 1912, appointed Bakerian lecturer for 1916, and in November 1918 was awarded the Nobel Prize for physics for 1917 for his discovery that each element emits a characteristic spectrum of X rays.

In 1907, after a special lectureship in advanced electricity had been created for him, Barkla married Mary Esther Cowell, elder daughter of the receivergeneral of the Isle of Man. They had three sons and a daughter. Their residence was always in a rural setting. Barkla was a tall, solid, healthy man with delicate hands; he had a friendly, charming manner and a great fondness for children. His recreations were golf and singing. "Barkla," H.S. Allen records, "was a deeply religious man, and like his ancestors was a faithful adherent of the Methodist Church."

Barkla's first researches at the Cavendish were measurements, employing standing waves and Rutherford's magnetic detector, of the velocity of transmission of electromagnetic waves along wires of different materials and diameters, a question that J.J. Thomson and A. Sommerfeld, among others, had tackled theoretically. In his third year at Cambridge, he began investigations of the secondary X rays emitted by substances in the path of a beam of X radiation, a topic toward which virtually all his researches were to be directed in the following forty years. The first studies, completed at Liverpool and published in June 1903,[1] showed that the secondary radiation emitted by "all gases"—in fact, sulfur was the heaviest atom involved—was of the same absorbability (average wavelength) as that of the primary beam—not, as Georges Sagnac (1898) reported of secondary X rays from solids, of distinctly greater absorbability.

Demonstration of the existence of such an unmodified scattered radiation was strong support for the "ether pulse" theory. According to this theory, X rays are the narrow pulses of radiation that classical electromagnetic theory requires be emitted when the rapid motion of the electrors in the X-ray tube is arrested by impact upon the anode. The classical theory—in contrast with the subsequent quantum theory (Compton effect, 1923)—further requires that as this pulse passes through matter, the loosely bound electrons contained therein must undergo accelerations whose time dependence (frequency, wavelength) is that of the electric field of the pulse. Thus these electrons must, in turn, emit electromagnetic radiation with the same time dependence; the energy of this "scattered" radiation is drawn from the energy of the primary pulse. Barkla's discovery of this unmodified secondary radiation was most welcome, making it unnecessary to introdcue extra hypotheses and analogical arguments (e.g., by J.J. Thomson[2]) to account for the theretofore accepted fact that the secondary radiation was softer (more absorbable, of greater average wavelength) than the primary.

Barkla also emphasized the not unexpected, but highly satisfactory, result that "this scattering is proportional to the mass of the atom." "This gives further support to the theory [the electron theory of matter] that the atoms of different substances are different systems of similar corpuscles, the number of which in the atom is proportional to its atomic weight."[3] The further possibility of using X-ray scattering for an experimental determination of this number was easily conceived when, in the autumn of 1903, J.J. Thomson published a calculation of the fractional energy loss of the X-ray beam per unit path length of the scattering substance due to this classical scattering process, obtaining $8\pi/3.\,Ne^4/m^2$, where e and m are the charge and mass of the electron, and N is the number of electrons per unit volume in the scattering substance.[4]

Barkla now measured the fractional energy loss due to scattering,[5] showing that, contrary to the general assumption,[6] this was not a negligible factor. From Thomson's formula there then came a value for N that Barkla described as in "close agreement" with "that calculated on the electronic theory of matter."[7] Actually, the results were rather embarrassing to this theory which supposed atoms to be composed solely of electrons, for the number of electrons per atom (although Barkla did not express his results in these revealing terms) came out only about five times the atomic weight. Through these same measurements Barkla believed that he had confirmed a striking feature of Thomson's formula, namely, that the energy loss is independent of the wavelength (hardness) of the X rays.[8] As others soon emphasized, this result holds only in the long wavelength limit.

Meanwhile, Barkla had found another property of the secondary radiation which argued strongly that X rays were indeed transverse electromagnetic radiations. On the ether pulse hypothesis, the radiation scattered at 90° with respect to the primary beam should be plane polarized; the intensity of the radiation scattered from a plane polarized beam would be zero in the direction of the electric field of these polarized pulses and would reach a maximum in the plane perpendicular to this direction. R.L. Wilberforce suggested to Barkla that he look for this polarization by scattering the scattered radiation and observing the distribution of intensity of this—necessarily very weak—tertiary radiation in the plane perpendicular to the secondary radiation.

It was two years before Barkla was able to perform this difficult experiment,[9] but by March 1904 he had demonstrated the polarization in a much simpler way.[10] It occurred to him that the electrons impinging upon the anode of the X-ray tube should be more accelerated in the direction of their motion than perpendicular to it, and thus the radiation they would emit in the plane perpendicular to their motion would have a stronger electric field perpendicular to that plane than in it, i.e., the primary X-ray beam should be partially polarized. Rather than rotating his detector—an ionization chamber in which the density of ions was measured by the rate of leak of the charge on a gold-leaf electroscope—about the primary beam, Barkla rotated the plane of polarization of the beam by rotating the X-ray tube (and stream of cathode rays) about the beam as axis. A 15 percent variation of intensity was found.

