HEINRICH HERTZ AND THE DEVELOPMENT OF PHYSICS

In addition to confirming Maxwell's electromagnetic theory, Hertz's experimental and theoretical work one hundred years ago helped lay the foundation for quantum theory and relativity.

Joseph F. Mulligan

The discovery that electromagnetic radiation in the microwave and radio regions of the spectrum displays the same basic behavior as visible light—reflection, refraction, diffraction, interference, polarization—was made in Karlsruhe in 1888 by Heinrich Rudolf Hertz. Some special events last year marked the centennial of Hertz's momentous discovery. The Technical University in Karlsruhe, at which Hertz did his electromagnetic research, held a symposium on Hertz and the consequences of his work, and devoted one complete volume of its publication *Fridericiana* to him.[1] In the US, the Microwave Theory and Techniques Society of the Institute of Electrical and Electronics Engineers held a symposium in New York City to celebrate Hertz's achievements. On display at this meeting, from the Science Museum in London, was a refurbished set of replicas of Hertz's original apparatus.[2] These replicas were exhibited at the MIT Museum in Cambridge, Massachusetts, before returning to London late last year.

These tributes to Hertz concentrated in great part on his life, his experiments at Karlsruhe and the significance of his work for microwave and radio-frequency technology. While this article will look at these more well-known aspects of Hertz's work, it also will cover his lesser-known work, including his theoretical contributions to electromagnetism and his work in fields related to what we now call modern physics.

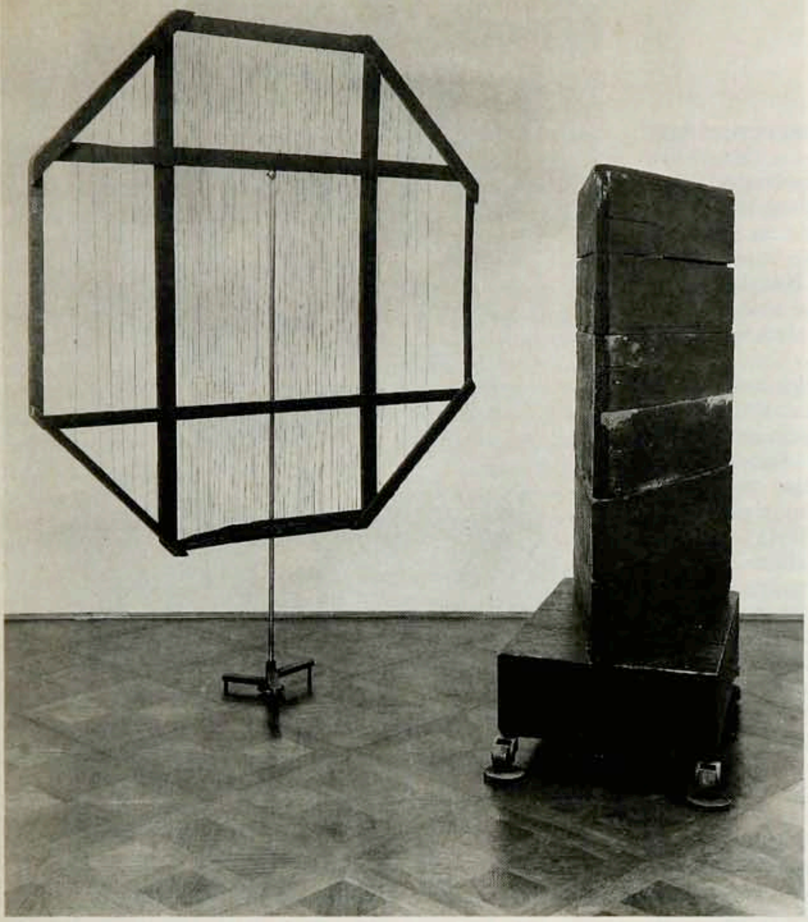
Joseph Mulligan is a professor of physics at the University of Maryland, Baltimore County, in Catonsville, Maryland.

Hertz's life

Hertz was born in 1857 into a well-to-do German family in Hamburg. A very bright student, he did equally well in the humanities and the sciences, and showed great manual skill in drawing, sculpting, woodworking, metal fabrication and the design and construction of scientific apparatus such as sensitive galvanometers and voltaic cells. These abilities were to stand him in good stead throughout his scientific career. Hertz started out studying engineering, but soon gave it up for physics. In 1878 he enrolled at the University of Berlin to work under Hermann von Helmholtz and Gustav Robert Kirchhoff.[3]

Hertz quickly established himself as a promising student by solving a prize problem, posed by Helmholtz, on whether the electric charge moving in a conductor has inertial mass. Helmholtz then proposed in 1879, through the Berlin Academy of Sciences, another prize for anyone who was able to "establish experimentally any relation between electromagnetic forces and the dielectric polarization of insulators." Encouraged by Helmholtz, Hertz considered taking this on as his doctoral dissertation subject, but a careful analysis led him to the conclusion that "any decided effect could scarcely be hoped for, but only an action lying just within the limits of observation." He therefore put the problem aside, only to return to it—and solve it—nine years later, in 1888, as part of his classic experimental work on electromagnetic waves.

