STANFORD LINEAR ACCELERATOR CENTER

Beam Line

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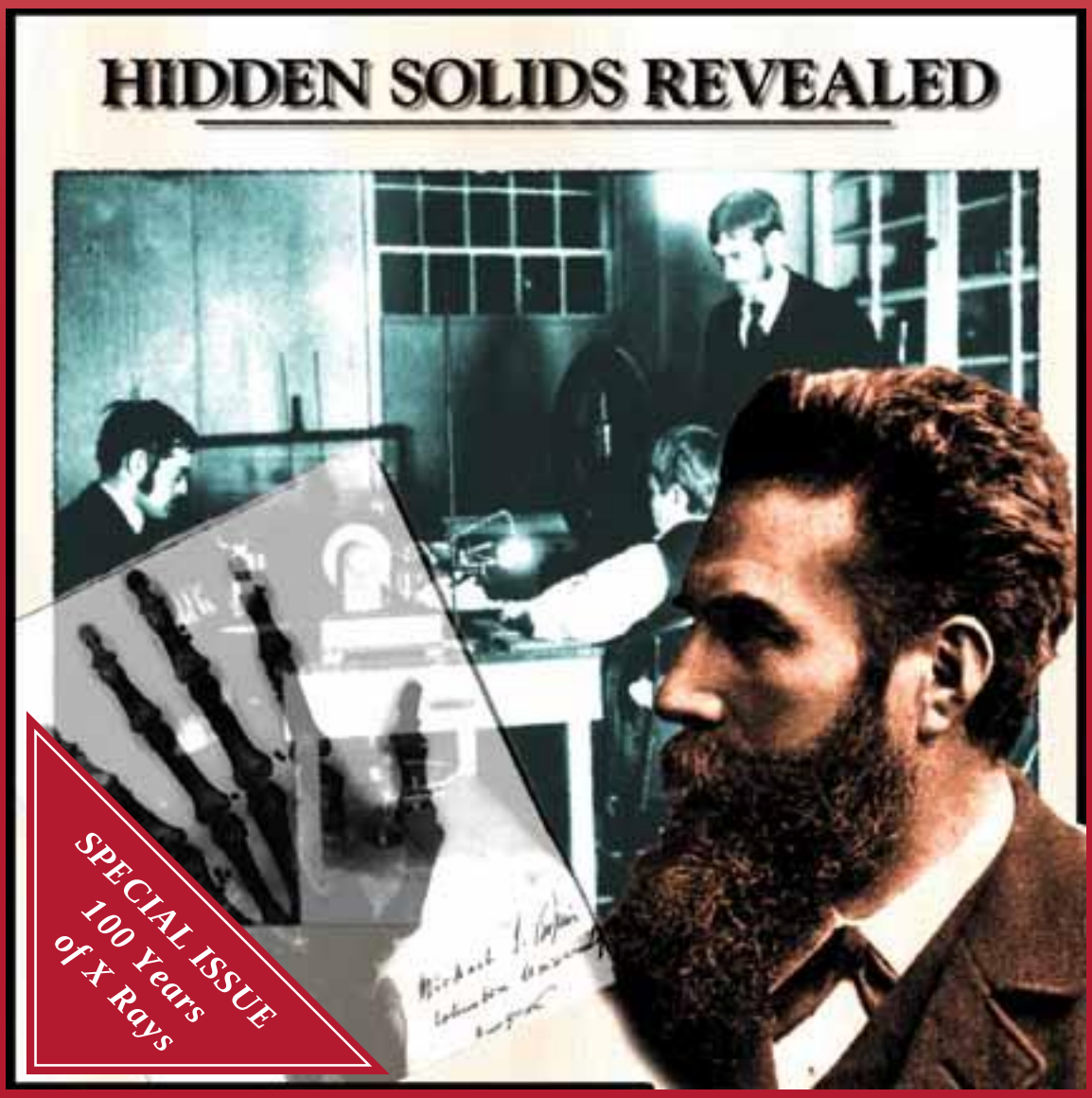

Beam Line

A PERIODICAL OF PARTICLE PHYSICS

SUMMER 1995 VOL. 25, NUMBER 2

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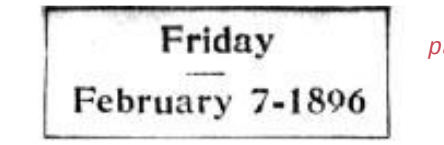
Cover: A photo montage created electronically by graphic artist Terry Anderson for this issue commemorating the discovery of X rays 100 years ago.


Friday
February 7-1896

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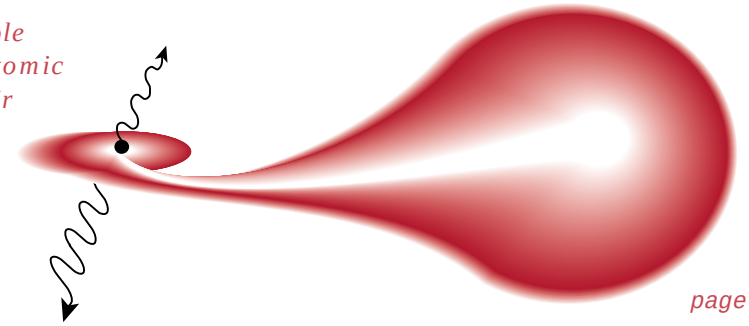

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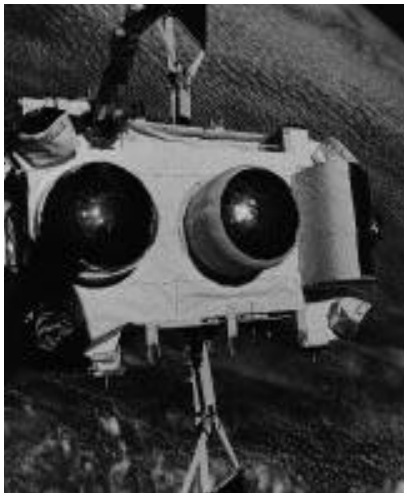

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FROM THE EDITORS' DESK

HIDDEN SOLIDS REVEALED

Prof. Routgen's Experiments with Crookes's Vacuum Tube.

BULLETS FOUND BY USING LIGHT

Opaque Bodies Covered by Other Bodies Photographed — Views of Profs. O. N. Rood and Halleck of Columbia.

Men of science in this city are awaiting with the utmost impatience the arrival of European technical journals, which will give them the full particulars of Prof. Routgen's great discovery of a method of photographing opaque bodies covered by other bodies, hitherto regarded as wholly impenetrable by light rays of any kind.

Prof. Routgen of Würzburg University has recently discovered a light which, for purposes of photography, will penetrate wood, paper, flesh, and nearly all other organic substances. Thus, the bones of the human frame can be photographed in relief without the flesh which covers them, or metals inclosed in a box covered with a woolen cloth can be photographed as if the cloth and the wood did not exist.

In one sense, it is a misnomer to call the process photography, as now understood, because no lens is employed to project the image. It also seems, from the brief accounts of the process which have already been sent by cable, that the new images of concealed bodies resemble rather the old-fashioned daguerreotypes than the modern finished photographs, inasmuch as they appear only in outline.

Briefly, the new images are obtained by the energy given out in a Crookes's vacuum tube. The object to be photographed is placed behind the tube, and a dry plate is placed behind the object. If the object be, say, a hand, the image on the dry plate will be the bones in it, without any flesh covering whatever.

Prof. Routgen has already used his process to detect the exact location of bullets in gunshot wounds, and one of its first practical uses is expected to be a transformation of modern surgery by enabling the surgeon to detect the presence of foreign bodies of whatever kind in any part of the human body.

The germ of Prof. Routgen's discovery is to be found in an experiment made a few years ago by Prof. William Crookes. He found that when a glass bulb from which all the air possible has been extracted has a current of electricity passed through it, a beautiful light in the interior of the bulb is the result. If now a body, whether transparent or opaque, is placed between the poles between which the current passes in the vacuum, sharply defined shadows of these bodies are projected on the wall of the bulb behind the negative pole.

"It seems," says Prof. Sylvanus Thompson in his recent work on electricity, "as if the transparent or opaque bodies stopped the way for some of the flying molecules and prevented them from striking the opposite wall."

Hertz, the great electrician, better known in connection with the Panama scandals, discovered that while these rays will not pass through glass, mica, or any transparent substance, they will pass through a thin sheet of metal foil.

THIS ISSUE of the SLAC *Beam Line* is unusual in several ways. First, at 64 pages it is the longest issue that we have yet produced. Second, rather than a collage of different physics topics it concentrates on a single theme: the centennial celebration of Wilhelm Roentgen's discovery of X rays in 1895. Third...well, let's back up a bit before we write down what comes third.

This issue begins with an article by Philip Morrison, who tells us, from a physics perspective, "How the 20th century started ahead of time" with the discoveries of X rays, radioactivity, and the electron. This issue ends with an article by Virginia Trimble, who tells us how astrophysics may go "On beyond X" into the next century to view the Universe in the light of gamma rays, neutrinos, and gravitational radiation.

Thus Morrison and Trimble are, in several senses, the bookends for this issue, and what a pair of bookends they are! It is probably not true that Philip Morrison and Virginia Trimble

have read everything and know everything. It is probably only half true. But even the polymathic minds are not the full story. To know it is a necessary but not sufficient condition of being able to say it or write it. If there is an exemplar of all that is best in English prose style, it is probably someone like Bertrand Russell, and reading Morrison and Trimble gives rise to much of the same pleasure that one takes in the clarity, grace, and wit of the prose.

But enough already. Part three of the special character of this issue is to welcome Phil Morrison as a first-time contributor to our journal, and also to emphasize our continuing pleasure in the superb articles that Virginia Trimble produces for each issue of the *Beam Line* in "The Universe at Large."

Rene Donaldson Bill Kirk

Lenard, by using a window of aluminium foil at one end of the bulb, succeeded in making the rays pass out into the atmosphere, where they excited phosphorescence. Hertz made the shadows appear in ordinary air by covering the negative pole of an electrical machine with silk, on which the shadows were thrown.

Prof. O. N. Rood, who occupies the Chair of Physics in Columbia College, was asked yesterday by a reporter for THE NEW-YORK TIMES if this discovery was in line with the previous anticipations of men of science. Although the information which the reporter was able to give Prof. Rood was of the briefest character, he kindly consented to explain the analogies which occurred to him as having any bearing on the new discovery.

"The phenomenon which we call light," said the professor, "is a peculiar manifestation of energy in the ether which pervades all substances. It consists of short vertical waves, roughly speaking, from one-forty-thousandth to one-sixty-thousandth of an inch in length. These waves are visible to our eyes only for the length of the spectrum, which displays the component parts of white light, from red to violet.

"The most familiar example of the spectrum which we have is the rainbow. Men of science have been long aware that there are rays of light imperceptible to the senses. For example, in that part of the spectrum beyond the violet rays there are rays which, though imperceptible to our eyes, can be seized by the sensitive plate of a photographic apparatus. It so happens that the violet and ultra-violet rays are those which are chemically the most active. At the red end of the spectrum we have every reason to believe that there are other rays imperceptible to our senses, and which we have hitherto not been able to measure or detect directly for want of a suitable apparatus.

"The modern theory of light presumes that light, heat, and even electricity are merely different forms or manifestations of the same energy. The only difference between light and heat is in the length of the waves, those of light being much shorter than those of heat. If we call light and heat, therefore, radiant energy, we shall have a general term to express the subtle force which acts through the ether.

"Now, when we want to examine light we pass it through a prism or through a transparent substance, which polarizes it, such as tourmaline. Hertz showed by substituting a large prism of melted pitch that heat rays could be polarized in the same manner as light rays. The quantity of these heat rays can be actually measured by delicate electrical instruments, known as thermo-piles.

"I can quite readily conceive how heat rays could be passed through organic substances in the manner you describe. It is also quite conceivable to me that these heat rays would be stopped by a bullet or any substance which was a good electrical conductor. Eighty or ninety per cent. of the rays would be reflected and the remaining 10 or 20 per cent. would be absorbed by the metallic substance."

Prof. Rood then introduced the reporter to his colleague, Prof. Halleck, who was greatly interested in the discovery, and who spoke of another aspect of it.

"The tenuous substance, which we can hardly call matter, because it is so foreign to our ideas of anything palpable," said Prof. Halleck, "is supposed to pervade the universe, and everything it contains.

"The modern theory of matter presumes that that no two atoms—an atom being the smallest possible particle of matter—touch each other. In spite of the close adhesion of even steel, each separate atom has a kind of spiral motion impelling it to fly away from its neighbor. Between these atoms is the all-pervading ether which transmits the rays of light or heat, as the case may be.

"Nothing is more familiar to our minds than that all substances transmit heat more or less perfectly according to their degree of conductivity. Now, as we believe that heat and light are simply manifestations of radiant energy, there is nothing impossible in the idea that this radiant energy may be conveyed so as to cast shadows, as it were, according to the relative permeability of the different parts of the same substance.

