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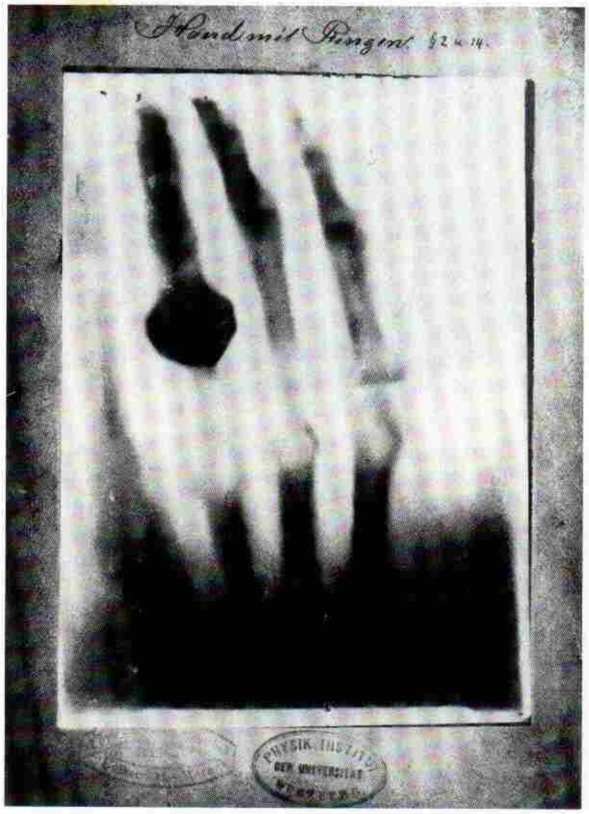
WILHELM CONRAD RÖNTGEN AND THE GLIMMER OF LIGHT

A faint fluorescence spied out of the corner of a man's eye in a darkened laboratory heralded the discovery, one hundred years ago, of 'a new kind of rays' that would revolutionize physics and medicine.

Howard H. Seliger



'HAND MIT RINGEN,' Röntgen's second x-ray shadowgraph of his wife's hand, with slightly more contrast than the first. Through no design of Röntgen's and much to his surprise, copies of these dramatic photos (both taken on 22 December 1895) were circulated rapidly throughout the world and in the press, turning him into an instant celebrity. (All photos are from Otto Glasser, *Wilhelm Conrad Röntgen und die Geschichte der Röntgenstrahlen*, Springer-Verlag, Berlin, 1931.)

On Friday evening, 8 November 1895, Wilhelm Conrad Röntgen, a 50-year-old professor of physics and recently elected rector of the Julius Maximilian University of Würzburg, Germany, was unusually late for dinner. And when he did arrive at the family living quarters above his laboratory in the Physical Institute, he did not speak, ate little and then left abruptly to return to the experiments that had so disturbed him that afternoon.

Hours before, after more than a year of preparation and while testing his cathode-ray tube prior to carrying out his first experiment, Röntgen had discovered[1] *"eine neue Art von Strahlen"*—"a new kind of rays." These invisible rays, which Röntgen called *X-strahlen*—"X-rays" ("X" for unknown)—not only would mark the beginning of the era of atomic physics and of an undreamed-of succession of medical applications but also would illuminate this discoverer's niche in the pantheon of scientific immortals.

On that Friday afternoon a century ago, a faint glimmer of light from a fluorescent screen caught Röntgen's eye and lit his path to discovery.[2] His catching that first glimpse was no accident. Chance favors those prepared to see, and Röntgen was superbly prepared. Had he not seen that faint fluorescence at the end of his laboratory table as he tested his equipment, he would have seen the screen glow brightly a few minutes later, for he had intended to place the screen next to the face of his black-cardboard-covered cathode-ray tube. Röntgen's first observation was followed that evening by a second fortuitous discovery, which was among the most important and immediate applications of a physical phenomenon in the history of science: the visualization of the bones inside live human beings.