Instead of tackling this difficult prize problem, Hertz



Apparatus that Heinrich Hertz used to study the polarization and refraction of electromagnetic waves. The wire frame, almost 2 m high and strung with parallel wires, acted as an analyzer for the polarized radiation produced by Hertz's spark transmitter. The 30° prism, when filled with hard pitch, weighed more than 1000 lbs. (Courtesy of the Deutsches Museum, Munich.)

chose a theoretical dissertation on inductive effects in charged rotating spheres, and he successfully completed it under Helmholtz's direction in January 1880. His dissertation contains some powerful and (for that time) sophisticated mathematics, and was completed in less than a year—clear evidence that Hertz was a first-rate mathematical physicist in addition to being a remarkable experimentalist. He took his doctoral examination in February 1880 after only three semesters at Berlin, and received his degree *magna cum laude*, a rare distinction in Helmholtz's institute.

Hertz stayed on in Berlin for three years as Helmholtz's assistant at the Physical Institute, during which time he published 13 scientific papers on a variety of subjects. He was appointed *Privatdozent* at the University of Kiel in 1883, was called to Karlsruhe as professor of physics in 1885 and spent his final, difficult years from 1889 to 1893 as successor to Rudolf Clausius in Bonn. Hertz never had robust health and suffered from recurring problems with his teeth, jaw, nose and eyes. He died of chronic blood poisoning on 1 January 1894, just a few months before his 37th birthday. His mentor Helmholtz, whom he revered and loved, died just eight months after Hertz, at age 73.

Theoretical electromagnetism

Hertz learned electromagnetic theory from Helmholtz, one of the very few physicists on the continent to appreciate the importance of the work of James Clerk Maxwell. Most German physicists accepted the action-at-a-distance theories of Franz Neumann and Wilhelm Weber, which maintained that electromagnetic forces propagated from one body to another at infinite speed, as was then assumed also to be the case for gravitational forces. Helmholtz had developed a compromise theory that attempted to reconcile these ideas with Maxwell's theory of the electromagnetic field. His compromise was to accept the action-at-a-distance theory for free space, but to adopt Maxwell's theory in the case of dielectrics, in which electromagnetic disturbances were assumed to propagate by means of the polarization of the medium.

Hertz's first year in Kiel was not a happy one. He was lonely, longed for the stimulating scientific atmosphere of Berlin and lacked the equipment necessary to continue the experimental research on electromagnetism he had begun there. It seemed natural, then, for him to turn to Maxwell's theory (as modified by Helmholtz) for guidance on the crucial experiments needed to decide once and for all among the competing theories of electromagnetism.

It did not take Hertz long to see the inconsistency of his mentor's ideas, however, and he proceeded in a very important, and often overlooked, paper of 1884 to derive Maxwell's equations from first principles by a new method.[4] This avoided both the mechanical analogies Maxwell had originally used and the explicit idea of the displacement current he had introduced. Both of these approaches were out of favor in Germany, and Hertz wrote his paper in an attempt to win his German colleagues over from the theories of Neumann and Weber to that of Maxwell. In this paper Hertz obtained Maxwell's fundamental equations in the symmetric form we use today, free of scalar and vector potentials. The fundamental equations of the electromagnetic field in this form were always referred to at the turn of the century as "Maxwell's equations in the Hertz–Heaviside form," in recognition of the contributions made by Hertz and by Oliver Heaviside, the self-taught British physicist and electrical engineer who made many important contributions to electrical theory. Hertz always insisted that it was Heaviside who deserved credit for this form of Maxwell's equations, but it was the clarity of Hertz's presentation that won over physicists to this formulation.

In 1890, after his experiments on electromagnetic waves had demonstrated his experimental skill, Hertz wrote two other important theoretical papers on electromagnetism. The first of these, "On the Fundamental Equations of Electromagnetism for Bodies at Rest,"[5] helped overcome the repugnance most German physicists retained for Maxwell's theory even after Hertz's convincing experimental verification of its predictions. Arnold Sommerfeld recalled that on reading this paper of Hertz, "the shades fell from his eyes," and he understood electromagnetic theory for the first time.[6] The once-neglected equations of Maxwell, stripped by Hertz of the mechanical models on which Maxwell had based them, soon became the basis for all research in electromagnetism and optics in Germany, as they were throughout the rest of the scientific world.