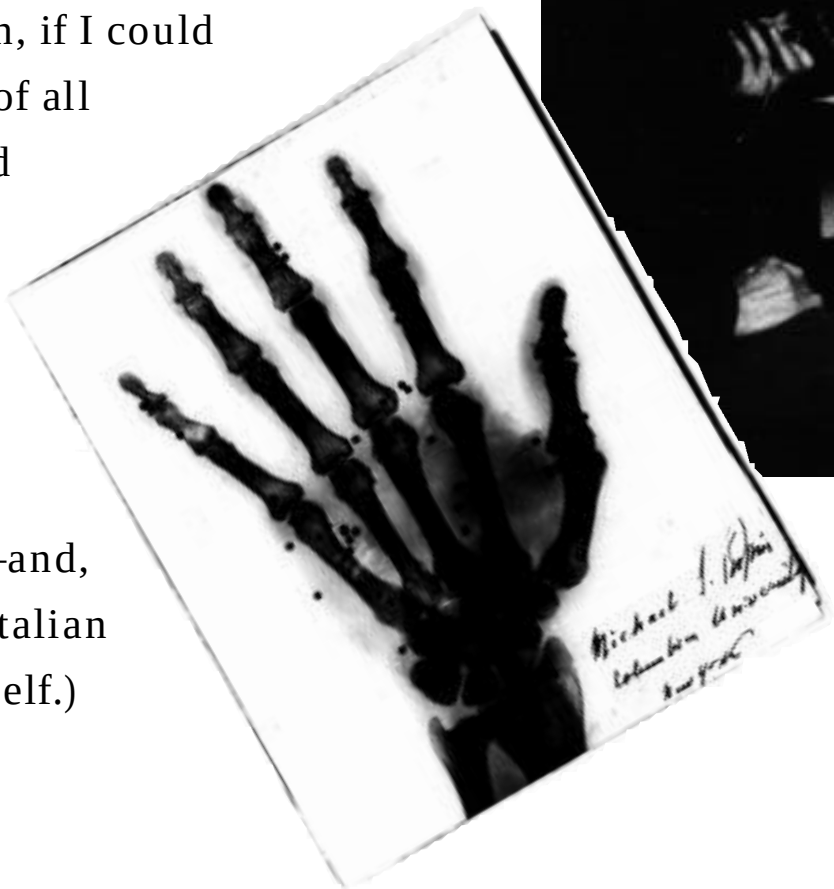
"There is only one point in the statement you make which seems a little confusing. If Prof. Klopathy of Pesth University has succeeded in making this invisible light or radiant energy pass through aluminium, what becomes of the theory that metals should reflect it in proportion to their electrical conductivity? Aluminium, though not heavy, is still a regular metal in its behavior, and is a relatively good conductor of electricity. These points, I hope, will be cleared up when we get the full reports of the experiments."

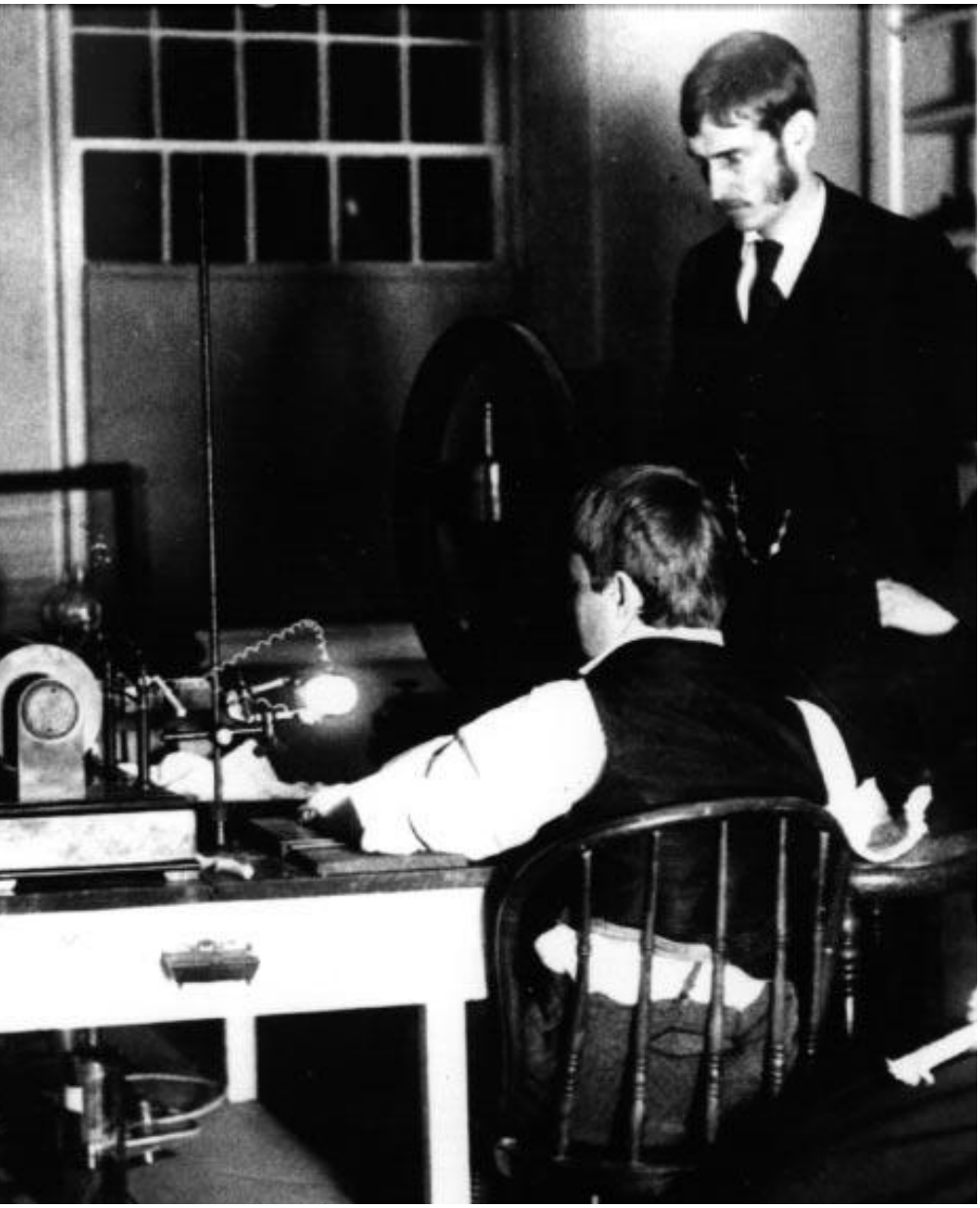
How the Twentieth Century Started Ahead of Time

The Centennial Encounter of a Physicist

by PHILIP MORRISON

ENRICO FERMI is said to have evaded some query about a new particle with this rebuff: "Young man, if I could remember the names of all those particles I would have become a botanist."
(It is true that the first really new particle, the neutrino, was first understood—and, in fact, was given its Italian name—by Fermi himself.)





The New-York Times.

Wednesday

February 5-1896

PROF. ROENTGEN'S X-RAYS

May Be Due, He Says, to Longitudinal Vibrations of Ether.

HE WRITES OF HIS GREAT DISCOVERY

Difference Between His and the Kathode Rays of Lenard—Some of the Substances He Has Photographed.

The preliminary communication of Prof. Wilhelm Konrad Röntgen to the Würzberg Physico-Medical Society of his discovery of a new form of radiant energy appears this week translated in full in several of the English papers. As the chief interest of men of science is centred in the question of the nature of the rays, these portions of Prof. Röntgen's paper which deal with this aspect of the subject are here reproduced in full.

The name given by Prof. Röntgen to the newly discovered form of radiant energy is X-rays. The translation appended was made by Arthur Stanton, and appears in the current number of Nature. After describing his experiments in making shadow photographs of various substances, Prof. Röntgen says:

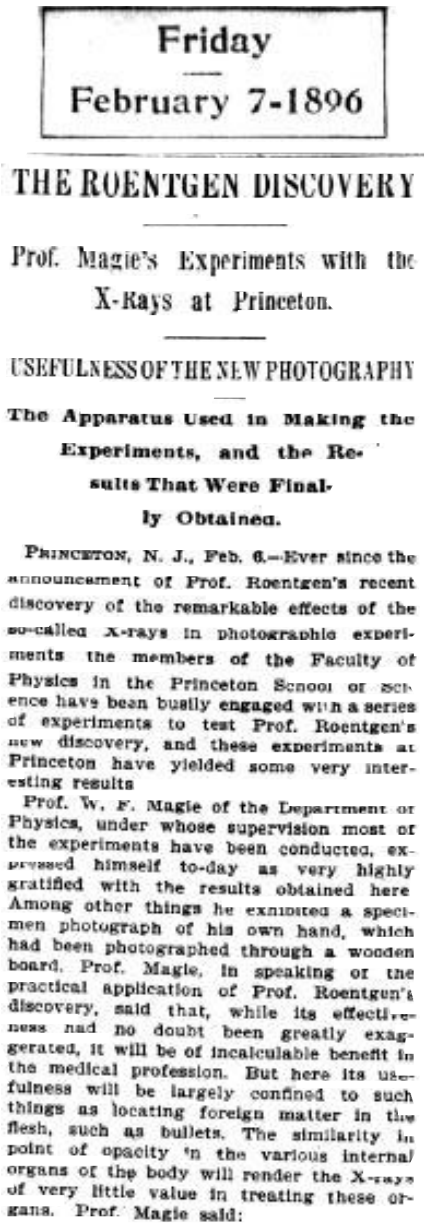
7. After my experiments on the transparency of increasing thicknesses of different media, I proceeded to investigate whether the X-rays could be deflected by a prism. Investigations with water and carbon bisulphide in mica prisms of 30° showed no deviation either on the photographic or the fluorescent plate. For comparison, light rays were allowed to fall on the prism as the apparatus was set up for the experiment. They were deviated 10 mm. and 20 mm. respectively in the case of the two prisms.

With prisms of ebonite and aluminium I have obtained images on the photographic plate which point to a possible deviation. It is, however, uncertain, and at most would point to a refractive index 1.05. No deviation can be observed by means of the fluorescent screen. Investigations with the heavier metals have not as yet led to any result, because of their small transparency and the consequent enfeebling of the transmitted rays.

On account of the importance of the question it is desirable to try in other ways whether the X-rays are susceptible of refraction. Finely powdered bodies allow in thick layers but little of the incident light to pass through, in consequence of refraction and reflection. In the case of the X-rays, however, such layers of powder are for equal masses of substance equally transparent with the coherent solid itself. Hence we cannot conclude any regular reflection or refraction of the X-rays. The research was conducted by the aid of finely powdered rock salt, fine electrolytic silver powder, and zinc dust already many times employed in chemical work. In all these cases the result, whether by the fluorescent screen or the photographic method, indicated no difference in transparency between the powder and the coherent solid.

It is, hence, obvious that lenses cannot be looked upon as capable of concentrating the X-rays; in effect, both an ebonite and a glass lens of large size prove to be without action. The shadow photograph of a round rod is darker in the middle than at the edge; the image of a cylinder filled with [illegible]

X-ray photograph of a snail shell taken by SLAC physicist Hobey DeStaebler at the Stanford Physics Department in 1962 (×2.4).



Friday

February 7-1896

THE ROENTGEN DISCOVERY

Prof. Magie's Experiments with the X-Rays at Princeton.

USEFULNESS OF THE NEW PHOTOGRAPHY

The Apparatus Used in Making the Experiments, and the Results That Were Finally Obtained.

PRINCETON, N. J., Feb. 6.—Ever since the announcement of Prof. Roentgen's recent discovery of the remarkable effects of the so-called X-rays in photographic experiments the members of the Faculty of Physics in the Princeton School of Science have been busily engaged with a series of experiments to test Prof. Roentgen's new discovery, and these experiments at Princeton have yielded some very interesting results

Prof. W. F. Magie of the Department of Physics, under whose supervision most of the experiments have been conducted, expressed himself to-day as very highly gratified with the results obtained here Among other things he exhibited a specimen photograph of his own hand, which had been photographed through a wooden board. Prof. Magie, in speaking of the practical application of Prof. Roentgen's discovery, said that, while its effectiveness had no doubt been greatly exaggerated, it will be of incalculable benefit in the medical profession. But here its usefulness will be largely confined to such things as locating foreign matter in the flesh, such as bullets. The similarity in point of opacity in the various internal organs of the body will render the X-rays of very little value in treating these organs. Prof. Magie said:

If I could have recalled dates well, I might have become a historian! Many physicists share my inner need for such approximation, and so it is not really remarkable that twentieth-century physics itself began a few years early, on New Year's Day of 1896. On that day Professor Wilhelm Roentgen mailed from his university at Würzberg the preprints of his forty-ninth paper. (His first forty-eight are less well known.) He included an X-ray photo of his own hand, a piece of bone-hard evidence for the new penetrating radiation. So much the books tell us.

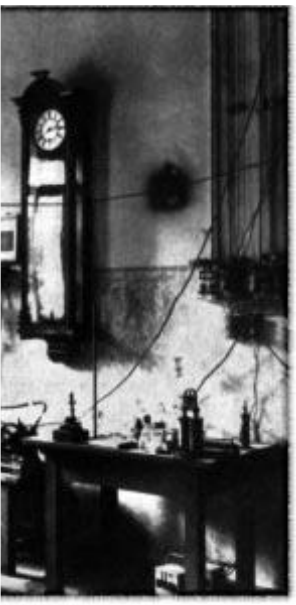
My own encounter with the dawn of twentieth century physics was personal, but of course second-hand. Even so veteran a member of the APS as myself doesn't go all the way back to Gibbs and Helmholtz. But the anecdote makes vivid connection with Roentgen on this present occasion, the hundredth anniversary of his recognition of X rays.