Röntgen was looking for the "invisible high-frequency rays" that Hermann Ludwig Ferdinand von Helmholtz had predicted from the Maxwell theory of electromagnetic radiation. (Their true origin was to be understood much later.) Following the advice of that towering figure of German science had previously led Röntgen to what he considered his most important scientific contribution. Years earlier von Helmholtz had prevailed upon both Heinrich Hertz and Röntgen to test the experimental predictions of James Clerk Maxwell's new theory. In 1887 Hertz, at the University of Bonn, produced electric spark discharges and demonstrated the propagation of electromagnetic waves through space. The next year Röntgen verified that a dielectric moving in an electric field induces a magnetic force that acts on the dielectric.

More recently von Helmholtz had predicted the existence of electromagnetic radiations with frequencies much higher than the natural frequencies of inducible dipoles

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RÖNTGEN as shown in a photograph from "Les Prix Nobel en 1901," a booklet issued in conjunction with the very first Nobel Prizes. Röntgen was awarded the physics prize for discovering x rays.

in matter. These radiations would therefore interact minimally with matter and exhibit great penetrating power. Since cathode rays were then thought by the German school of physics to be "ether" phenomena, it was proposed that these high-frequency radiations might be present in cathode-ray discharges. A paradox arose: If these radiations interacted minimally with matter, that would explain why they had not yet been detected—but how could their existence be verified?

This was precisely the type of research problem in which Röntgen excelled: the painstaking measurement of difficult-to-detect electromagnetic phenomena. Röntgen was red–green color-blind, and color-defective individuals tend to become extremely discriminating observers, unconsciously compensating for their deficiency by correlating shapes, shades and textures of familiar objects with their true colors. Indeed, Röntgen's entire scientific career was a succession of exceedingly difficult physical observations, often requiring detailed construction of apparatus.

Missed opportunities

The discovery of cathode rays had followed continued improvements in the art of pumping gases out of closed containers. The first step in the chain of discovery leading to x rays was the Geissler discharge, the same gas discharge now used for advertising displays. In the late 1870s the eclectic English scientist, William Crookes, applied high-vacuum techniques to the Geissler discharge, thereby discovering the "Crookes dark space." At the low pressures Crookes produced, the Geissler discharge disappeared and as the voltage was increased a new type of visible discharge appeared: a beam moving in straight lines from the cathode. He had rediscovered Johann Wilhelm Hittorf's *Kathodestrahlen*—"cathode rays." In a short time Crookes tubes (in the shape of present-day television tubes) and Hittorf tubes (pear shaped) became standard equipment for cathode-ray research throughout the world.