Experiments on electromagnetism

Hertz's 1884 paper on Maxwell's theory of the electromagnetic field convinced him that the crucial proof needed to decide between Maxwell's ideas and those of Neumann, Weber and Helmholtz was not to establish the relationship between electromagnetic forces and dielectric polarization, as set forth by Helmholtz in the prize problem of 1879. Rather it was to determine whether empty space behaves like all other dielectrics. To prove that it does he set out to measure the speed of long-wavelength electromagnetic waves in air—the best available approximation to free space—to see if they propagated at the speed of light, as Maxwell's theory predicted.

One reason that Hertz accepted a professorship at Karlsruhe, despite the lack of advanced students there to test and develop his ideas, was the presence of a considerable amount of equipment that he could use in his research. Among this apparatus he found a pair of Riess spirals, which he used for a lecture demonstration on electromagnetic induction. Impressed by the distances over which changes in the current in the primary coil produced detectable electrical changes in the secondary coil, Hertz set out to modify this arrangement until any direct inductive effects could be ruled out. The only explanation of observed currents in the secondary coil would then be the propagation of electromagnetic radiation through space. Hertz's many modifications of this apparatus finally produced the experimental equipment he needed to verify Maxwell's theory.

He began with a primary circuit, or transmitter, consisting of a piece of copper wire forming a closed loop except for a small air gap between its two ends, and driven by the spark discharge from an induction coil; and a secondary passive circuit, or receiver, consisting of a similar coil with an air gap between its ends. Hertz could adjust the length of this secondary gap with a micrometer screw and obtain an estimate of the signal strength at the position of the receiver from the distance the spark could jump. Hertz obtained all of his monumental results in this way.

Hertz in military uniform. This photograph was probably taken in 1877, when Hertz was 23 years old and serving his year of military service with the First Railway Guards Regiment in Berlin. In the fall semester of 1877 he began his physics studies in Munich, but a year later transferred to the University of Berlin to study under Hermann von Helmholtz and Gustav Kirchhoff. (Courtesy of the Deutsches Museum, Munich.)

In September 1889 in Heidelberg, Hertz delivered the keynote address at the annual meeting of the German Association for the Advancement of Natural Science and Medicine. In this talk, "On the Relations Between Light and Electricity," Hertz pointed out that the thin thread on which the success of his research in Karlsruhe in 1885–89 hung was the fact that sparks about 0.01 mm in length and lasting about a microsecond can be seen by a dark-adapted human eye in a perfectly dark room. He pointed out that "the success of a workman depends upon whether he properly understands his tools."[7] Even today, physicists who have tried to repeat Hertz's experiments with his Karlsruhe apparatus have come away with a new respect for his experimental abilities and with amazement at what he was able to accomplish with such primitive equipment.

Hertz later improved on the sensitivity of his original apparatus by adjusting the dimensions of his receiver until it was in resonance with the transmitter. The tuning required was not very precise, because the transmitter produced a highly damped oscillating spark that radiated a rather broad band of frequencies. When Hertz tuned the detector to any frequency within that band, he achieved resonant enhancement of the signal. He also found that the distance over which signals could be detected increased considerably when he reduced the inductance and capacitance of the transmitting coil and thus increased the frequency. (As we know today, the energy radiated varies as the fourth power of the frequency.) The reduction in inductance and capacitance also sufficiently shortened the wavelengths to allow Hertz to carry out standing-wave measurements in the limited laboratory space he had available.

With this apparatus Hertz set out to verify the predictions of Maxwell's theory. By using the variation in the length of the sparks across the adjustable secondary air gap to locate the nodes and antinodes in standing-wave patterns, he was able to obtain the wavelength of the radiation, which was about 9 meters. He obtained the frequency f of his transmitter from the equation $f = 1/(2\pi\sqrt{LC})$, using calculated values for the inductance L and capacitance C of his circuit. He then obtained the speed of light from the equation $c = f\lambda$. His results were not very accurate because of uncertainties in his calculated value for the frequency and because diffraction effects and spurious reflections perturbed his wavelength measurements. Despite these problems, Hertz was able to show in early 1888 that these long-wavelength electromagnetic waves did not travel at an infinite speed, but at a speed of the same order of magnitude as that of visible light. In this way, he verified one of the major predictions of Maxwell's theory.

Hertz then proceeded, in his classic paper of 1888, to show that 66-cm waves—microwaves—travel in straight lines and can be reflected, refracted and polarized in the same way light waves can.[5] His source in these experiments was a linear dipole positioned on the focal line of a cylindrical parabolic reflector so as to produce a linearly polarized plane wave. His detector coil was symmetrically positioned on the focal line of an identical parabolic reflector. Again, sparking across an air gap was both the source and the means of detecting the radiation.