The story unfolds in an unexpected location in space-time, Oklahoma City, Oklahoma, about 1976.

I found myself in Oklahoma through the formidable persuasive powers of Jerrold Zacharias, physicist and impresario at MIT. Zach had already drawn me to MIT years before. He was so energetic and effective as an organizer and standard-setter for science education at every level that he was then a very fountain of opportunity to do good for physics students anywhere. This time it was the Oklahoma City University that would provide me an audience for a rousing popular talk on something new in physics. I cannot really recall my topic; pretty surely it was about quasars or supernovae or the microwave background, something out of current astrophysics, presented for the interested but unspecialized student of physics.

The details were elided by Zach; we always worked on mutual trust. There would be an evening public lecture on the Oklahoma City campus to which I had acceded cheerfully long before. But a luncheon meeting earlier in that day was my first encounter with my hosts. It was marked by experiences unique in all my years of such little formalities.

The luncheon setting was not at all novel; a lot of people sat at table in some club or hotel dining room, whom I faced from my place at a long table among a dozen or so who were singled out for introduction. What was novel was my luncheon partner, who was sitting beside me. He was a spry and articulate elder, and I soon learned that this day was—at least for official purposes—his own hundredth birthday. Not only was he a man of unrivaled seniority, but he was the focus of the whole event, my



The interior of Roentgen's laboratory at Würzburg.

X-ray photograph of two spring-blooming daffodils taken by Hobey DeStaebler (×0.5).

lecture and all. A pillar of Oklahoma City life, he was a generous benefactor to the City University, and the owner, if I remember well, both of the city's main newspaper and of its chief TV station. Plainly he was ruler on this day of all days.

I was there, a visitor from MIT, to speak about physics on campus at his express request for a good lecture. He had very sound reason; the now-powerful centenarian had been a physics student while an undergraduate, and he still loved and admired the subject. He had drifted away into a long career in journalism to reach an elevated level of achievement, but he still wanted to talk physics when he could. At some point I came to ask him about his days as a student of physics so long ago, and he unfolded this wonderful narrative.

He was then a student at Colorado College in Colorado Springs. One morning in January 1896 he came to the physics lecture room as usual. But the lecturer was filled with uncommon excitement. (Here I can only paraphrase what I recall from my hundred-year-old companion .)

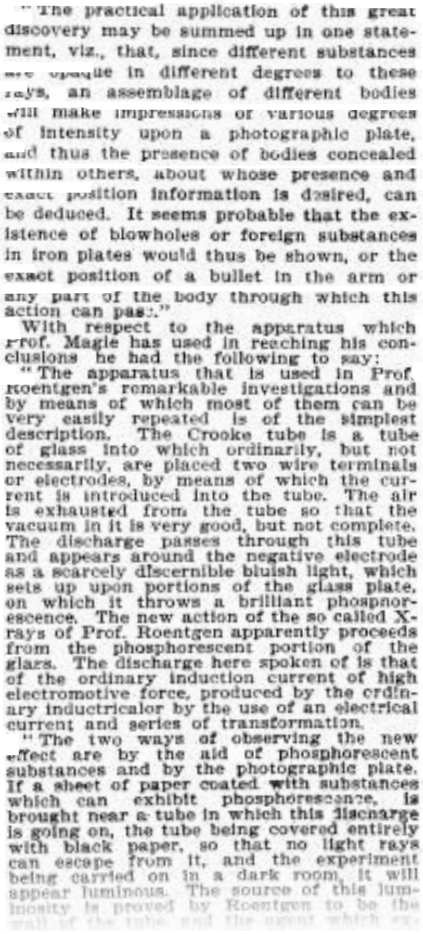
"Gentlemen," began the lecturer, "something so unusual has happened that I want to seek your help. If you consent, we will not simply go ahead with the planned lecture. Instead we will all work together in the lab to an amazing new purpose.

"This morning's newspaper brought a report that a German professor has discovered an extraordinary new form of radiation, one so penetrating that for instance he is able to photograph the bones within the living hand, or a coin hidden inside the pages of a thick book. The story is not very complete, but it says enough about how it was done that I think we could duplicate the results with apparatus we have right here in our college laboratory.

"It would be wonderful to do that, and perhaps we might even be the first in all America to repeat his result, since we are getting started in the first hours of the morning. Let's get going; first we'll collect what we need and then set it up.

"If we all work together we can easily do the job by lunchtime. Will you join me?"

The delighted class set about the task. The needed materials were all soon found on the lab shelves: the big sparky induction coil, the Crookes tube, the fluorescent screens, the darkroom materials, the filters of black paper....Soon it all came together. And it worked! By lunchtime my host recalled running over

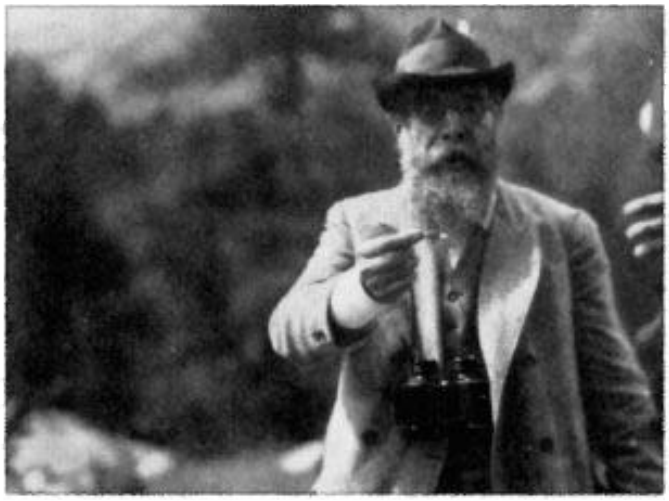


"The practical application of this great discovery may be summed up in one statement, viz., that, since different substances are opaque in different degrees to these rays, an assemblage of different bodies will make impressions of various degrees of intensity upon a photographic plate, and thus the presence of bodies concealed within others, about whose presence and exact position information is desired, can be deduced. It seems probable that the existence of blowholes or foreign substances in iron plates would thus be shown, or the exact position of a bullet in the arm or any part of the body through which this action can pass."

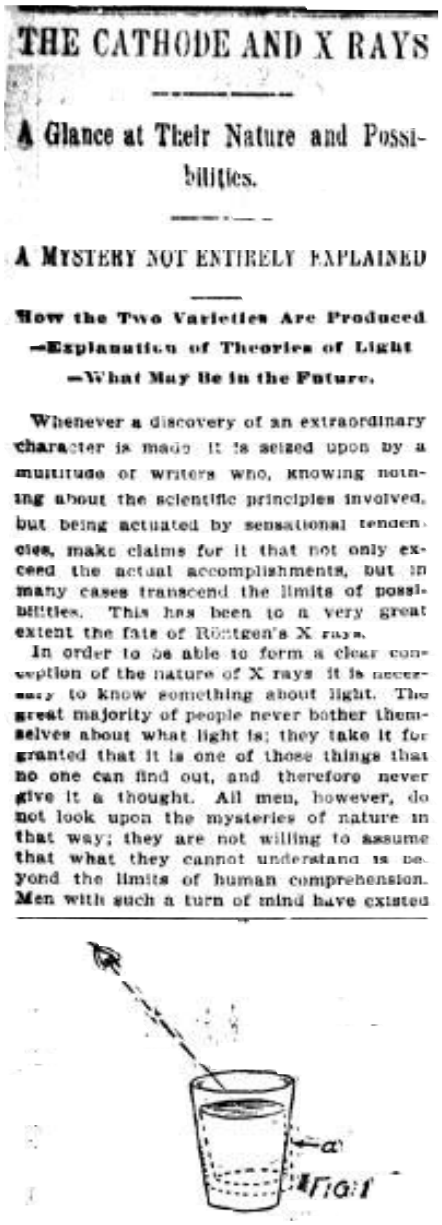
With respect to the apparatus which Prof. Magie has used in reaching his conclusions he had the following to say:

"The apparatus that is used in Prof. Roentgen's remarkable investigations and by means of which most of them can be very easily repeated is of the simplest description. The Crooke tube is a tube of glass into which ordinarily, but not necessarily, are placed two wire terminals or electrodes, by means of which the current is introduced into the tube. The air is exhausted from the tube so that the vacuum in it is very good, but not complete. The discharge passes through this tube and appears around the negative electrode as a scarcely discernible bluish light, which sets up upon portions of the glass plate, on which it throws a brilliant phosphorescence. The new action of the so called X-rays of Prof. Roentgen apparently proceeds from the phosphorescent portion of the glass. The discharge here spoken of is that of the ordinary induction current of high electromotive force, produced by the ordinary inductricalor by the use of an electrical current and series of transformation.

"The two ways of observing the new effect are by the aid of phosphorescent substances and by the photographic plate. If a sheet of paper coated with substances which can exhibit phosphorescence, is brought near a tube in which this discharge is going on, the tube being covered entirely with black paper, so that no light rays can escape from it, and the experiment being carried on in a dark room, it will appear luminous. The source of this luminosity is proved by Roentgen to be the wall of the tube and the agent which ex-



Roentgen out walking later in life.



THE CATHODE AND X RAYS

A Glance at Their Nature and Possibilities.

A MYSTERY NOT ENTIRELY EXPLAINED

How the Two Varieties Are Produced —Explanation of Theories of Light —What May Be in the Future.

Whenever a discovery of an extraordinary character is made it is seized upon by a multitude of writers who, knowing nothing about the scientific principles involved, but being actuated by sensational tendencies, make claims for it that not only exceed the actual accomplishments, but in many cases transcend the limits of possibilities. This has been to a very great extent the fate of Röntgen's X rays.

In order to be able to form a clear conception of the nature of X rays it is necessary to know something about light. The great majority of people never bother themselves about what light is; they take it for granted that it is one of those things that no one can find out, and therefore never give it a thought. All men, however, do not look upon the mysteries of nature in that way; they are not willing to assume that what they cannot understand is beyond the limits of human comprehension. Men with such a turn of mind have existed

to the Colorado College chapel to borrow a large Bible in whose pages they could hide a silver coin. The excitement was unforgettable.

Of course they were not to be the first in America to run the experiment. For the morning papers had carried the story very widely. Colorado had an irremediable handicap: its longitude. So far west, they were late in starting, behind the many physics labs of the Eastern time zone a couple of hours as the earth turns. Many had had a similar idea, and some of the Easterners would surely be first. I have no real data on exact times or even dates, but I do know that Penn, Princeton, Columbia, Cornell, Harvard, Dartmouth, and others recall very prompt repetitions of Roentgen's wonderful result.

This result came as though a seed crystal had been dropped into a saturated solution! The new physics crystallized out everywhere at once; the requisite apparatus was already there in all serious labs around the world. On the 20th of January, Henri Poincaré, who had received a New Year preprint from Roentgen himself, showed the marvelous photos to the session of the Paris Academy. Henri Becquerel was there, an expert on fluorescence like his father before him, and by March 2 Becquerel had found, largely by happy accident, that a uranium compound emitted some such active radiation spontaneously, without requiring exposure to light or any other energizing input. Radioactivity had been discovered, and the physics of the twentieth century had begun, for good and for ill.

What a story! Yet it was to be capped that very evening. Of course I could not fail to re-tell the physics student's birthday story as a preface to my lecture. It went well, although certainly it was a digression. After my talk, a young man came up to speak to me. He was no undergraduate; he introduced himself as a physics postdoc at work for a year or two in Oklahoma. His home was Germany, where he had taken his doctor's degree. What he told me was a family story that he had first heard in his childhood, often told and retold in his presence. It was his elderly uncle, a physician, who was the storyteller.

That man had been a medical student in Würzberg in 1896. He took physics from Roentgen. One day the Professor told his physics class of his recent work and demonstrated it briefly. Now, it is an ancient custom in the German universities for students to indicate high pleasure and approval by remaining seated in place while beating their shoes smartly on the floor. In the usual lecture theater there the seats rise up in rows step after step, to allow all to view the lecture table. The floor structure is thus hollow and resonant, and the noise of the footbeats is grand. The students that day approved mightily of Roentgen's miracle, and continued their racket, so Uncle reported, for *one full hour* without stopping. Twentieth-century physics was made welcome for the first time.