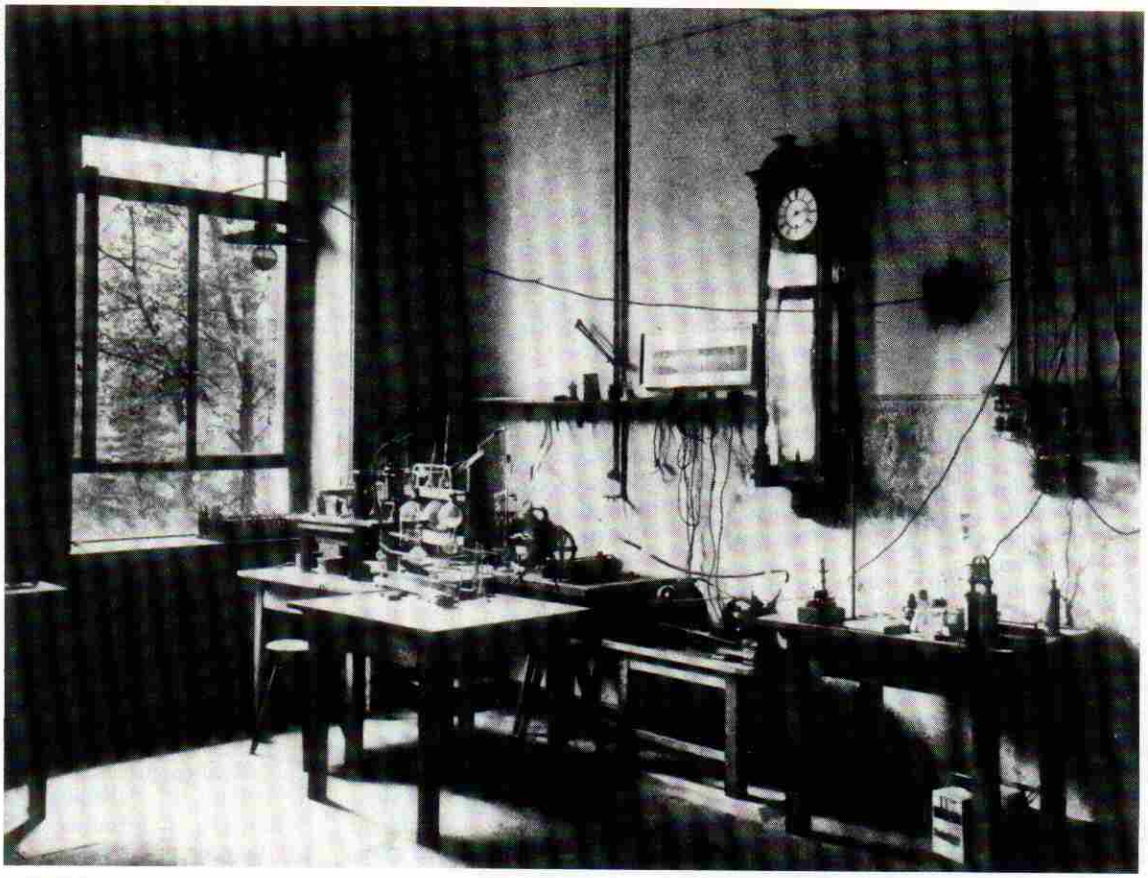
By increasing the applied voltages (necessary to produce the discharge) Crookes also inadvertently produced the conditions for the generation of x rays. Only a small fraction (on the order of 10^{-4}) of the energy of Crookes's cathode rays was emitted as x rays. The remainder was dissipated as heat. Therefore cathode-ray tube operation was normally limited to gas pressures and voltages (approximately 9 keV) sufficient to produce visible beams, but not so great that the glass faces of the tubes would melt where the rays impinged.

In the 1880s Crookes also developed the prototype of the modern x-ray tube. Using a concave cathode to focus cathode rays to a spot on an iridio-platinum anode, he unknowingly optimized the efficiency for production of x rays. During this research he was occasionally bothered by unaccountable fogging of unexposed photographic plates that he stored near his equipment. On occasion he even returned the plates to their manufacturer as defective. Later, when news of Röntgen's discovery reached Crookes, it may have become distressingly obvious to him that he owed the plate manufacturer an apology.

In 1888, seven years before Röntgen's discovery, Philipp Lenard, following Eilhard Wiedemann's prediction, attempted to observe high-frequency ultraviolet radiations from a cathode-ray tube. He failed. Had he evacuated his tube to Crookes's low pressures, he would have had to apply higher voltages that generated energetic x rays and would have immediately detected fluorescence of crystals placed just outside the blackened 2.4-millimeter-thick quartz face of his tube. But he produced only soft x rays, which the quartz absorbed completely.

Lenard missed the golden ring a second time in 1893, when he served as Hertz's assistant. This time he did produce much lower pressures in his cathode-ray tubes, requiring much higher operating voltages. The much-higher-energy cathode rays that resulted were able to penetrate thin aluminum windows into the outside air, where they produced brilliant fluorescence of a calcium sulfide phosphor. Lenard subsequently used fluorescent screens of pentadecylparatolylketone crystals, obtained from the chemist Friedrich Krafft. Lenard saw intense, easily visible fluorescence of the ketone screens and intense blackening of photographic plates, but "only for a distance in air of a few centimeters."[3] He did find occasional unexplained blackening of a photographic plate covered by a sheet of cardboard thick enough to stop his cathode rays, and his extracted rays "still showed electrical discharge effects at much greater distances," up to 30 cm, in air.

These were x-ray effects, but Lenard was unprepared to recognize them. It apparently did not occur to him to repeat his experiment of 1888 under his improved high-vacuum conditions. He might have done so, but his research was interrupted by the sudden death of Hertz on the first day of 1894. Lenard then assumed Hertz's duties as director of the physical laboratory at Bonn and spent the year completing the editing and publication of Hertz's three-volume final scientific work. Further delay ensued when in 1895 Lenard accepted a professorship at the University of Breslau, which he relinquished within the year, as there were no facilities for continuing his cathode-ray experiments. By January 1896, when he was at the Technische Hochschule in Aachen and had finally returned to his cathode rays,



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CORNER OF RÖNTGEN'S LABORATORY in the Würzburg Physical Institute, containing some of his original equipment. The "shoestrings" on which he carried out his research are still hanging from the wall in this 1923 photograph.