To study refraction Hertz used a wooden container in the shape of a prism 1.5 m long (see the figure on page 51). This box, whose cross section was an isosceles triangle 1.2 m on a side with an apex angle of about 30°, was filled with asphalt or hard pitch; the resulting prisms weighed over 1000 lbs. To study polarization Hertz used an octagonal frame almost 2 m high strung with parallel conducting wires. These wires could be aligned at various angles with respect to the axis of the transmitter by rotating the frame. By making use of this property of the device Hertz was able to show that the radiation was indeed linearly polarized and that the amount of radiation transmitted depended on the orientation of the wires with respect to the axis of the transmitter. In this way he established the transverse nature of radiation.

By painstaking experiments such as these, Hertz confirmed fully the predictions of Maxwell's theory and eliminated from consideration the theories of Neumann, Weber and Helmholtz. As he stated at the end of his Heidelberg lecture:[8]

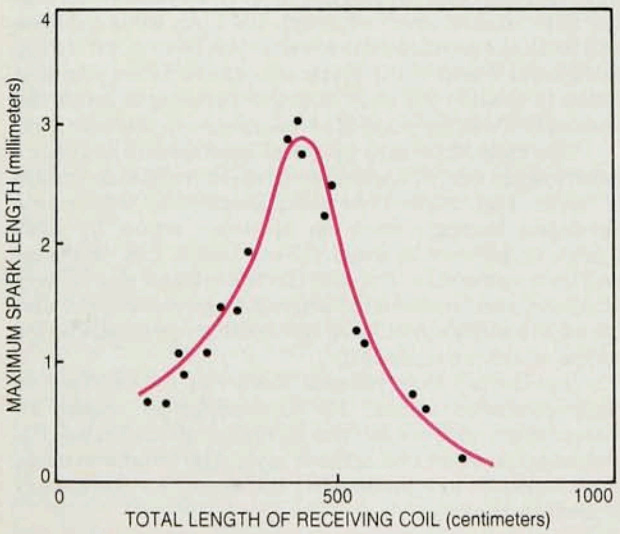
> The connection between light and electricity, of which there were hints and suspicions and even predictions in the theory, is now established.... Optics is no longer restricted to minute ether waves, a small fraction of a millimeter in length; its domain is extended to waves that are measured in decimeters, meters and kilometers. And in spite of this extension, it appears merely... as a small appendage of the great domain of electricity. We see that this latter has become a mighty kingdom.

Hertz's measurement of the speed of unguided electromagnetic waves at radio frequencies was the first such measurement to use a standing-wave technique. This extension of measurements of the speed c of electromagnetic waves from time-of-flight techniques in the visible to standing-wave techniques in the radio and microwave regions of the spectrum has an interesting parallel in the research in the 1970s that extended modern standing-wave techniques for measuring c from the radio and microwave regions back into the visible.[9] In fact Hertz's description of what had to be done to measure the speed of radio waves sounds much like Charles Townes's outline of the best way to measure the speed of light, namely by wavelength and frequency measurements on stabilized lasers.[10]

Beyond verifying Maxwell's theory

While working to verify Maxwell's theory, Hertz made a number of other discoveries, any one of which could have established a physicist's scientific reputation. For example, Hertz appears to have been the first to record resonance curves for the tuning of a radio receiver to a transmitter. The figure below, which is taken directly from one of Hertz's papers, shows the spark length he observed in the air gap of his receiver as a function of the total length of the wire in the rectangular coil of his detector. One can see a clear resonance at about 450 cm, indicating that this length of wire had a distributed inductance that led to resonance at the frequency of the transmitting circuit and so produced stronger and longer sparks in the receiver's air gap.

Hertz's 1889 paper, "On the Propagation of Electric Waves by Means of Wires," contains a very detailed



Resonance curve for tuning Hertz's receiving coil to the frequency of a transmitter. The receiving coil was a rectangle, two of whose opposite sides were fixed in length at about 100 cm and whose other two sides varied from 10 cm to 250 cm. (Based on a drawing published by Hertz, ref. 5.)

discussion of the "skin effect."[5] He was able to show conclusively that at the frequencies he used in his research the current was confined to the exterior skin of the wires, as Heaviside and J. H. Poynting had predicted on the basis of Maxwell's equations.

The ingenuity with which Hertz confirmed this prediction shows a great experimentalist at work. He studied the effect on a high-frequency current through a central conductor of adding, one by one, 24 additional conductors arranged in a circle parallel to and surrounding the first conductor. He found that the current in the central conductor decreased as the other conductors were added and finally went to zero when the other conductors completely surrounded it, even though the resistance of the inner wire was much smaller than the combined resistance of all the outer wires. Hertz extended this work to a convincing study of the shielding of electrical equipment from high-frequency radiation. He showed that a conducting sheet only $\frac{1}{20}$ mm thick (or even a wire gauze) completely surrounding a spark gap was sufficient to shield the spark gap completely from strong, high-frequency radiation in the 100-MHz range.