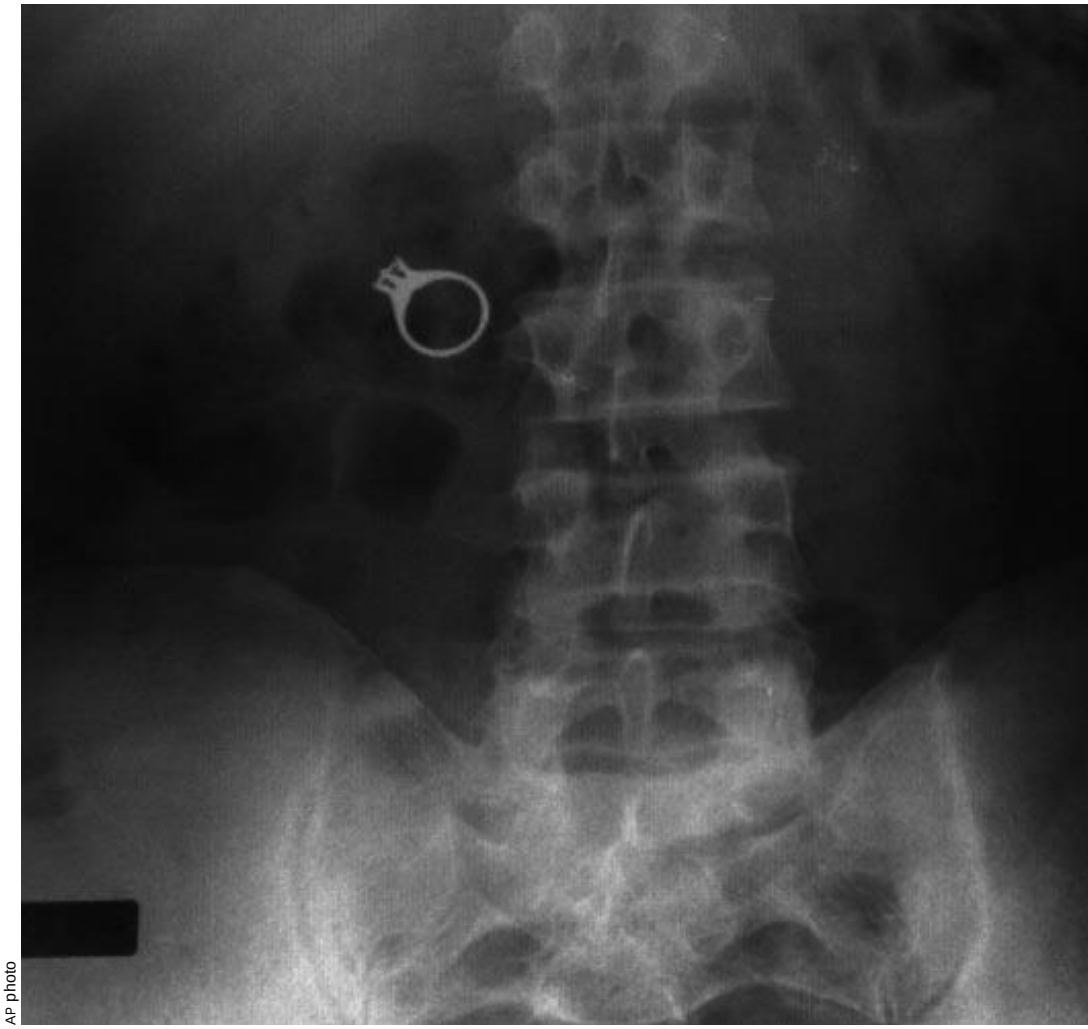
It is curious that the best-known finding of twentieth century physics was made in the same well-seeded

context on the brink of WWII in January 1939. The celebrated Berlin experimenter Lise Meitner, newly exiled in Sweden, spent Christmas Day in a park near Stockholm with a visitor from Copenhagen, her younger nephew, physicist Robert Frisch. The two talked over the amazing new report from Meitner's old lab that demonstrated that uranium upon irradiation by neutrons yielded radioactive products that included not only the expected elements close to uranium in atomic weight, but one that was only about half as heavy. At one point in the conversation they both came to an explanation and soon mutually understood that uranium had fissioned into two heavy fragments, and that the fragments must fly apart with unprecedented energy, to be detectable by the heavily ionized tracks they left in matter. Within two weeks Frisch had seen on the oscilloscope screen the unmistakable strong spikes of ionization they had expected.

Their news came out even before publication, by word of mouth direct from Niels Bohr, who had sailed off to a conference in Washington held in the last week of January. Within days eager phone calls back to home labs by the physicists who had heard Bohr had induced the production of those very spikes in many places (I saw them myself then at Berkeley); within weeks they were certainly familiar all over the world. You had mainly to scrounge a small amount of uranium compound in the chemistry storeroom. The fission spikes were easy to find with the little ion chambers, oscilloscopes of modest gain, and weak neutron sources that every serious nuclear physics lab then held, as forty-three years before every lab working with electrical discharges through gases already had its Crookes vacuum tube and high voltage source on the shelf.

History had repeated itself. The first time the stunning discovery was rather light-hearted, in those shadow photos through closed books and bony hands, but the second time it was fateful. By the spring of 1940 six governments, all of them already at or close to war, had each formed its own initial organization to seek large-scale energy from uranium.

For the last few years we have come to share reason for hope that the hundredth anniversary of fission, when it arrives, will indeed be commemorated mainly among the physicists, and not everywhere to universal public dismay instead of prolonged applause.



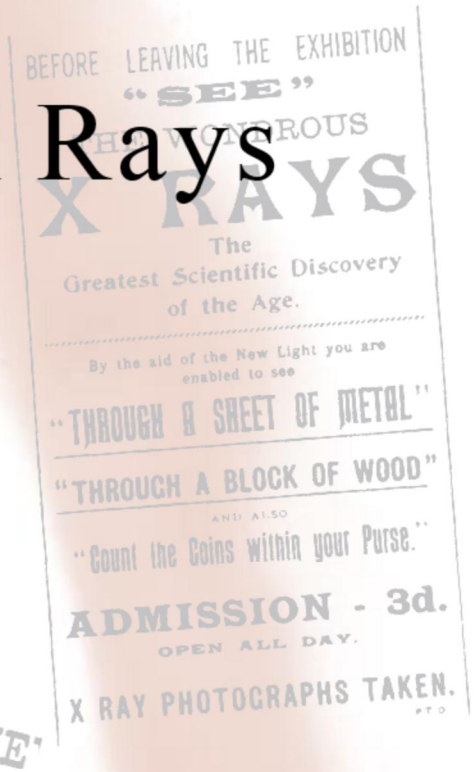
AP photo

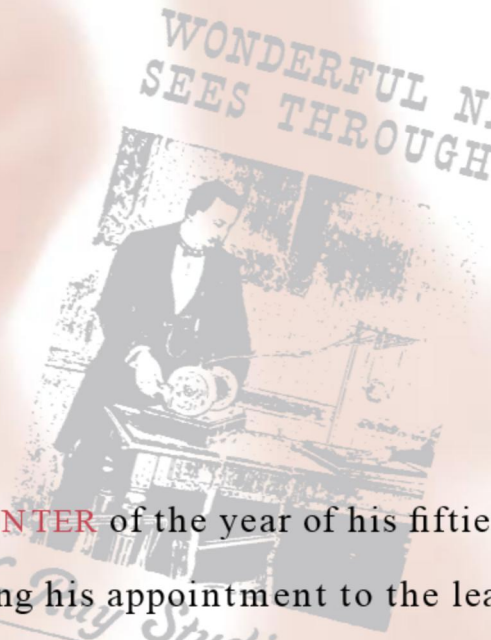
This X ray image, taken in North Providence, Rhode Island, Thursday, Feb. 16, 1995, shows a diamond ring that was swallowed by a robber to fool police.

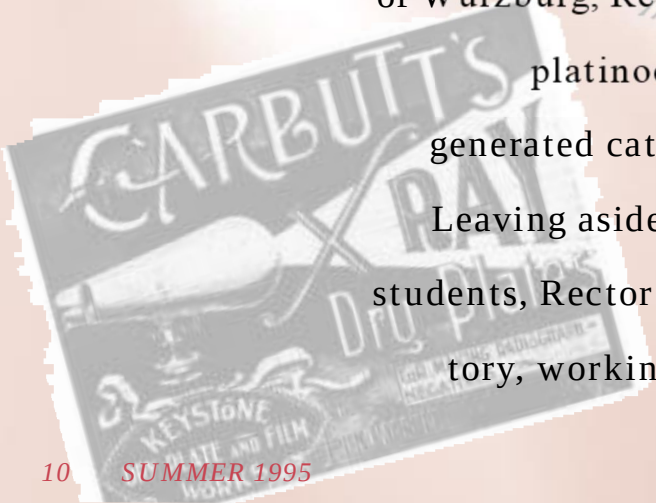
Early History of X Rays

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.

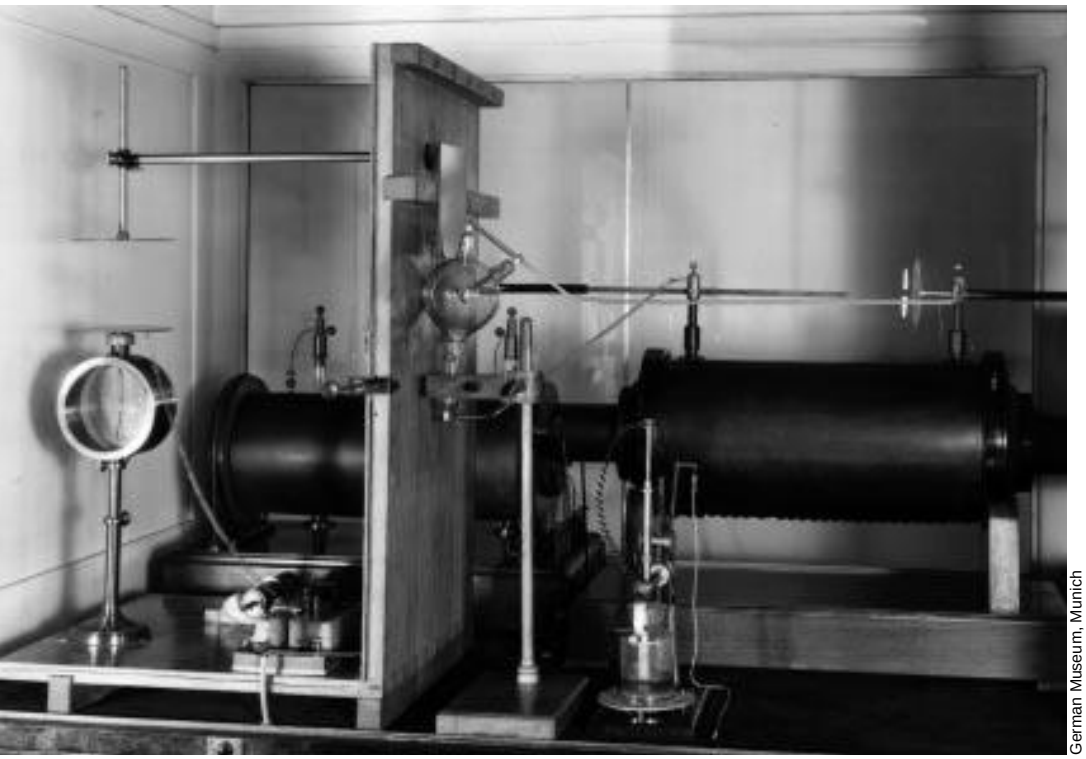
On the 13th of January, Roentgen presented himself to the Kaiser and was awarded the Prussian Order of the Crown, Second Class. And on the 16th of January the *The New-York Times* announced the discovery as a new form of photography, which revealed hidden solids, penetrated wood, paper, and flesh, and 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

German Museum, Munich

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



German Museum, Munich

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

Sir Joseph John Thomson, 1856–1940. (Courtesy of the AIP Niels Bohr Library)

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

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."*

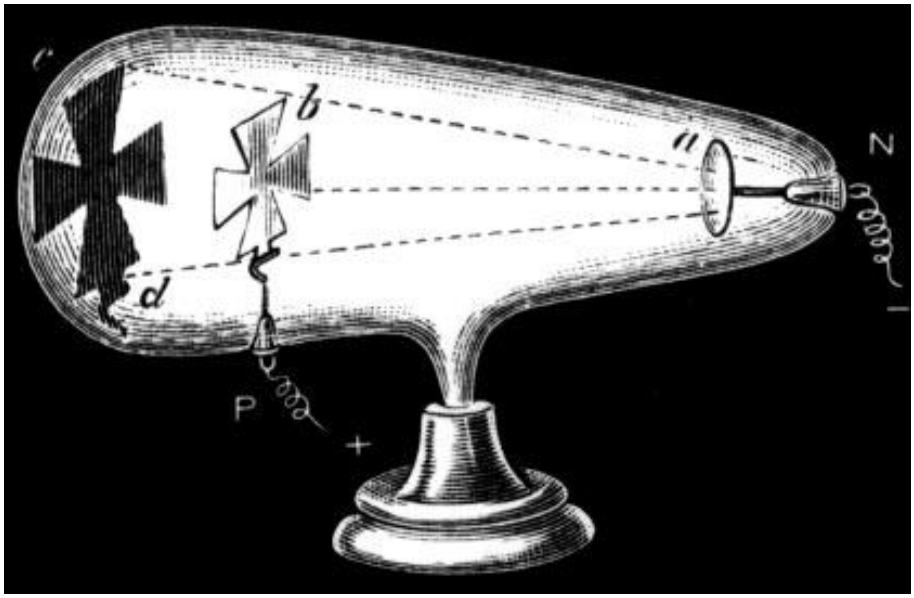
Roentgen's pride could rest in the over forty papers he had published from Strasbourg, Giessen, and Würzburg. These early interests ranged widely—crystals, pyroelectrical and piezoelectrical phenomena, and the effects of pressure on liquids and solids—but did not yet include electrical discharges in 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

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.