Barkla became ever more firmly convinced of the ether pulse theory, for it had guided him to the discovery of new phenomena and had given his discoveries meaning and general significance. Understandably, he was aroused when in September 1907 W.H. Bragg published an attempt to construe the known facts about X rays, including Barkla's phenomenon of polarization, on the hypothesis that the rays are corpuscular, namely, a pair of oppositely charged particles with a net angular momentum.[11] Searching for a crucial experiment, Barkla hit upon the angular distribution of the scattered radiation with respect to the direction of the primary beam. Supposing the beam to be unpolarized, Barkla averaged the scattered radiation from electrons accelerated in all directions in the plane perpendicular to the beam—which, curiously, had not previously been done—and found $I_\theta = I_{\pi/2}(1 + \cos^2\theta)$, the "Thomson" scattering distribution. He then verified the rather surprising conclusion that the intensity of the scattered radiation was a minimum at 90° with respect to the beam.[12] This "waist" in the distribution of the scattered radiation came to be generally regarded as one of the strongest pieces of evidence that X rays were electromagnetic radiations interacting with matter according to the Maxwell-Lorentz theory. The controversy with Bragg in the letter columns of *Nature* following Barkla's presentation of his "quite conclusive evidence in favor of the ether pulse theory"[13] attracted considerable attention and resulted in considerable personal stress for Barkla. Although Bragg had less right on his side, he outclassed Barkla as a strategist of controversy as well as of physical research.

It was by confining himself ot the scattering by light elements that Barkla was able, at first, to deny that the secondary X radiation was softer than the primary. and thus to construe the emission of these secondary radiations as a classical scattering of the primary beam. In his polarization measurements of 1904 Barkla had found that the effect (i.e., variation of the intensity of the secondary radiation with the angle of rotation of the X-ray tube) tended to disappear as the atomic weight of the scatterer increased. This led him to recognize that a softened secondary radiation from heavier elements did indeed exist and moreover was emitted isotropically, thus with no relation to the direction or polarization of the primary beam. Barkla tried to fit these two leading characteristics (softer, isotropic) into the ether pulse theory by supposing that in heavier atoms the electrons were no longer free to follow the electric field of the pulse: rather, their motion was constrained by intra-atomic forces and neither the direction nor the time dependence of their accelerations was that of the electric field of the pulse.[14]

This physical picture did not, however, lead Barkla immediately to speculate that such secondary radiations may not be pulses but highly homogeneous wave trains, X-ray spectral lines. His first efforts were directed toward the intensity of this secondary radiation: ignorance of the peculiar constitution and conditions of excitation of these characteristic X rays almost inevitably led Barkla astray.[15] He then went off on a sidetrack, an attempt to determine the relative atomic weight of nickel through the dependence of the properties of secondary radiation upon atomic weight.[16] This was not a complete waste, for it raised the problem of precise discriminations of hardness—Barkla was beginning to fasten upon the hardness of the secondary radiation as characteristic of the element. At this point (early 1907) Barkla was joined by Charles A. Sadler, demonstrator in physics at Liverpool. Their first results, published that September, showed the homogeneity of this secondary radiation (the criterion being exponential decrease of intensity in traversing a homogeneous absorber).[17] During the next four years they followed up this fundamental discovery. Two groups, A and B (afterward labeled L and K, respectively), of homogeneous X rays from each heavy element were distinguished; and the condition (analogous to Stokes's law of fluorescence) was established that they could be excited only by exposing the element to X rays harder than its own characteristic X rays.[18] The natural and widespread—although not universal—assumption that these characteristic emissions were monochromatic X-ray "spectral lines" caused this work to be recognized immediately as "of the utmost importance."[19]

By 1911, after barely ten years of research on secondary X rays, Barkla had achieved an international reputation as the leading physicist in this field. Five years later he had lost this position and was rapidly isolating himself from the professional community he had led. To say this is not to dismiss him from further consideration. On the contrary, Barkla's later years are of great interest to the historian of science precisely because they offer a striking example of a man "passing out of physics"—departing so far from the accepted conceptual foundations and methodological canons of his field as to preclude acquiescence in its consensus. That Barkla had tended from the start to cite only his own work and to base theoretical conclusions solely on the phenomena he investigated himself may have helped prepare the way for the professional seclusion of his later years.