Röntgenstrahlen rather than *Lenardstrahlen* were being announced in the world's newspapers.

The first glimmer

Lenard's report that his extracted rays "still showed electrical discharge effects at much greater distances" must have provided the final impetus for Röntgen's decision in 1894 to abruptly change the direction of his research to cathode rays. He may have inferred that Lenard had inadvertently detected von Helmholtz's predicted high-frequency radiations but was unaware of their having been predicted.

(In writing about Röntgen, one is often forced to speculate about his views and motivation, in that he was an extremely reticent man. Except for a lecture at his own university the month following his discovery, Röntgen declined all speaking invitations, even as honorary degrees flooded in, even upon receiving the first Nobel Prize in Physics in 1901. On one occasion, in response to a question, his brief reply was, "There were some aspects of the Hertz–Lenard experiments with cathode rays that needed further investigation." On one other occasion he said only that he had been "looking for invisible high-frequency radiations from cathode rays.")

Röntgen purchased a small number of Hittorf-type cathode-ray tubes. He wrote to Lenard for advice on reproducing Lenard's cathode-ray experiments, even requesting a "reliable" tube, according to a Lenard biographer. Late in the fall of 1895 Röntgen had reproduced all of Lenard's experiments. He was now ready for his first attempt to detect von Helmholtz's penetrating, invisible high-frequency electromagnetic radiations. He used a fluorescent screen as his detector—George G. Stokes's barium platinocyanide crystals, adhering to a thin sheet of paper.

Röntgen's plan was simple: to eliminate all extraneous light so that he would have the highest sensitivity for detecting any fluorescence in his test screen that might be produced by von Helmholtz's high-frequency rays. Then—if operating the tube at the lowest pressures (highest voltages) increased the intensities of the sought-after rays, if the cathode rays were completely absorbed in the tube's glass walls (eliminating their fluorescence effects on the screen), if the cathodoluminescence produced in the glass face were blocked, and if he examined the screen carefully in the darkened room—he might observe a trace of fluorescence, at least with the screen placed just outside the face of his tube.

He covered the tube and the sparking interrupter completely with black cardboard. He drew the curtains of his laboratory windows. Then he closed a switch, producing a series of high-voltage pulses of cathode rays, and looked carefully for any stray light that would indicate that the glass tube had not been completely shielded. Out of the corner of his eye he discerned a pulsating glimmer at the end of his laboratory table. Was some sliver of stray light being reflected from an object on his bench?

He opened the switch. The glimmer disappeared. He closed the switch. Again, a wispy glimmer. A lighted match revealed that the source of the glimmer was his barium platinocyanide fluorescent screen, still sitting more than a meter from the darkened tube. Were radiations from the tube producing the glimmer? He placed a sheet of black cardboard between the screen and the tube, then another, then a book of 1000 pages, then a wooden shelf board more than two and a half centimeters thick. The glimmer remained. In the dark he moved the screen closer and closer to the face of the blackened tube, and finally to its intended position directly in front of the tube. The glimmer brightened to a green, pulsating cloud. (The mercury contact interrupters then used with Ruhmkorff induction coils to produce pulsed high voltages in cathode-ray tubes did not make and break currents reproducibly. Hence the x-ray intensities were variable and produced variations in the fluorescence of test screens.) Röntgen now moved the screen farther and farther away, this time up to 2 meters. The bright glow became a faint glimmer, barely visible even to his dark-adapted eyes. He repeated and re-repeated his observations. That was the evening he was very late for dinner.

Later that same evening, still working in the dark, Röntgen tested thin plates of aluminum, copper, lead and platinum for their abilities to shield the fluorescent screen from the new radiations. Only lead and platinum absorbed the radiations completely. A lead sheet placed halfway across the screen shielded the covered half of the screen, which became dark. The line between the dark and light portions was sharp, analogous to shadows cast by light rays.