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

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.

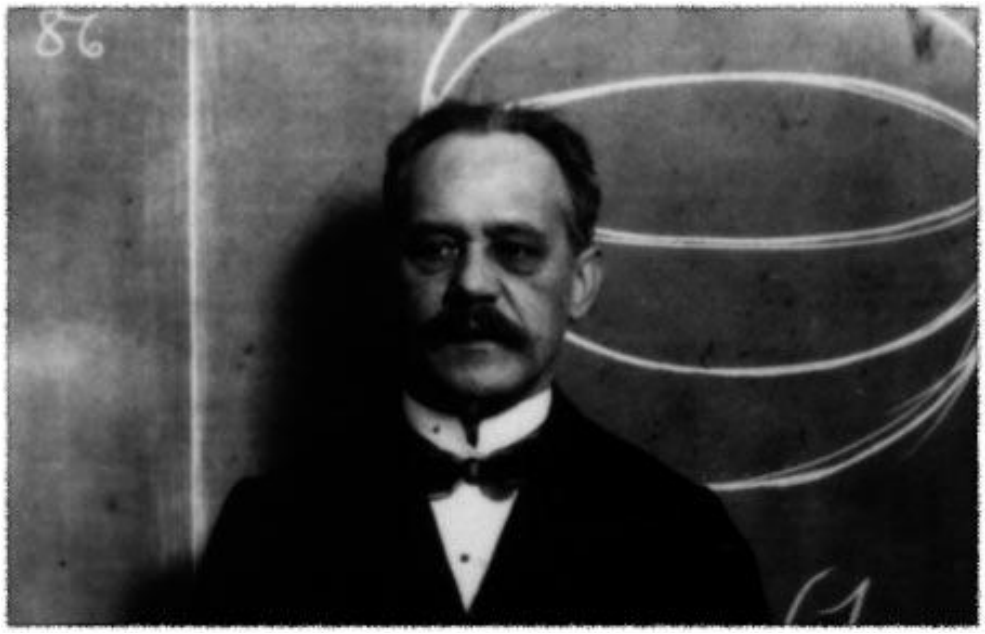
Electricians and physicists speculated on the nature of these X rays. Albert Michelson thought they might be vortices in the ether. Thomas Edison and Oliver Lodge suggested acoustical or gravitational waves. But the rays ability to photograph was decisive, and serious thinkers settled on three possibilities, 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

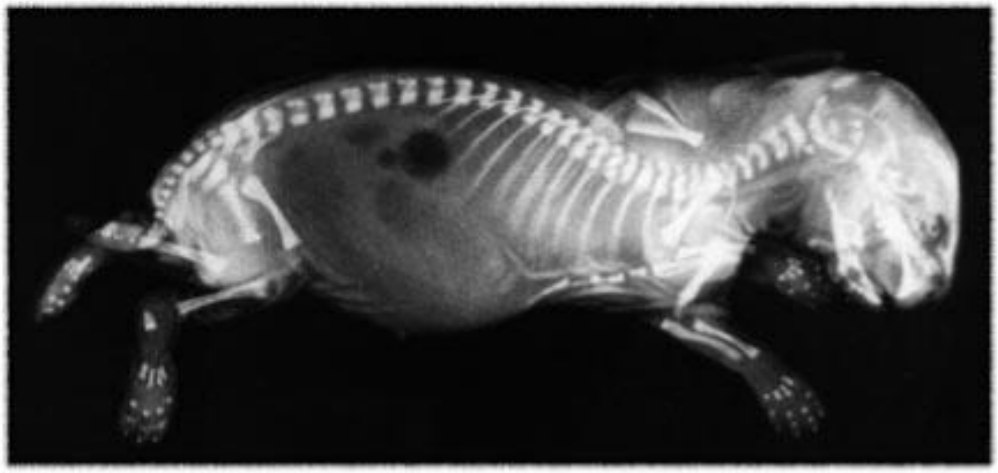
velocity of the electrons excited by X rays is greater than could be given to them by a wave. By this time Bragg and his physicist son were back in England, and their theory caused great controversy even in the country where particles were in favor and where exotic modeling of physical phenomena was 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!)

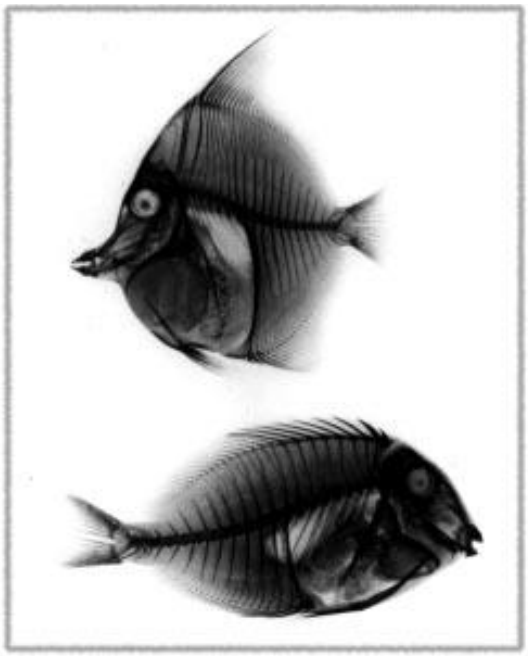
When in 1899 Roentgen was offered a position at Munich and the chance to build up physics there, he accepted. Five years later, in negotiations with the minister of education over another possible move, this time to the Reichsanstalt, Roentgen received, in return for a pledge to stay in Munich, a second 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.

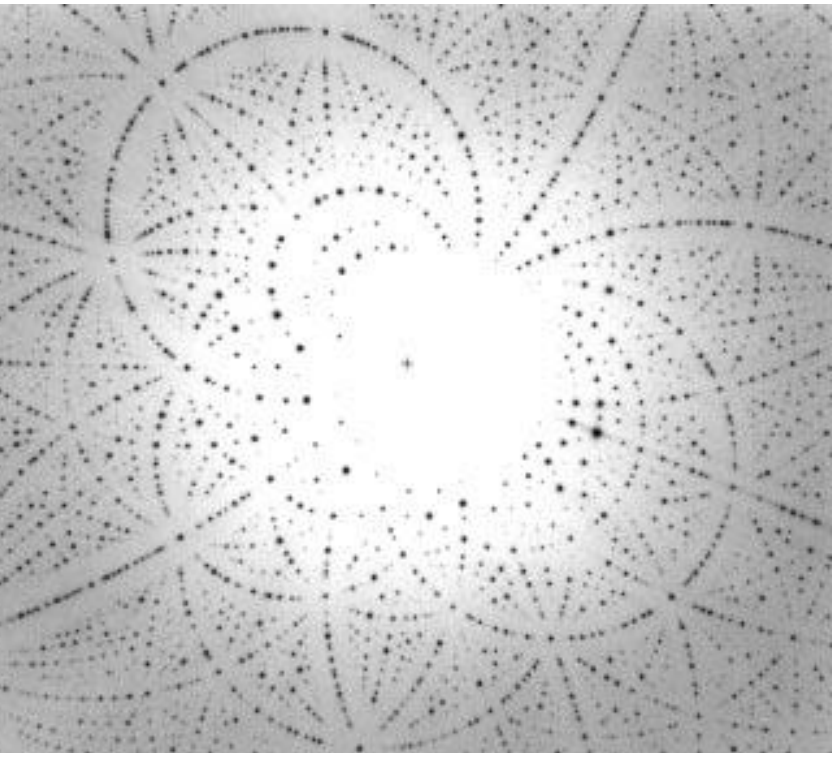
Sommerfeld was initially unenthusiastic about assistant Max von Laue's idea that regularly spaced atoms in a crystal might act as a diffraction grating for X rays, the fine distances between the atoms serving, as no hand- or machine-ruled grating could, to diffract ultra-high frequencies. If, of course,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





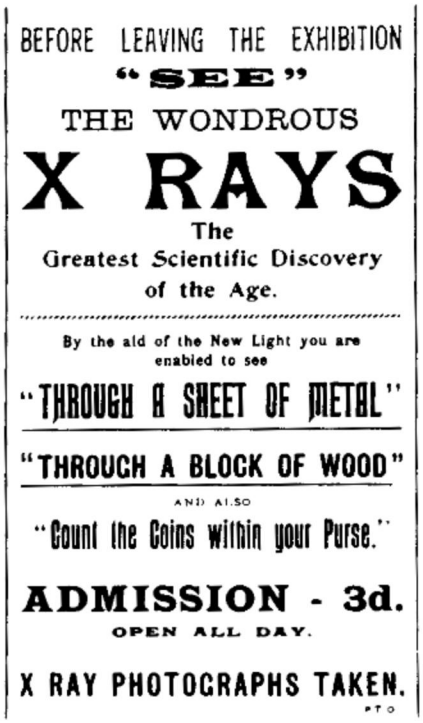
White radiation Laue diffraction pattern from the protein trimethylene dehydrogenase (an enzyme that catalyzes the conversion of trimethylamine to dimethylamine and formaldehyde) recorded on SSRL beam 10–2 with a 5 msec X-ray exposure. The photograph was taken by Scott Matthews and Scott White of Washington 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.

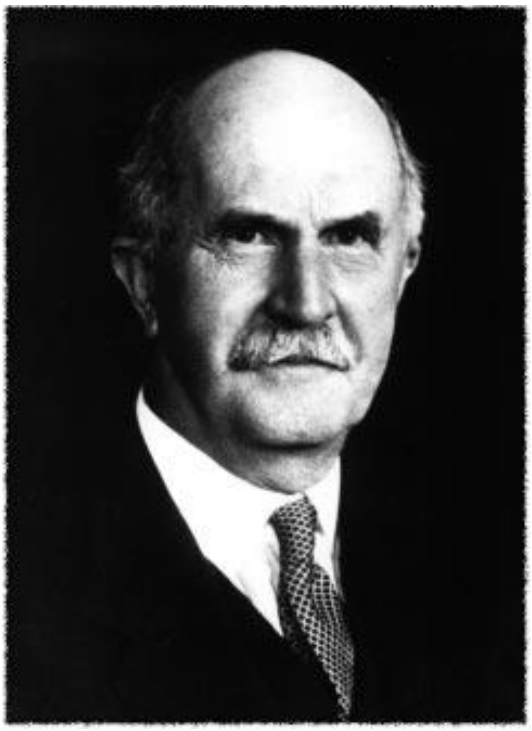
Laue persisted in asking that the experimentalists try out X rays on crystals. A student of Max Planck's (in fact, his favorite), Laue had worked on a theory of the interference of light in plane parallel plates. By 1912 his specialty had become the theory of relativity, but he was not averse to following 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.

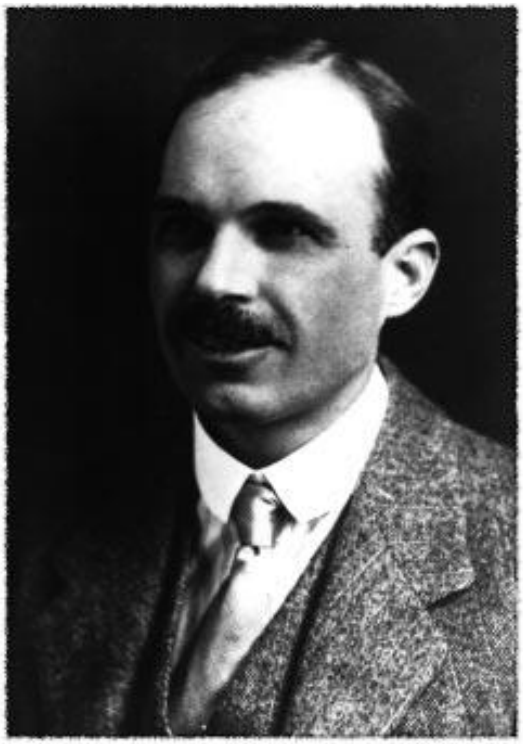
The new field was pioneered by the Braggs. They were inspired by the Cambridge theorists who argued that a diffraction grating imposes a structure on an inhomogeneous pulse of white light, picking out, as if in a Fourier transform, the wavelengths into which the beam can be decomposed. William Henry 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