While it was evident to his contemporaries that Barkla was weak as a theorist, it was not at all evident to Barkla. By 1916 his sense of proportion had eroded so far that he devoted the larger part of his Bakerian lecture, "On X-rays and the Theory of Radiation"[20] to his own theoretical consideration—an involved and confused attempt to express his results in terms of the quantum, energy levels, and energy balance in the excitation and emission of radiation by atoms. His conclusion that "absorption is *not* in quanta of primary radiation" was already scarcely defensible in 1916; it is an index of Barkla's increasing rigidity that he repeated himself, *verbatim*, in his Nobel lecture in 1920.[21]

After 1916 Barkla committed himself to the pursuit of a will-o'-the-wisp he called the "J-Phenomenon." Originally a radiation more penetrating (and thus, presumably, of shorter wavelength) than that of the K series, about 1920 the phenomenon was transferred to absorption, about 1925 to the conditions of excitation of the X-ray tube, and finally, about 1930, to a state of the absorbing-scattering substance. Barkla's reaction to the Compton effect—which seemed to threaten much of his own work, and all that he stood for—suggests that his J-Phenomenon served also to protect his personal conceptual world from external challenge. The J-Phenomenon shows that "a change in the activity (photoelectric action, ionization, absorption) of a radiation can take place without a change in the wave-length.... we are very sceptical as to whether a change in the diffraction angle in [Compton's] spectroscopic measurements really does correspond to a change of wave-length."[22].

NOTES

1. "secondary Radiation from Gases Subject to X-Rays," in *Philosophical Magazine*, 6th ser., 5, 685–698.

2.*The Conduction of Electricity Through Gases* (Cambridge, 1903), p. 270.

3.*Philosophical Magazine*, 6th ser., **5** (June 1903), 697.

4. Thomson, op, cit., pp. 268–270. Due to an error in integration, which Barkla caught, Thomson found $4\pi/3$.

5. "Energy of Secondary Röntgen Radiation," in *Philosophical Magazine*, 6th ser., **7** (May 1904), 543–560.

6. E.g., E. Rutherford and R.K. McClung, *Philosophical Transactions of the Royal Society*, **A196** (1901), 38–39.

7.*Philosophical Magazine*, 6th ser., **7** (May1904), 556–557.

8. This result, apparently at variance with the very notion of hardness, caused Thomson no difficulty because he did not think this process contributed appreciably to the absorption.

9. "Polarization in Secondary Röntegen Radiation," in *Proceedings of the royal Society*, **A77** (Jan. 1906), 247–255.

10. "Polarization in Röntgen Rays," in *Nature*, **69** (17Mar. 1904), 463.

11. W.H. Bragg, "On the Properties and Natures of Various Electric Radiations," in *Philosophical Magazine*, 6th ser., **14** (Sept. 1907), 429–449.

12. "The Nature of X-Rays," in *Nature*, **76** (31 Oct. 1907), 661–662,

13.*Ibid*.

14. "Secondary Röntgen Radiation," in *Nature*, **71** (9 Mar,1905), 440; "Secondary Rötgen Radiation," in *Philosophical Magazine*, 6th ser., **11** (June 1906), 812–828.

15. "Secondary Röntgen Rays and Atomic weight," in *Nature*, **73** (15 Feb. 1906), 365.

16. “The Atomic Weight of Nickel,” in *Nature*, **75** (14 Feb. 1907), 368.

17. Barkla and sadler, “secondary X-Rays and the Atomic weight of Nickel,” in *Philosophical Magazine*, 6th ser., **14** (Sept, 1907), 408–422.

18. Barkla and sadler,“The Absorption of Röntgen Rays,” *ibid*., **17** (May 1909), 739–760; Sadler, “Transformations of Röntgen Rays,” *ibid*., **18** (July 1909), 107–132; Barkla, “The Spectra of the Fluorescent Röntgen Radiations,” *ibid*., **22** (Sept.1911), 396–412.

19. J.J Thomson, “Röntgen Rays,” in *Encyclopaedia Britannica* (11th ed., 1911).

20.*Philosophical Transactions of the Royal Society*, **A217** (1917), 315–360. Foreshadowed in “Problems of Radiation,” in *Nature*, **94** (18 Feb. 1914), 671–672: “X-Ray Fluorescence and the Quantum Theory,” *ibid*., **95** (4 Mar. 1915), 7: “Indeed, the theory was forced upon the writer directly by the experimental results, and it was only afterwards that he was reminded of some similarity with the theory of Bohr....”

21. “Characteristic Röntgen ratiation.,” in *Les Prix Nobel en 1914–1918* (Stockholm, 1920), Barkla’s only publication in the five years 1918–1922.

22. Barkla and R.S. Khastgir, “The ‘Modified Scattered’ X-Radiation,” in *Nature*, **117** (13 Feb. 1926), 228–229.

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An excellent chronological bibliography is appended to H.S. Allen, “Charles Glover Barkla, 1877–1944,” in *Obituary Notices of Fellows of the Royal Society of London*, **5** (1947), 341–366. The only publications whose absence I have noted are Barkla’s Nobel lecture (1920) and “‘J’-Phenomenon and X-Ray Scattering,” in *Nature*, **112** (12 Nov. 1923), 723–724. See also F. Horton, “Prof. C.G. Barkla, F.R.S.,” *ibid*., **154** (23 Dec.1944), 790–791; Niels H.deV. Heathcote, *Nobel Prize Winners in Physics 1901–1950* (New York, 1953), pp. 141–150; but above all R.J. Stephenson, “The Scientific Career of Charles Glover Barkla,” in *American Journal of Physics*, **35** (Feb. 1967), 140–152.

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