Then Röntgen made one of the most bizarre and serendipitous observations in the history of science. He held a small lead disk in front of the brightly glowing green screen. What he saw was not only the anticipated dark circular shadow of the disk but also the shadows of the bones of his own fingers—an apparition so unearthly as to undoubtedly stir in him thoughts of his own mortality. He quickly withdrew his hand and the disk. Then he extended his open hand, and the dark skeletal shadows of his fingers moved slowly across the still brightly glowing screen.

Mistrustful of his own senses—he recounted in his lecture at Würzburg, "I . . . still believed that I was the victim of deception when I observed the phenomenon of the ray"—he turned to photographic film for greater objectivity and for permanent records. In the following weeks Röntgen was driven to secrecy and to feverish experimental verification and reverification of x rays. Shortly before Christmas, he invited his wife, Bertha, into the laboratory and had her place her hand for 15 minutes on a film cassette opposite his cathode-ray tube. Little could he have known that the morbid image of the bones of Bertha's fingers would catapult him to worldwide celebrity.

Serendipity

The glimmer of the barium platinocyanide screen at the far end of Röntgen's laboratory table was orders of magnitude dimmer than the dazzling fluorescence produced by cathode rays in Lenard's test screens, much dimmer than the luminescence produced by cathode rays in the glass walls of Hittorf and Crookes tubes. However, in the minutes required to adjust the curtains and to test whether they excluded all outside light, Röntgen's visual sensitivity for discerning that first glimmer increased by a factor of approximately 1000. His eyes had changed over from photopic, or cone, vision to scotopic, or rod, vision. Fortunately for the color-blind Röntgen, rod visual sensitivity is independent of cone pigment deficiencies.

A second fortuitous factor arose from the then-unknown physiology of the retinal rods and cones. At the expense of fine spatial resolution, many rod cells are connected in parallel to a single neuron. Hence light-intensity thresholds for the rod visual system are much lower than for the cone visual system. If a viewer first sees the image of a dim point source indirectly—such as a star seen in peripheral vision—it is the result of the image being focused on the retina's parafoveal region, which contains the major concentration of rods. Once the viewer becomes aware of the image or makes a conscious effort to see the star, the eye will focus the faint image onto the central, foveal region, which contains the highest concentration of cones but no rods. The foveal cones will send negligible signals to the brain, and the visual image will disappear. Early astronomers knew of this effect and learned always to look indirectly at faint objects. Röntgen similarly first saw the first glimmer from his barium platinocyanide screen out of the corner of his eye. But his star was earthbound, and its image was much larger than those viewed by the early astronomers. The fluorescent screen was a square many centimeters on a side, so that even after he directed his attention to the source of the glimmer, the image of the screen extended into his parafoveal region.

As an added fortuitous factor, the blue-green fluorescence emission of the heat-treated barium platinocyanide crystals of Röntgen's test screen significantly overlapped the visual spectral sensitivity of the rods of the dark-adapted human eye ($\lambda_{\max} \approx 507$ nm), so that the fluorescence was optimally effective in stimulating the rods of his retina.

Of the two types of x rays—"characteristic" rays and bremsstrahlung—only the latter were detected in Röntgen's experiments. (Characteristic x rays emitted from the silicon atoms of the cathode-ray tube's glass face or from an aluminum window were less than 2 keV in energy and could not penetrate to the outside of the tube.) Judging from his reported relative transmissions in aluminum, Röntgen's bremsstrahlung distribution had maximum energies of 30–50 keV, with peak intensities at around 20–30 keV as a result of energy losses by the incident electrons in the thick glass face of the tube. At such energies, x rays interact with matter predominantly by the photoelectric effect. There were three fortunate consequences:

▷ The probability of producing a photoelectron (which can then excite fluorescence) varies as approximately the fourth power of the atomic number of the atoms within the microcrystals making up the fluorescent screen. Because of the nature of the ionization produced by charged particles passing through matter, Röntgen's barium platinocyanide and Lenard's ketone screens were equally effective in detecting cathode rays. However, the barium and platinum atoms in Röntgen's screens made them approximately 100 times more efficient for the detection of x rays than Lenard's low-atomic-number screens.