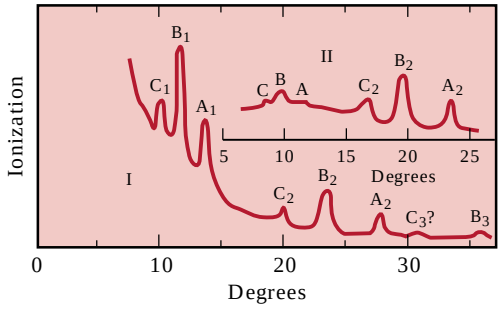
$$n\,\lambda = 2d\,\sin\theta,$$

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

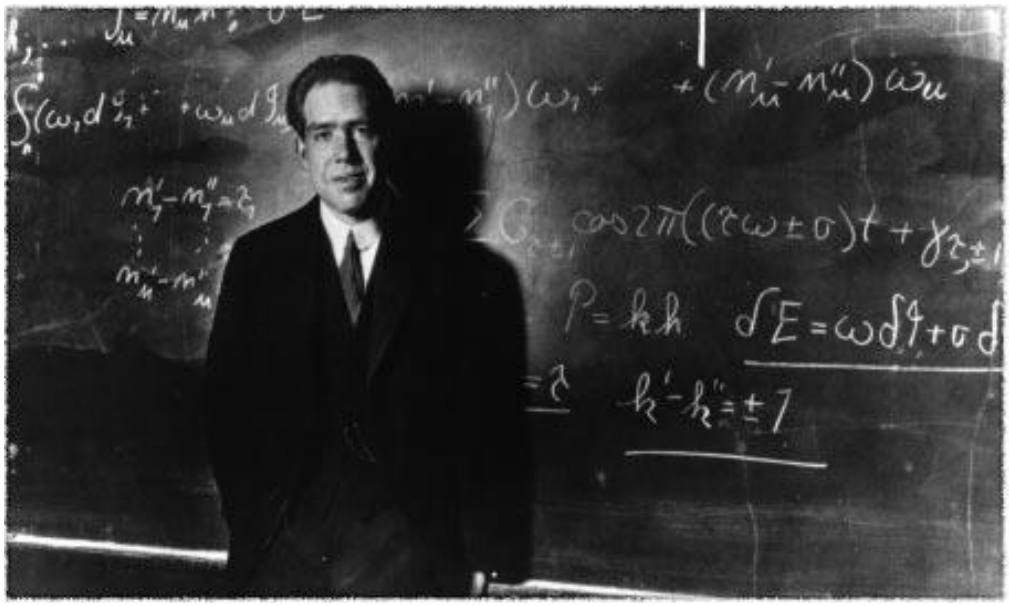
Arthur Holly Compton, 1892–1962. (Courtesy of the AIP Niels Bohr Library)

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)

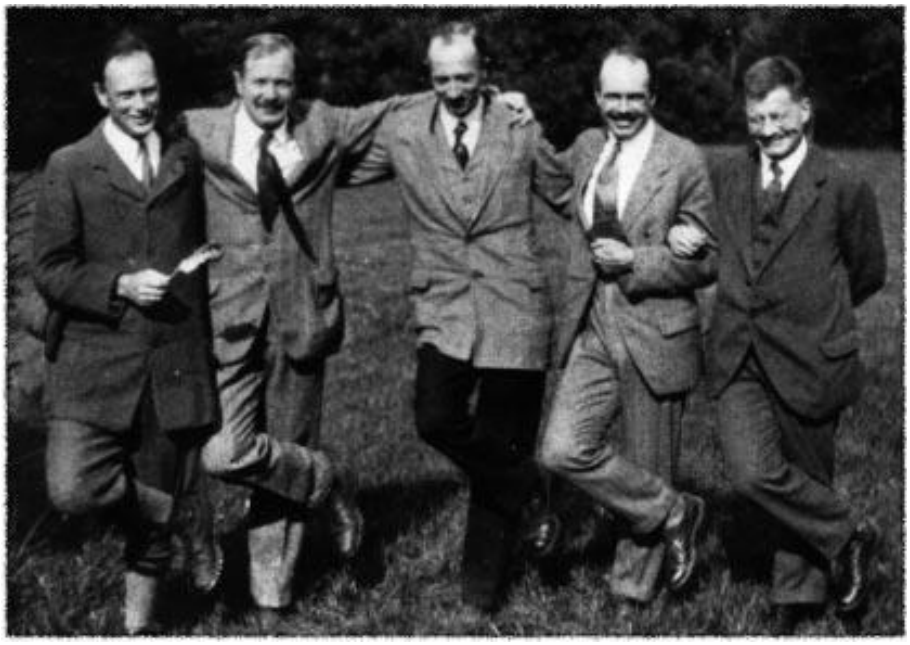
right leg of a young boy. The military first used X rays in Naples in May of 1896 to locate bullets in the forearms of two soldiers who had been wounded in Italy's Ethiopian campaign.

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.

Medical Applications of X Rays

by OTHA W. LINTON

IN THE DAYS following his discovery of a new, invisible ray in November, 1895, Professor Wilhelm Conrad Roentgen experimented doggedly to test its properties. He noted quickly that solid objects placed in the beam between the Crookes' tube and the fluorescent screen serving as an image receptor attenuated or blocked the beam, depending upon their density and structure.

A CENTURY OF RADIOLOGY: 1895–1995

The discovery of the X ray in 1895 was one of the most momentous events in science and medicine, but it was only the beginning of what was to be accomplished in the next 100 years in radiology. What follows are some highlights provided by American College of Radiology.

1895

- German physics professor Wilhelm Conrad Roentgen discovers the X ray on November 8 in his laboratory in Würzburg.
- On December 28, Roentgen announces his discovery with a scientific paper, *W. C. Roentgen: About A New Kind of Rays (preliminary communication)*, that is widely reprinted.

1896

- On January 23, Roentgen delivers his first lecture about the X rays.
- Roentgen's discovery launches a flurry of experimentation around the world with the Crookes' tubes. Researchers study what the X rays will do and tinker with refining the design of the tubes. Although the shapes and configurations of the tubes change, the basic concept will stay the same until 1913.
- Fluoroscopy is invented in January by Italian scientist Enrico Salvioni, while American inventor Thomas Edison, an early and active X-ray enthusiast, works on a similar device. The fluoroscope is a hand-held or mounted device consisting of an oblong box, one end of which fits tightly against the eyes, the opposite end of which is a fluorescent screen. The basic concept is still used today.
- In March, a "Roentgen photograph" is introduced as evidence in a Montreal courtroom by a man suing a defendant who allegedly shot him. The X ray proves the presence of a bullet not detected by exploratory surgery.
- Hospitals begin acquiring X-ray equipment to be used by people with and without medical qualifications.
- One of the first physicians to specialize in X rays in 1896 is Dr. Francis Henry Williams of Boston. He is also a graduate of the Massachusetts Institute of Technology, making him one of the few physicians intimately conversant with the physics that create X rays. He is instrumental in early uses of X rays for medical diagnosis, including the use of fluoroscopy to study the blood vessels. Later this will be known as angiography.

1898

- In December, Marie and Pierre Curie, working in Paris, discover radium, a new element that emits 200 million times more radiation than uranium. In 1903, the Curies and Antoine-Henri Becquerel share the Nobel Prize in Physics for their work on radioactivity.

  "Like the discovery of X rays, the discovery of radium captured the world's imagination," says Nancy Knight, Ph.D., historian and director of the Center for the American History of Radiology. "Scientists knew that the radiation from X rays and radium was similar, but radium was considered the 'natural' version of X rays."

Then, in a heart-stopping moment, he chanced to pass his hand through the beam. As he looked at the screen, the flesh of the hand seemingly melted away, projecting only the outlines of the bones. The hand was intact, unharmed. But on the screen, only the bones showed up. With that observation, the science of medical radiology was born.

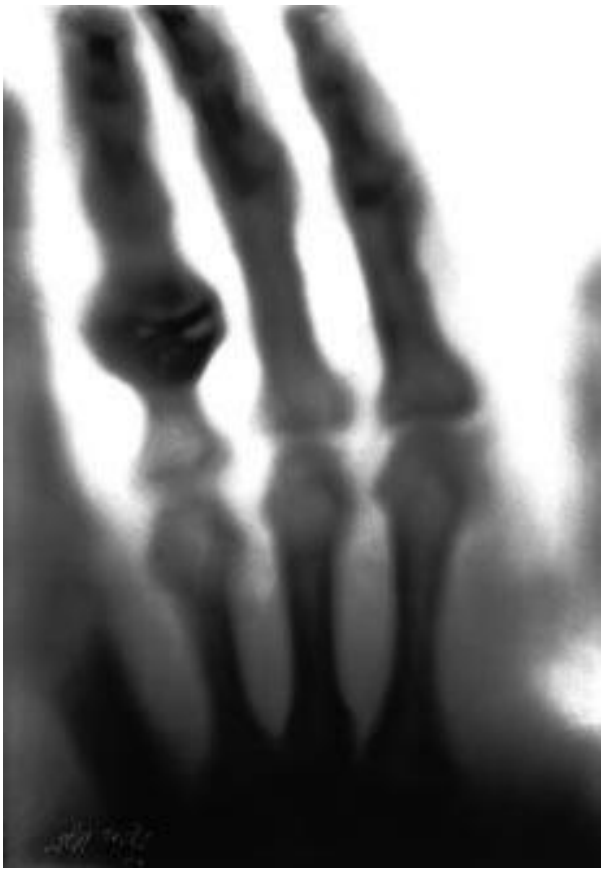
A few days later, Roentgen made a photographic image of his wife's hand, using the new rays instead of light for the exposure. Again, only the bones showed, this time on a permanent record which others could see—and believe.

The discovery of a new form of energy that could penetrate solid objects and record their structure excited Roentgen's scientific contemporaries. But it was the skeletal hand that captured the imagination of the public and of physicians, who recognized instantly that this discovery could change medical practice forever.

A century later, the vastly more sophisticated arts of medical imaging are still based upon the recognition that body parts absorb a beam of X rays according to their density, producing an image which allows identification of body structures as well as the recognition of abnormalities reflective of injury and disease conditions.

Take a chest X-ray image, for example. The calcium density of the spine and ribs blocks the most X rays, leaving white areas on a film. No X rays penetrate to expose the film and darken those spots. The water densities of the stomach and liver are grayish. They block less of the X-ray beam than bones. It's easy to see the contrast between them. The fat density of muscles is less than that of the water. They look only slightly darker, but the distinction is there for a trained eye. Finally, the air spaces in the lungs allow penetration of most of the X-ray beam, and look almost black on the films.

Allow that the chest X-ray image looks complex because three dimensions are recorded as two. Muscle tissue overlies the ribs, which in turn overlie the lung cavities. The shapes of blood vessels (water density) and the esophagus, which carries food and liquids to the stomach, can be seen. Fractures of the ribs, abnormal curves of the spine, unusual heart silhouettes are readily visible. Irregular shadows, caused by cancers growing in the lung, may require a sophisticated viewer to pick



German Museum, Munich

The famous radiograph made by Roentgen on December 22, 1895. This is traditionally known as "the first X-ray picture" and "the radiograph of Mrs. Roentgen's hand." However, it was not actually the first X-ray picture (others exposed photographic plates to X rays previously, without knowing the images' significance), and was not labeled as Mrs. Roentgen's hand when it was first published.

up in the welter of overlapping shadows. The pattern of coal particles retained in the lung field of miners may be even more subtle, but is essential to a diagnosis of black lung.

IN THE WEEKS after the first medical X-ray images early in 1896, scientists and physicians began to improve on the faint images produced by tubes and generators like the ones Roentgen used. How they made improvements—borrowing from advances in physics, chemistry, pharmacology, nuclear science, computers, telemetry and information science—is the story of a century of medical radiology.

Those early X-ray experiments also led scientists to observe that the passage of X rays through living tissue could cause changes. The low-energy X rays appeared to have a good effect on many skin diseases. Open cancers shrank and the sores dried up. Arthritis sufferers reported relief from their pains. When exposures were seen to make hair fall out, the X ray was touted as an end to men's daily shaving chores. But just as quickly, workers with X rays noted that repeated exposures seemed to cause skin inflammations, ulcers, sores, superficial and deeper cancers, blood abnormalities, and even death. The question arose: must X-ray workers inevitably forfeit their own health, as some pioneers did, to the promise of this new science?

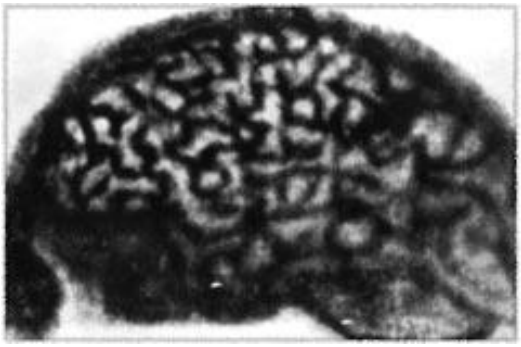
The struggles of radiation scientists to develop radiation safety protocols, to devise measurements, to learn to control X-ray production, and to exploit the seeming paradox that higher energies of radiation kill more cancer cells while sparing normal ones are also parts of this century of remarkable progress.

The earliest X-ray images were more useful to surgeons than to other doctors. Bone fractures or displacements, gallstones, kidney stones, and bullets or other metallic fragments could be located reliably. With the improved tubes and films that relaced the original glass plates, doctors began to see organ shapes. But they still could not see *into* organs, which had the same water density inside and out.

Nevertheless, other advances came quickly. In 1896, the inventor Thomas Edison devised the fluoroscope, a calcium tungstate coated screen which glowed when X rays hit it, allowing direct viewing of any part of the anatomy. In 1913, William D. Coolidge of the General Electric Laboratories devised an improved hot cathode X-ray tube, which produced consistent repeated exposures and was shielded to prevent the scattered radiation that had harmed the early X-ray users. X-rays emerged from Coolidge's tubes only through an aperture in the lead shielding. The patient could then be placed into the beam while others were kept away from it. Additionally, filters were devised to absorb soft, useless X rays, and a device called a grid, placed in front of the film, absorbed much of the X-ray scatter that could cause fuzzy images. Screens similar to the fluoroscope surface were used in film holders to enhance X-ray images.