Hertz carried out many of his experiments with electromagnetic waves of 66-cm wavelength, and thus deserves to be called the discoverer of microwaves. He constructed the first coaxial transmission line and used it to carry 50-MHz, or 6-m, radiation. He made a coaxial line 5 m long and 30 cm in diameter, with a wire running down the center through insulating supports.[11] The outer conductor consisted of 24 copper wires set along the outer perimeters of seven equidistant circular rings of heavy wire. With this coaxial line Hertz was able to study the electric field configurations in the space between the inner and outer conductors.

Hertz also designed a resonant detector to explore this electric field. It consisted of 125 turns of 1-mm copper wire wound in a tight helix 1 cm in diameter and then bent into a toroid 12 cm in diameter, with a small spark gap interrupting the windings at one point in the toroid. This detector was small enough to be introduced between the central wire and the outer conducting shell of the coaxial line. (As has been pointed out by J. H. Bryant,[11] this was the first "slotted line," although the term came into use only with the development of radar just before and during the Second World War.) Hertz was able to detect standing waves in the line and show that the wavelength inside the coaxial line was the same as in free space—in this case, 6 m.

The most important practical consequence of Hertz's experiments was, of course, our present worldwide system of radio and microwave communications, which was developed through work on Hertzian waves by Karl Braun, Gugiliemo Marconi, Oliver Lodge, Lee de Forest and their successors. Because Hertz's interest was focused exclusively on fundamental physics, he never realized that his experiments might have remarkable consequences for communications technology.

But Hertz's experimental work was not confined to electromagnetic waves. He also published papers on meteorology, mechanics, the hardness of materials, the photoelectric effect and cathode rays. The latter two areas of his research are particularly important for the history of modern physics.

The photoelectric effect

The year 1987 was the centenary of Hertz's discovery of the photoelectric effect. (See Giorgio Margaritondo's article in PHYSICS TODAY, April 1988, page 66.) Although Hertz discovered this effect by accident in the course of his work on electromagnetic waves, he recognized its importance immediately, because the only other effect of light on electrical phenomena known at that time was the change in the electrical resistance of selenium when it was exposed to light. Hertz saw that an interaction between light and electricity of the kind he had observed could clarify the nature of both light and electricity. He therefore interrupted his electromagnetic wave research for six months and explored "this new and very puzzling phenomenon."

In a 16-page paper in the *Annalen der Physik* in 1887 Hertz described his observations of the photoelectric effect.[5] In the course of his experiments with spark transmitters and receivers he had noticed that the maximum length of the spark in the gap of his detecting coil was decidedly shorter when he enclosed the receiving spark gap in a dark case to make it easier to see the sparks. He suspected at once that light from the transmitting spark was perturbing the receiving spark. As we know today, this light falling on the pole pieces of the secondary spark gap produced electron emission from the poles and thus facilitated sparking across the gap.

The figure on page 55 shows the original apparatus Hertz used to study the effect of light on an electric discharge. To clarify how light enhanced the sparking, Hertz used poles of copper, brass, aluminum, iron, tin, zinc and lead; next he varied the light source, using sunlight, gas flames and electric arcs, among other sources; and lastly he interposed various gases, liquids and solids between the light source and the receiving spark gap. The interposed materials included metal and glass sheets of various thicknesses, paraffin, shellac, mica, agate, wood, cardboard, paper, rock salt and more esoteric substances such as ivory, feathers and the skins of animals.

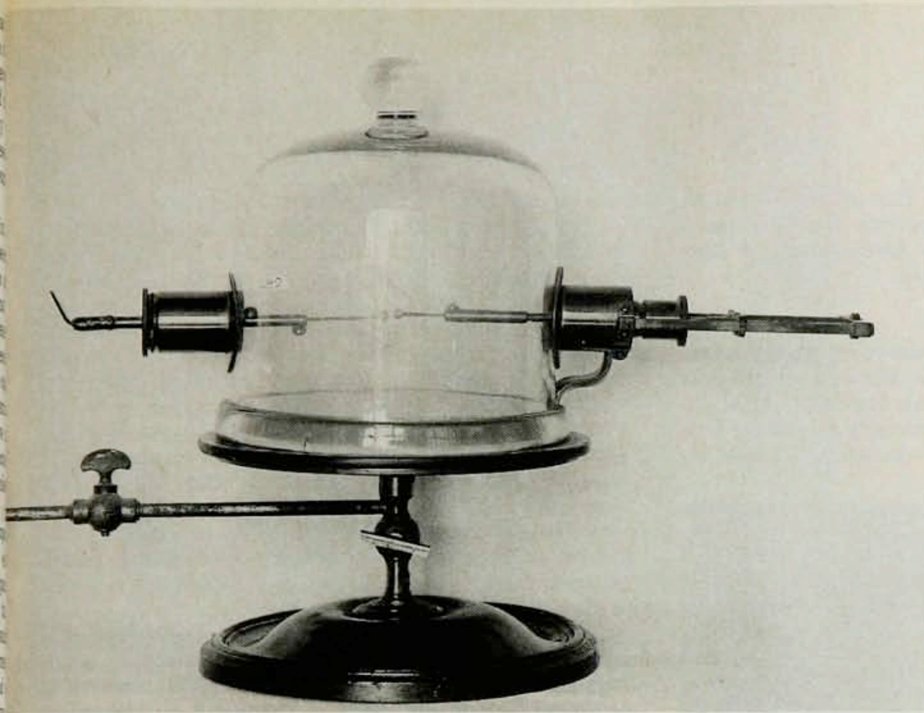
Hertz's observations suggested to him that the radiation that was effective in increasing the observed spark length lay near the short-wavelength limit of the visible spectrum. He then used a quartz prism to disperse the radiation from his light sources, and found that the wavelengths enhancing the sparks were indeed in the ultraviolet. This was, of course, the case for the metals he used as his pole pieces because they all had work functions close to 4 eV, which puts their threshold wavelength below 310 nm, in the ultraviolet.