▷ Calcium, atomic number 20, constitutes approximately 10 percent of bone, giving bone a photoelectric absorption up to ten times that of tissue. For x rays of approximately 25–30 keV, this absorption ratio of bone to tissue is a maximum. Hence the shadowgraphs of the bones of Bertha's hand exhibited optimum contrast.

▷ The production of photoelectrons within the silver halide crystals of the photographic emulsion also was maximum for x rays of around 25–30 keV.

Priority

Röntgen may have been seized with a sense of foreboding about the unearthly visual effects he had just witnessed.

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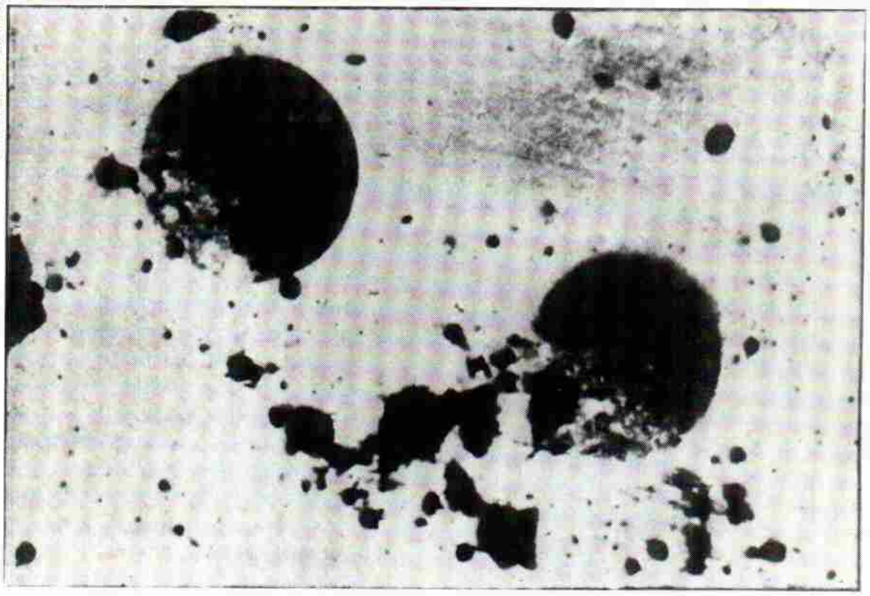

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FIRST SHADOW PHOTOGRAPH produced by x rays. In 1890 Arthur W. Goodspeed, a professor at the University of Pennsylvania, inadvertently left two coins on an unexposed photographic plate next to a Crookes tube. Among the clutter of plates that he developed the next day was this one, with its unmistakable but then-unexplainable shadows.

His pulsating fluorescence appeared as "luminous green clouds" floating in air. (In the dark, without visual reference points for perspective, dim light sources seem to float.) It seemed impossible that such easily observable effects had not been seen by Lenard, Crookes, J. J. Thomson or by any of the other cathode-ray researchers during the previous two decades. So why was he, Röntgen, seeing these ethereal glows and the shadows of bones? Röntgen was aware that Crookes, just prior to discovering cathode rays, had become involved with spiritualism following the death of his brother. (See Janet Oppenheim's article in PHYSICS TODAY, May 1986, page 62.) Did the loss of a loved one make a person more sensitive to spiritualistic phenomena? The year 1894 was not only when Röntgen had decided to study cathode rays but also when three of his close friends had died: Hertz, von Helmholtz and his teacher, August Eduar Kundt. Crookes had reported seeing "luminous green clouds" during séances. The skeletal shadows of bones were also characteristic of spiritualistic phenomena. Were cathode rays somehow associated with spiritualism? Was it coincidence that Thomson, the English leader in cathode-ray research, also was studying psychic phenomena? Might Röntgen's own bizarre shadow images of bones be the link between science and spiritualism for which Crookes had been searching?