And the problem of looking within body structures was finally addressed as well. Liquids opaque to X rays were found that could

This much admired "first radiograph of the human brain" from 1896 is actually a pan of cat intestines. Since the X ray was so novel to the public, falsified images appeared frequently after Roentgen's discovery.



American College of Radiology

Around the world people believe radium to have marvelous medicinal properties. It is said to lessen constipation, lower blood pressure, cure insomnia by soothing the nerves, and increase sexual activity, and is put in skin creams and toothpastes. People flock to radium springs, where the water is mildly radioactive, a craze that lasts into the 1930s, and use 'radium drinkers,' ceramic vessels made of irradiated earth, at radium cocktail parties, where inside everyone's drink is a vial of 'radium emanation'—radon gas—to make the drinks glow in the dark. Also popular is 'radium roulette,' in which the roulette balls and table are painted with radioactive paint.

1900

- German scientists Friedrich Giesel and Friedrich Walkhoff discover that radium rays are dangerous to the skin; Pierre Curie purposely leaves a radium sample on his arm for ten hours and produces a sunburn-like rash. En route to a conference, Henri Becquerel unthinkingly carries a sample in his lower vest pocket and suffers a burn on his abdomen.
- Radiology begins to emerge as a medical specialty. It becomes increasingly clear that producing an X-ray image requires skill and technical know-how, and interpreting the image requires a knowledge of anatomy.

1901

- Roentgen wins the first Nobel Laureate in Physics prize for his discovery.

1904

- Clarence Dally, Thomas Edison's assistant in X-ray research, dies of extreme and repeated X-ray exposure. X rays had already caused severe burns on his face, hands, and arms, resulting in several amputations. From this point on, the risks posed by radium and X rays become more clear. X-ray use begins to be confined largely to doctor's offices and hospitals.

1910

- Eye goggles and metal shields are commonly used to shield X-ray users.

1917

- During World War I, X-ray equipment is an accepted component of aid stations and hospitals in the field.

1919

- Dr. Carlos Heuser, an Argentine radiologist, is the first to use a contrast medium in a living human circulatory system. The compound, potassium iodide diluted with water, is acceptable because it is excreted by the body and causes the blood vessels to appear opaque on the X-ray image. Dr. Heuser successfully injects the compound into a vein of a patient's hand and simultaneously takes an X ray to visualize the veins in the forearm and arm. His discovery, however, is lost on the scientific world because it is published only in Spanish, in an Argentine medical journal.

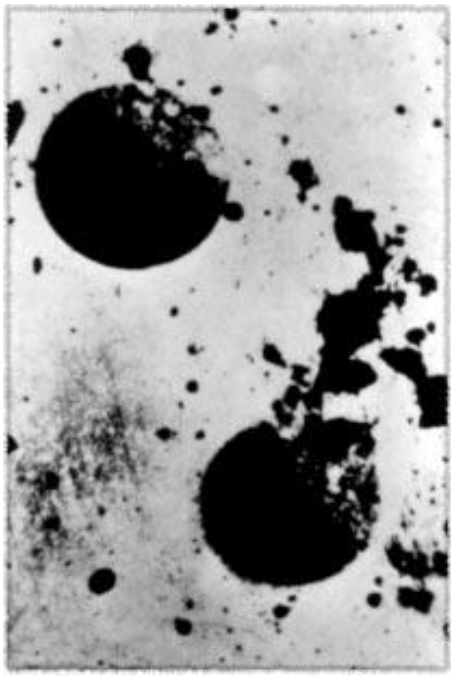
be ingested or otherwise placed within a patient. For instance, barium sulfate, a common mineral, could be ground up and swallowed to outline the esophagus, stomach, and small intestine. Barium sulfate could also be inserted as an enema to visualize the large intestine. This practice allowed the viewing of strictures, blockages, ulcers, cancers, and other defects. But the development of other radio-opaque liquids, now called contrast agents, which could be used with the kidneys, the brain and spinal canal, the circulatory system and the lungs, took much longer and required far more complex solutions.

ROENTGEN'S DISCOVERY was artificial ionizing radiation. Two years later, a French physicist, Henri Becquerel, discovered that certain rocks emitted natural ionizing radiation with characteristics much like Roentgen's X rays. Becquerel's colleagues Pierre and Marie Curie refined the naturally radioactive ores to derive uranium, polonium, and radium.

Radium was perceived to have a value in treating cancers, already seen to be responsive to X rays. Marie Curie's work produced only tiny amounts, with one ounce of radium being offered for sale at $1 million. The radium salt (usually radium sulfate) was sealed in hollow gold or platinum needles and inserted into or against cancerous lumps to deliver cell-killing doses of radiation. A decay product of radium, radon gas, was used in hollow glass seeds for insertion in tumors which could not be reached with the removable needles.

William Coolidge soon improved his X-ray tubes to deliver energy levels of 200 kilovolts and more, and as doctors used radium coupled with the high energy X-ray beams, they noted the seeming paradox that higher energies killed more cancer cells and spared more normal tissue than lower-energy radiation. Radiobiologists came to understand that the rapid mitosis of cancer cells made them more susceptible to radiation destruction and less capable of regeneration than slower-growing normal cells. But because some normal cells were necessarily radiated in the process of getting the energy to the cancers, the success of treatment depended upon the ability of the radiologist to plan and deliver a dose that would kill all of the cancer cells without destroying an unacceptable amount of normal cells.

X-ray image of coins made by physicist A.W. Goodspeed and photographer William Jennings in 1896, duplicating one they had made by accident in Philadelphia in 1890. When the two made the 1890 radiograph, they did not realize its significance, and the photographic plates lay unnoticed and unremarked until Roentgen's announcement of the X-ray discovery caused them to review the images.



American College of Radiology

Optimal dose levels, time intervals for treatment to take advantage of the mitotic cycle, ways of protecting normal parts of the patient, medical care to protect patients against infections, and other products of white blood-cell radiation destruction all began to contribute to improved radiation treatment. Even so, surgery remained the first choice of treatment for many kinds of cancers, leaving radiation as an adjunctive method for destroying cancer cells not removed by surgery and for trying to control metastases from advanced cancers.

DURING THE FIRST four decades of this century, many advances in medical radiation uses came from gradual improvements in equipment and techniques. The availability of X-ray machines in military hospitals during World War I convinced many physicians of the usefulness of X-ray studies in detection of somatic problems, as well as trauma. A chest X ray became the standard method of diagnosing tuberculosis. About all that could be offered the active tubercular patient was nursing care, but isolation of such patients helped to break the spread of the highly contagious disease to other family members and co-workers. Tuberculosis was the target of the first X-ray population screening efforts.

The creation of artificial isotopes in the 1930s by Frédéric Joliot and Irene Curie, daughter of Pierre and Marie, opened new dimensions in radiation science. Soon, Ernest Lawrence was making artificial isotopes in the cyclotron of the Donner Laboratory at the University of California in Berkeley. Lawrence invited Robert Stone, the chief of radiology at the University of California Medical Center in San Francisco, to bring cancer patients for treatment with neutrons produced in the Donner lab. Cancers treated with neutrons melted away. Soon, so did the cancer patients. Neutrons had more energy and different biological characteristics than high energy X rays. Stone discontinued his treatments until the characteristics of neutrons could be understood better.

World War II arrived, and in quick succession Lawrence, Stone, and most of the leading radiation scientists in the free world were drawn into the Manhattan project to develop an atomic bomb. Wartime imperatives drive science more strongly than peaceful objectives. But there was an appreciation within the Manhattan project that biological problems were created by the physical and chemical advances, and after the war, the congress created the Atomic Energy Commission to further peaceful applications of the new radiation science.

FOR PHYSICIANS, these peaceful applications took two directions. One was the development of artificial reactor-produced isotopes as high energy sources for radiation treatment. During the war years, there had been development of Robert van de Graaff's million volt static generators and Donald Kerst's high energy betatron, the first supervoltage therapy machines. But the simplicity of using cobalt 60 or cesium 137 in rotating-head

1920–1929

- Chest X rays are used to screen for tuberculosis—a scourge of even greater concern to the public than cancer. Exposures of up to 1 minute, with 10 to 20 rads (units of absorbed radiation dose) are used.
- Roentgen dies February 10, 1923.
- The first practices of modern angiography are developed in 1927 by a Portuguese physician, Dr. Egaz Moniz, who is the first to create images of the circulatory system in the living brain. He develops a carotid angiography technique, which involves making a surgical incision into the neck, identifying the carotid artery and injecting contrast into the artery, which transports it to the brain.
- Drs. Evarts Graham and Warren H. Cole of Washington University, St. Louis, discover in 1923 how to visualize the gall bladder with X rays by using contrast media, a discovery significant in the diagnosis of gall bladder disease.

  This discovery demonstrates the role of chance in science, in that the doctors tried for four and one half months to visualize gall bladders in dogs by injecting contrast medium into the dogs in the morning, then taking X rays in the evening, to no avail. One day they finally produced a picture of a gall bladder in one particular dog, but for several days thereafter were unable to recreate the results. In their hunt for an explanation for this anomaly, they confronted the kennel attendant—had he done anything different to that one dog? The attendant confessed that due to a severe hangover he had not gotten around to feeding that particular dog on the morning of the test. If he had, the dog's gall bladder would have emptied when the dog's food was digested. Thus the discovery was made.

1930–1939

- In 1934, the American Board of Radiology is officially formed and recognized by the American Medical Association.
- In 1936, the first "tomograph"—an X-ray "slice" of the body—is presented at a radiology meeting. This revolutionary concept, in which the X-ray tube is moved by pulley around the patient in order to take pictures on various planes, can focus on certain internal structures that cannot otherwise be seen clearly. This technique, also called "laminagraphy," foreshadows the development in the 1970s of CT, or computed tomography.
- While higher voltage X rays are being developed, their actual clinical benefit remains untested. Beginning in March 1932, clinical trials are initiated. Results of the studies, comparing 70,000-volt X rays to 200,000-volt X rays used on cancers of the larynx and tonsils, among others, are reported by scientists this way: "The same results [cures] can be obtained using a [higher] dosage which causes considerably less discomfort to the patient." These results encourage further research into super-voltage equipment, although the equipment has some limitations; "patient discomfort" is not well-measured and the tumors evaluated are not the deep body lesions that physicians still want to treat.
- Blue Cross/Blue Shield and other insurance or medical prepayment plans start to cover X-ray services, vastly increasing their availability.

treatment devices soon eclipsed the early electronic generators. Cobalt 60, with an energy of 1.33 million electron volts, emerged in the late 1950s as the workhorse for radiation therapy.

The second direction was the development of lower energy isotopes such as iodine 131 for use as diagnostic tools. Trace amounts of iodine or other isotopes could be given a patient. By measuring the output of urine, for example, using a Geiger counter, a physician could assess kidney function. With scintillation crystal detectors, a doctor could study an image of radioactive iodine uptake in the thyroid gland, to study function and to infer the presence of tumors.

Advances in X-ray techniques continued apace. Russell Morgan at the University of Chicago developed phototiming, a method of matching exposures to physical characteristics of patients. Morgan, Edward Chamberlain of Temple University and, principally, John Coltman of the Westinghouse Corporation are credited with the conceptual development of electronic image intensification, together bringing fluoroscopic studies out of darkened rooms. Reduced amounts of radiation could be fed into a fluoroscopic screen and brightened several thousandfold before being displayed on an output screen. This procedure allowed recording of motion, such as the flutter of a heart valve, on motion picture film or videotape without subjecting patients to unacceptable levels of radiation.

Radiologists and some other physicians began to expand the uses of hollow catheters to inject contrast liquids into the vascular system and other body channels. The skills needed to thread a catheter tip into position to visualize the coronary arteries or the vessels of the head were compared by one investigator to the task of pushing a rope through twisted passageways.

A major advance in isotopic diagnosis resulted from the development by Harold Anger of the University of California of the gamma camera, with its array of photomultiplier tubes and a large crystal which shortened scanning time. This was coupled with the development of various chemical forms of technetium 99m, an isotope with a six-hour half life. Technetium could be tagged to various chemicals to allow concentration in different organs of interest. Given its six-hour decay period, relatively larger amounts of isotope could be used without increasing patient exposures. Soon isotope

This X-ray image of a foot in a high-button shoe was typical of early images reproduced in the popular press after the discovery of the X ray. This image was made by Francis Williams of Boston, one of the first radiologists, in March 1896.

scans were the preferred method of exploring many problems in the brain and liver.

By the late 1950s, investigators including Henry Kaplan and the Varian brothers at Stanford University were working on a device called a linear accelerator to generate high energy X rays or electrons for cancer treatment. Referred to as linacs, the devices soon grew smaller, delivered higher energies and became safer and more reliable. They produced controlled energy beams in ranges from 4 to 25 million electron volts, and gradually displaced cobalt units as the primary radiation therapy sources in most advanced countries.