After six months of intense effort on the photoelectric effect, Hertz put it aside "so as to direct my attention once more to the main question," which in this highly productive period of his life was the nature and properties of radiofrequency waves. In 1888 Wilhelm Hallwachs, a *Privatdozent* at Leipzig, published a paper in which he extended Hertz's work on the photoelectric effect. In his diary entry of 29 January 1888, Hertz commented, "My consolation must be that I expected and accepted this happening; moreover, I have reached the goal that I wanted to reach, the goal for which I set aside those other experiments."

The six months Hertz stole from his electromagnetic wave research to straighten out the physics of the photoelectric effect were well spent. His results, although obviously incomplete, provided a firm experimental foundation for the work of Hallwachs, Julius Elster and Hans Geitel, Philipp Lenard and Robert Millikan, which led to today's full picture of the photoelectric effect. The experimental data of these researchers, in turn, eventually led to the verification of Einstein's photoelectric equation, which played such an important role in the development of quantum physics.

Cathode rays

While serving as an assistant to Helmholtz in Berlin, Hertz was a friend of Eugen Goldstein, who was doing experiments under Helmholtz's direction on the conduc-



Photoelectric apparatus. Hertz used this equipment in Karlsruhe in 1887 to study the effect of light on the spark jumping a gap between two electrodes in an evacuated bell jar. (Courtesy of the Deutsches Museum, Munich.)

tion of electricity in gases. Goldstein, who gave the name "cathode rays" to the emissions from the negative electrode in evacuated Geissler tubes, passed on to Hertz his enthusiasm for this area of research. Hertz published some of his Berlin work on the glow discharge in evacuated tubes in a paper entitled "Experiments on the Cathode Discharge,"[8] and he used this work as his *Habilitationsschrift*—the postdoctoral thesis required to become a university lecturer—when he was appointed *Privatdozent* at Kiel in 1883.

At that time it was unclear whether cathode rays were waves or particles. Hertz succeeded in deflecting them with magnetic fields, but failed to do so with electric fields. This was because he was able to achieve only a poor vacuum, so that ions from the residual gases built up static charges that tended to nullify the applied electric field. Hertz was also unable to observe the magnetic field of the cathode-ray beam outside the discharge tube and came to the incorrect conclusion that the cathode rays were not particles but waves or some new kind of disturbance in the ether.

To see if the cathode rays were indeed some kind of wave, Hertz tried to diffract them by sending a thin beam of cathode rays through a diffraction grating, but he obtained negative results.

When Hertz arrived in Bonn in 1889, he felt that he had done as much with radio waves as seemed possible at that time, and he was looking about for an exciting new field of research. When Lenard became his assistant in April 1891, Hertz was stimulated to return to the study of electric discharges in gases. He noted that he "was rewarded by the immediate and unexpected discovery" that cathode rays could pass through thin sheets of metal. Lenard took hold of this idea and in December 1892 produced a beam of cathode rays outside the evacuated discharge tube by using windows made of thin metallic foil of the kind Hertz had employed.

This work of Hertz and Lenard made up for Hertz's failure to deflect cathode rays in electrostatic fields, for it made possible unambiguous experiments on cathode rays that were outside the discharge tube and therefore were not perturbed by static charges within. Such experiments were performed by Lenard, J. J. Thomson and others, and led to Lenard's Nobel Prize in 1905 "for his work on cathode rays" and to Thomson's Nobel Prize in 1906 "for his theoretical and experimental investigations on the conduction of electricity by gases" and especially for his measurement of the charge-to-mass ratio of the electron. If Hertz had lived, it is likely that he would have shared in one of these prizes. As Hendrik Lorentz recalled in his Nobel lecture in 1902, "Immediately after Maxwell I named [as one of the founders of Maxwell's electromagnetic theory] Hertz, that great German physicist, who, if he had not been snatched from us too soon, would certainly have been among the very first of those whom your academy would have considered in fulfilling your annual task."[12] Health problems forced Hertz to abandon all experimental work at the end of 1892, and he died just one year later.