Then, perhaps, came a sobering thought. Röntgen was acutely aware of the ridicule heaped upon Crookes for his spiritualistic investigations by some of his colleagues, despite his scientific stature, and that it had cost him election to the presidency of the Royal Society. Might the discovery of x rays now ensnare Röntgen in the raging spiritualism controversy, undermining his own legacy of scientific accomplishments? His career to date had been moderately successful. He was director of the Physical Institute at Würzburg and rector of the university, with a personal research laboratory. But Würzburg was not Bonn or Berlin or Heidelberg, and Röntgen's research, while reflecting significant experimental ingenuity, had not recently been at the forefront of science. His best work, the dielectric induction experiments prompted by von Helmholtz, had been carried out eight years earlier.

But more likely an even stronger drive took hold in Röntgen. The scientist's Grail, priority of discovery, might be his. But the new radiations were so easily detectable! Lenard had detected electrical discharge effects. Others must have made similar observations, probably of the same fluorescence Röntgen was now observing, and recorded them in laboratory notebooks under "effects of cathode rays." The slightest hint of new rays, and previously ignored observations would become "obvious" and prior discoveries. In that case, his almost two-year-long efforts and his momentous discovery on 8 November could end up as a mere footnote in Lenard's or Crookes's or Thomson's publication of the discovery of new rays ("W. C. Röntgen has recently repeated our earlier experiments"). There was only one avenue open to sole priority—publication in a scientific journal before any of the established workers could "appropriate" the discovery.

Röntgen had the advantage of time. No one had reported the amazing penetrating power of these new rays. Neither had anyone seen bizarre shadows of bones on a fluorescent screen. An extensive description of the properties of these new rays, of their fluoroscopic effects, of the fact that they were different from cathode rays, should far outweigh any priority claim based on previous chance observations of electrical discharge effects or fluorescence.

Thus, in the weeks following his discovery, Röntgen became uncommunicative and preoccupied, working, eating and even sleeping in the laboratory for days at a time. After Christmas, armed with experiments demonstrating the physical reality and unusual properties of x rays, with shadow photographs of the bones of Bertha's hand and, more prosaically, of a set of brass weights enclosed in a wooden box, Röntgen composed, with uncharacteristic speed, a summary of his results. On 28 December he asked his good friend Karl Lehmann, president of the Physical Medical Society at Würzburg, to prevail upon the editors of the *Sitzungberichte der Physikalisch-Medizinischen Gesellschaft zu Würzburg* to include his handwritten manuscript, "Über eine neue Art von Strahlen," in its December 1895 proceedings, even though the paper had not been presented at the December meeting and even though the proceedings were already at the printers. It was not possible at that late date to include his revolutionary x-ray shadowgraphs.

In the next three days he hurriedly produced enough copies of the crucial shadowgraphs to distribute them, along with preprints of the paper, to the leading physicists in Germany, England, France and Austria. He mailed the packages himself, on New Year's Day 1896. As he did so, he acknowledged his anxieties and his unseemly haste about achieving priority of discovery, remarking to Bertha, "*Nun wird man dem Teufel zahlen müssen*"—"Now the devil must be paid."

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Celebrity

One of the recipients of Röntgen's photographs and reprints was Franz Exner, a colleague from Röntgen's early days in Kundt's laboratory who was now director of the Physical Institute at the University of Vienna. Exner immediately showed the shadow photographs to colleagues invited to his home. Among them was a visitor from Prague, Ernst Lecher. Lecher immediately conveyed the report of the x-ray shadow photographs to his father, the editor of *Die Presse* in Vienna. On 5 January 1896 Röntgen's discovery was described on the front page of the paper's Sunday edition. Immediately thereafter the discovery of x rays was reported throughout the world—well before the scientific journal containing Röntgen's first paper left the printer's presses.

The news produced an instant sensation, not only among the public but within the medical community, which recognized the promise of a new diagnostic tool. By the following week Röntgen had been invited to demonstrate his x rays and photographs before Kaiser Wilhelm II, and was awarded the first of many medals, the Prussian Order of the Crown, Second Class. Physics laboratories throughout the world immediately verified Röntgen's discovery and produced their own x-ray photographs: hands, feet and fractures; fish, fowl and coins in purses. By February the first x-ray treatment for cancer was performed.

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THE EDISON APPROACH to x rays. This advertisement appeared in *Electrical Engineer* only four months after the announcement of Röntgen's discovery.

There were priority claims, but chance observations paled in the light of Röntgen's monumental first paper and his x-ray photographs. But not completely. There was much confusion about whether x rays were qualitatively different from the cathode rays Lenard had extracted. In his first paper, Röntgen, intent on priority, concluded that x rays could not be cathode rays, by virtue of the tremendous absorption differences. However, in his third paper, two years later, he reported that the absorption of soft x rays was similar to that of hard cathode rays and therefore he was not nearly as certain that these rays were different. X rays had a fan-shaped distribution, produced when cathode rays were absorbed. Outside Lenard's aluminum foil window, the initially parallel beam of cathode rays also took on a fan-shaped distribution. Evidence that cathode rays were electrons had not yet been presented, and the multiple scattering of electrons, which would explain their fan-shaped distribution, also was unknown. One assumption was therefore that Lenard's cathode rays had interacted with the aluminum to produce a new radiation, "Lenard rays." "Röntgen rays," it seemed, might very well be a highly penetrating tail of the distribution of "Lenard rays." In 1896 the British Royal Society contributed to the uncertainty by awarding its Rumford Medal to Lenard and Röntgen for the discovery of "Lenard or Röntgen rays." But since Röntgen had initiated the medically significant technique of x-ray photography of bones, the scientific community and the general public continued to use the term "Röntgen rays" or "x rays," as they have to the present day. (The embittered Lenard, however, referred only to "high-frequency radiation.")

Lenard's experiments with cathode rays laid the groundwork for Röntgen's discovery of x rays, for Thomson's discovery, two years later, that cathode rays were electrons and for Einstein's discovery, four years after that, of the photoelectric effect. Lenard's resentment focused on these individuals, who he felt had unfairly deprived him of credit for those discoveries. Even his own 1905 Nobel Prize, recognizing his cathode-ray work, appeared to be little consolation. In his Nobel lecture Lenard indicated that he had made available to Röntgen a new type of cathode-ray tube in which a platinum cylinder served as a support for the thin aluminum windows through which the cathode rays were transmitted. Because platinum's efficiency for the production of x rays is much higher than that of glass or aluminum, Lenard stated, "the discovery [of x rays] at this stage of development appears to follow automatically." However, because the platinum tube was concentric with the cathode-ray beam, it would have yielded negligible additional bremsstrahlung. There was one other type of Lenard tube, but in either tube the efficiency for production of bremsstrahlung would have been at best equivalent to, and more likely less than, that in the thick glass face of a Hittorf or Crookes tube. So Lenard's tubes could not have played a decisive role in Röntgen's discovery.

Lenard's weakness in physical theory, the real reason for his difficulty in translating his experimental results into discoveries, developed into an antipathy toward theoretical physics. Later, Germany's loss of World War I inflamed the Anglophobia and anti-Semitism that had played a part in his resentment of Röntgen, Thomson, Einstein and even Hertz. He attacked Einstein and his relativity theory and, by association, labeled theoretical physics as racially inferior *Judenphysik*. His four-volume work on *Deutsche Physik*, written during the Nazi period, did not include Röntgen's name—or Einstein's.

Radioactivity?

The uproar over the discovery of x rays took Röntgen away from the laboratory during the most productive period of his life. While he had suggested the obvious next step of enhancing the photographic effect of x rays by placing his barium platinocyanide screen directly on his photographic plate, he had not yet taken it. Had he done so, he might have found from control experiments (exposing the plate to the screen in the absence of x rays) that the barium platinocyanide crystals produced a general blackening of the film. That would have been due to additional unknown rays: the densely ionizing alpha particles from small amounts of the (then undiscovered) radium present in barite ores in equilibrium with its short-lived α-emitting daughters Rn, RaA and RaC′.

On observing this blackening, Röntgen would have tested whether Stokes's other fluorescent screen, uranium phosphate, produced similar effects. This time he would have observed significant plate-blackening effects, not only of the α particles from uranium but of the beta particles from its short-lived daughters. Simple substitution experiments with fluorescent and nonfluorescent uranium compounds, such as those Henri Becquerel carried out, would have isolated uranium as the source of the new radiations.

Had fame not diverted Röntgen's attention, the 1903 Nobel Prize, honoring the discovery of radioactivity, might have gone to Becquerel and the Curies—and to Röntgen.

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