The work of Hertz and Lenard was important for Wilhelm Roentgen's discovery of x rays in late 1895. Roentgen was using a cathode-ray tube to study the effect of cathode rays on the luminescence of certain chemicals when he first observed his mysterious x radiation. Hertz and Lenard had clearly produced x rays in some of their earlier experiments, but they were never able to distinguish those rays from cathode rays because at that time they were confused as to the exact nature of cathode rays. In his fundamental 1896 paper on x rays Roentgen refers to the work of Hertz and Lenard, pointing out that they had observed the deflection of cathode rays in a magnetic field.[13] This led Roentgen to conclude that x rays were not the same as cathode rays, because he had found that x rays could not be deflected magnetically. Rather, Roentgen rays with glass or metal surfaces inside the cathode-ray tube, although he was not able to explain the exact mechanism. It was only later that others clarified the distinction between the processes producing the continuous and discrete x-ray spectra. The short-wavelength cutoff of the continuous x-ray spectrum then became a crucial piece of evidence in the development of Max Planck's quantum theory of radiation.

Impact on relativity

Hertz did other work that turned out to be important for the development of modern physics. For example, Planck used Hertz's dipole oscillators in his treatment of blackbody radiation because Hertz had already calculated how such oscillators emit and absorb radiation; Planck acknowledged this in his 1918 Nobel Prize address.[12]

Wilhelm Roentgen, who discovered x rays in 1895. Roentgen was helped in his discovery by his knowledge of the properties of cathode rays as determined by many physicists, including Hertz and Philipp Lenard, Hertz's assistant in Bonn. (Courtesy of AIP Niels Bohr Library, Landé Collection.)

Hertz's contributions to the development of relativity theory were less direct, but two aspects of his influence are worth considering. First, Hertz's experiments on electromagnetic waves eliminated all action-at-a-distance theories of electromagnetism, and this rejection carried over to gravitational interactions. As Max von Laue wrote, "Albert Einstein's greatest contribution, a theory of gravitation according to which it propagates with the velocity of light, thus traces back directly to Heinrich Hertz."[14] Hertz himself raised this question about gravitation in his Heidelberg address: "We are at once confronted with the question of direct actions at a distance. Are there such? Of the many in which we once believed there now remains but one—gravitation. Is this too a deception? The law according to which it acts makes us suspicious."

Second, just as the first of Hertz's 1890 theoretical papers on electromagnetism was instrumental in establishing Maxwell's equations as the basis for all research on electromagnetism and light in Germany, so his second paper, "On the Fundamental Equations of Electromagnetism for Bodies in Motion,"[5] advanced ideas that eventually led to Einstein's special theory of relativity. In this paper Hertz postulated that the ether contained in a body moved with the body, even though he realized that this postulate was a temporary one that would one day have to be replaced by a more complete theory. Both Lorentz and Einstein had high regard for Hertz's paper. Although Lorentz made the opposite assumption—that the ether was always at rest and the body moved through it—he liked many of Hertz's ideas and modified them to his own purposes. Einstein wrote of Hertz's paper, "A study of Heinrich Hertz's investigation into the electrodynamics of moving bodies will give the reader a clear insight into the conception, prevalent at that time, concerning the electrodynamics of Maxwell."[15]

These varied contributions of Hertz show him to be the last great classical physicist and the precursor of a new generation of modern physicists. The use of his work by the founders of both quantum theory and relativity in their struggle to break with classical physics shows his ideas to be part of the groundwork for the two most important physical theories of the 20th century.

Place in history

Hertz's German colleagues had profound respect for him both as a physicist and as a man, and expected him to take Helmholtz's place as "Reichs-Chancellor of German physics." In a letter to Helmholtz written on 6 January 1894, a few days after Hertz's death, Ludwig Boltzmann paid tribute to Hertz's work by pointing out its impact on the direction of physics research: "One should emphasize the extraordinary import of Hertz's discoveries in relation to our whole concept of Nature, and the fact that beyond a doubt they have pointed out the only true direction that investigation can take for many years to come."[16]

Einstein, in an unpublished manuscript written in 1895, refers to "the wonderful experiments of Hertz,"[17] and elsewhere writes about "the great revolution forever linked with the names Faraday, Maxwell and Hertz"[18]—a clear indication of his appreciation of the importance of Hertz's work for the development of physics.

Bust of Hertz in the entrance courtyard at the Technical University in Karlsruhe. The inscription reads, "In this place Heinrich Hertz discovered electromagnetic waves in the years 1885–1889." (Photograph courtesy of IBM.)

The founder of quantum theory lavished similar praise on Hertz. In 1931 Planck summarized the importance of Hertz's research on electromagnetic waves[19]:

> Thus gradually the universal significance of Maxwell's ideas became to be more and more recognized on all sides, till at last the crucial experiments of Heinrich Hertz with very rapid electrical oscillations were crowned with an unexampled success, by the production of electrical waves of a few centimeters wavelength. Through this discovery, which produced the greatest sensation in all the scientific world, the speculations of Maxwell were translated into fact and a new epoch of experimental and theoretical physics was begun.

Hertz's brief life came to an end just when his ability and experience put him in a position to make even greater contributions to physics. After Hertz's death, Planck paid a final tribute to his colleague in an address to the Berlin Academy of Sciences[20]:

> Spoken or unspoken, the name of Hertz will be among the first of this generation, as long as men pay attention to electric waves. But we, the association of physicists, we will sun ourselves in the glow of this name, yes, we will share in its glory, for he was truly one of us.

References

1. Fridericiana: Z. Univ. Karlsruhe **41** (1988).
2. For an excellent catalog of this exhibit of Hertz's apparatus, see J. H. Bryant, *Heinrich Hertz: The Beginning of Microwaves*, IEEE, New York (1988).
3. The best English-language sources on Hertz's life are R. McCormmach, in *Dictionary of Scientific Biography*, C. C. Gillispie, ed., Scribner's, New York (1970–78); J. Hertz, M. Hertz, C. Susskind, eds., *Heinrich Hertz: Memoirs, Letters, Diaries*, San Francisco P., San Francisco (1977). This volume, arranged and edited by Hertz's two daughters, consists of facing pages in German and English, with an excellent biographical introduction by M. von Laue. On the influence of Helmholtz on Hertz's contributions to physics, see J. F. Mulligan, Am. J. Phys. **55**, 711 (1987).
4. H. Hertz, *Miscellaneous Papers*, Macmillan, London (1986), p. 273. On the importance of this paper see S. d'Agostino, Hist. Stud. Phys. Sci. **6**, 261 (1975).
5. H. Hertz, *Electric Waves*, Dover, New York (1962). This volume contains all of Hertz's experimental papers on electromagnetic radiation.
6. A. Sommerfeld, *Elektrodynamik*, Akademische Verlagsgesellschaft Geest und Portig KG, Leipzig (1954), p. 2.
7. H. Hertz, *Miscellaneous Papers*, Macmillan, London (1896), p. 313; reprinted with an introduction by E. C. Watson in Am. J. Phys. **25**, 335 (1957).
8. H. Hertz, *Miscellaneous Papers*, Macmillan, London (1896).
9. J. F. Mulligan, Am. J. Phys. **44**, 960 (1976).
10. C. H. Townes, in *Advances in Quantum Electronics*, J. R. Singer, ed., Columbia U. P., New York (1961), p. 5.
11. For a good photograph of this coaxial line and of the detector Hertz used inside this line, see J. H. Bryant, *Heinrich Hertz: The Beginning of Microwaves*, IEEE, New York (1988), p. 33.
12. *Nobel Lectures in Physics, 1901–1921*, Elsevier, New York (1967).
13. W. C. Roentgen, translated in H. A. Boorse, L. Motz, eds., *The World of the Atom*, Basic, New York (1966), p. 395.
14. M. von Laue, in *Heinrich Hertz: Memoirs, Letters, Diaries*, J. Hertz, M. Hertz, C. Susskind, eds., San Francisco P., San Francisco (1977), p. xxxv.
15. A. Einstein, quoted in E. Segrè, *From Falling Bodies to Radio Waves*, Freeman, New York (1984), p. 182.
16. L. Boltzmann, quoted in L. Koenigsberger, *Hermann von Helmholtz*, English edition, Dover, New York (1965), p. 421.
17. A. Einstein, "On the Examination of the State of the Aether in a Magnetic Field," unpublished 1895 manuscript referred to in A. Pais, *'Subtle is the Lord . . . ,'* Oxford U. P., New York (1982), p. 130.
18. A. Einstein, in *James Clerk Maxwell: A Commemoration Volume 1831–1931*, Cambridge U. P., Cambridge, England (1931), p. 70.
19. M. Planck, in *James Clerk Maxwell: A Commemoration Volume 1831–1931*, Cambridge U. P., Cambridge, England (1931), p. 62.
20. M. Planck, *Physikalische Abhandlungen und Vorträge*, vol. 3, F. Vieweg und Sohn, Braunschweig (1958), p. 288. ■