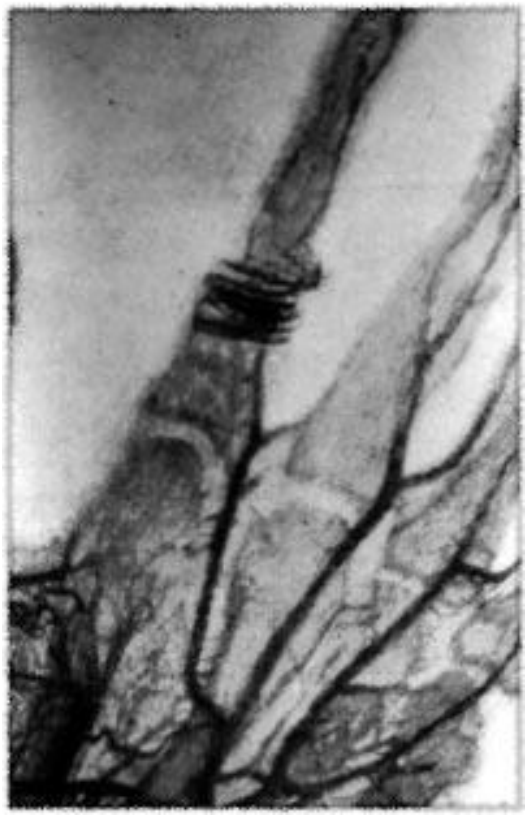
ON THE DIAGNOSTIC SIDE, the 1960s brought the advent of diagnostic ultrasound with great promise. Soon ultrasound devices utilized a crystal transducer that bounced pulses off body structures and displayed the echoes as a scan. Motion was added, and Doppler techniques rapidly allowed study of blood flow and other physiological processes. Even after 30 years, there are still no indications of harmful bioeffects from ultrasound exposures at the energy ranges used for diagnosis.

By this time, some radiologists had begun to inquire into the new information systems based upon huge, ungainly devices called computers. But computers soon shrank in size, grew in power, dropped in price and began to be available in research centers. They were used for complex radiation treatment plans, allowing far more speed and sophistication with isodose curves than was possible with manual calculations. Diagnosticians used computers first for image analysis, coupling densitometers with them to obtain basic data. These efforts met with limited success.

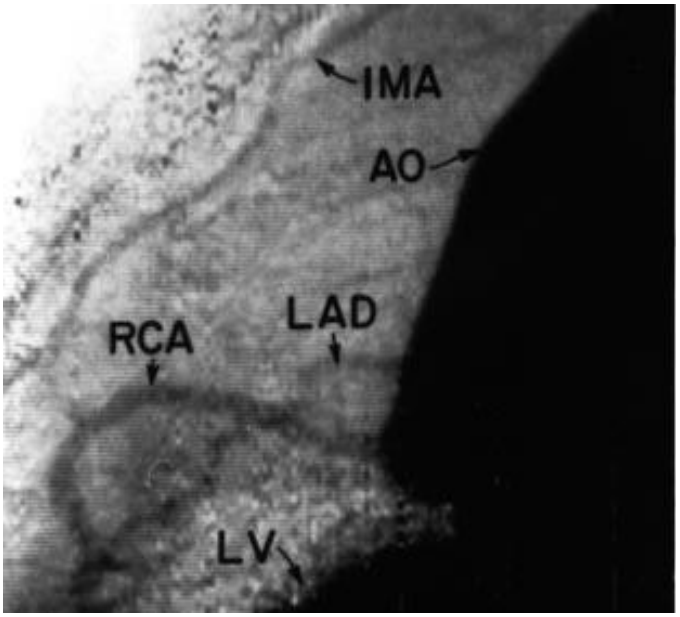
Early in the 1970s, diagnostic radiology made a huge leap into cross-sectional imaging with the development of computed tomography (CT). Earlier, mechanical tomography had been used for limited purposes. But here was a completely new technology, producing what looked like bloodless slices across the body area of interest. The first scanner, devised by Geoffrey Hounsfeld of EMI in England, could image only the head, and required a patient to place his skull into a water bath while the X-ray tube and receptor mechanically advanced around the head. Improvements were swift as other manufacturers replaced mechanical parts with electronic ones. Soon, a ring of X-ray tubes and receptors could obtain images of any transverse body plane in seconds, and complex mathematical algorithms could draw clear, sharp images out of millions of bits of information.

By advancing the plane of the scan in small steps, a three-dimensional construct of a suspect organ could be developed. Elliot Fishman at Johns Hopkins worked out a reconstruction method to give surgeons three-dimensional simulations of crushed or misshapen body parts for guidance in delicate operations. And radiation oncologists used computed tomographic images to plan their treatment fields.

Angiographic work began in January, 1896, with this post-mortem injection of mercury compounds. This image was made by E. Haschek and O. Lindenthal of Vienna.



American College of Radiology



The first image of a human coronary artery recorded in vivo *with synchrotron radiation. This coronary angiogram was done at the Stanford Synchrotron Radiation Laboratory at the Stanford Linear Accelerator Center in May 1986. The identified structures are an internal mammary artery (IMA), the aorta (AO), the left anterior descending coronary artery (LAD), the right coronary artery (RCA), and the left ventricle (LV). (Image courtesy of Edward Rubenstein, M.D.)*

1940–1949

- The Betatron, a circular electron accelerator, is developed by Dr. Donald Kerst of the University of Illinois between 1940–1943. It generates energy (20 million volts or more) by orbiting electrons, faster and faster, through a large "doughnut," a circular glass tube with a heated cathode inside a huge electromagnet.

1950–1959

- Dr. W. Goodwin introduces the concept of X-ray guided percutaneous nephrostomy, in which a needle and then a catheter are inserted directly into a kidney to create a drainage tract above an obstruction (kidney stone, cancer), allowing urine to escape from the kidneys. This procedure allows some patients to be treated without surgery.
- Radioisotopes are introduced as sources of gamma-ray beams for radiation therapy. The process works, for example, by changing harmless cobalt 59 into cobalt 60, a highly unstable nucleus that decays. As that happens, it releases two gamma rays. The gamma-ray beams adequately reach deep cancers without damage to the skin. Cobalt units are easy to make and quickly become a cheaper, safer alternative to the Betatron, though later they will become virtually unused.
- Ultrasound—images created from the echoes of sound waves bounced off tissue—which has its roots in World War II's sonar (sound navigation and ranging), begins to show promise in medical diagnostic applications.
- A Swedish physician, Dr. Sven Ivar Seldinger, refines Dr. Moniz's and Dr. Forssmann's work in angiography from the 1920s when he learns how to insert a catheter into a blood vessel without surgery. He uses a tiny guidewire inserted with the help of a needle into a blood vessel. The catheter is placed over the guidewire and into the vessel, after which the guide wire is removed. He then watches the location of the catheter on fluoroscopy.

Because of political decisions based on health planning laws, many CT scanners were located outside of hospitals. In just a few years, CT scanning had become state-of-the-art technology. The United States had more scanners than the rest of the world, and Los Angeles alone had more than Great Britain.

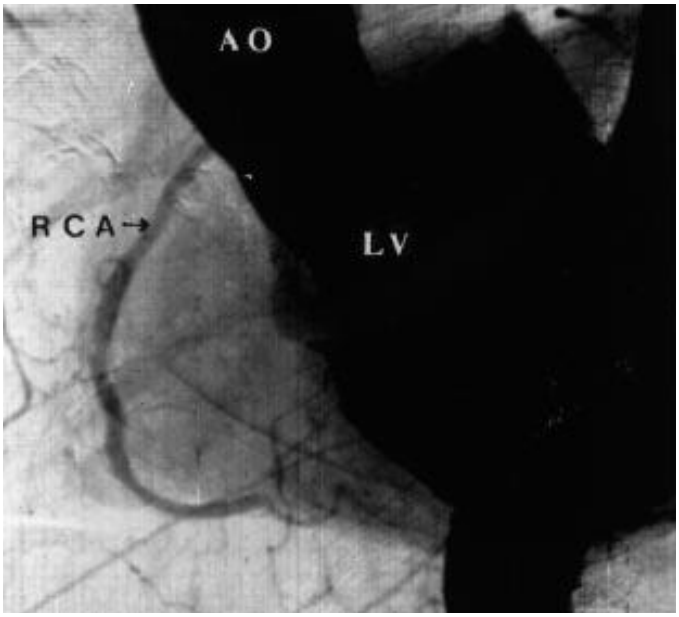
There was more to come. In less than a decade, magnetic resonance imaging burst on the scene with even more promising—and even more expensive—technology. MR image analysis technology was comparable to CT, but no X rays were needed. Instead, MR units relied on strong magnets, as much as 8000 times as strong as the earth's magnetic field.

In an MR unit, magnets rim an aperture into which patients slide on a gantry. The strong magnetic field acts upon the inherent magnetism of the trillions of hydrogen atoms in the human body. When the magnetic field is imposed and released, hydrogen atoms emit a faint radio signal. Detection and analysis of these signals produces the image.

MR proved to be complimentary to CT. MR images could be created in any body plane—axial, sagittal, oblique, AP, or all of them. Soft tissue detail allowed better study of glandular systems. And soon, new developments in CT resulted in spiral scanning, with the machine advancing across the chosen body area to produce hundreds of slices at any designated interval. Contrast agents, very different for CT and MR, allowed study of the inside of body organ systems. Various other mathematical tricks allowed the electronic subtraction of other anatomic structures to reveal a vascular system of the head and neck with the shadows of the skull, brain, and other structures erased. Strictures, emboli, kinks, and accumulations of plaque had nowhere to hide.

In the same years, the term "interventional radiology" came into use to describe the ability of physicians using catheters and fluoroscopy to detect and correct vascular insufficiencies and strictures in other body ductal systems. Initially, catheters inserted into arteries or ureters allowed deposit of contrast agents at suspect spots. Then micro-sized tools were threaded through the same catheters to correct problems. Andreas Gruntvig of Emory University refined this process, devising a balloon-tipped catheter that could be advanced within an artery

An image of a human coronary artery recorded in vivo *at the National Synchrotron Light Center, Brookhaven National Laboratory, in November 1992. Improvements in the imaging system have increased the quality of the angiogram from the image shown on the opposite page. In this image, the entire length of the right coronary artery (RCA) is shown. (Image courtesy of Edward Rubenstein, M.D.)*



to a narrowing. Once in position, the balloon is inflated, compressing the fatty plaque against the artery walls and restoring free blood flow. Soon the balloons were augmented with tiny rotary saws, lasers, and targeted medicines. Researchers also created collapsible baskets to snare kidney or gall stones for removal without an open surgical incision. Recently, stents (metal or plastic sleeves) have been developed for insertion into arteries or other vessels to keep critical spots from narrowing after the angioplastic procedure. Not all patients respond to these procedures, but those who do save considerable trauma and cost, sometimes even returning home the day of the procedure.

Of course, not all new ideas have been as fruitful as CT and MR and linacs. Hopes that the body's natural heat emissions could be a diagnostic tool were dashed when the heat-induced images, or thermograms, could not be correlated with disease problems. The use of oxygen potentiation devices like pressure chambers to treat cancer patients promised to help those with anoxic tumors. But after some years of tests, the results failed to justify the efforts. More recently, radiation oncologists have been experimenting with heat as a radiation potentiator. However, the technical problems of controlled heating of a single body area during radiation have not yet been overcome.

While diagnostic and therapeutic radiology have developed as separate and defined disciplines, there have always been synergisms with other medical specialties. Some two-thirds of all American cancer patients receive high energy radiation as a portion of their treatment. Currently, most cancer centers attack most forms of cancer with a combination of surgery, radiation, cancer-killing chemicals, and even monoclonal antibodies or immunological agents.

FOR THE ENTIRE CENTURY of radiology, physicians specializing in this area have performed most, but not all, of the procedures needed by Americans. Many primary care physicians undertake limited procedures in their offices. Some specialists, such as cardiologists or orthopedists, perform examinations related to their areas of interest. Dentists and podiatrists do likewise. About two-thirds of medical imaging procedures are done by radiologists.

1960–1969

- In 1960, Dr. Robert Egan of the University of Texas M.D. Anderson Tumor Institute, Houston, with the support of the U.S. Public Health Service, publishes the results of an intensive, three-year study of mammography. Although previous studies of X rays of the breast have been done, Egan's study conclusively proves mammography's effectiveness in early diagnosis. With neither physical exams nor any knowledge about the women's medical histories, Dr. Egan examines patients' mammograms and diagnoses whether or not cancer is present. Egan's accuracy in finding breast cancers is remarkable—97–99 percent—and his precisely controlled mammography techniques mean that other radiology facilities can duplicate his results.
- Drs. Charles Dotter and Melvin Judkins of Portland, Oregon, are the first to report performing a transluminal angioplasty, a non-surgical technique to unblock a vessel clogged with plaque. They insert screw-tipped catheters into the narrowed vessel, starting with small diameter catheters and sliding bigger and bigger catheters over them, to push the plaque to the interior walls of the vessel sides. The technique is not well-accepted except in Europe; bypass surgery is still the preferred treatment method in the United States.
- A survey conducted by the U.S. Public Health Service reports that 48 out of every 100 persons receive X rays during any one year, with urban residents having the most X rays (53 out of 100) and farm dwellers (31 out of 100) having the fewest.

1970–1979

- CT, or computed tomography, which takes X-ray "slices" of the body and images them on a computer screen, is introduced. Like the first tomography units introduced in 1936, the X-ray tube rotates around the patient's body, taking X-ray pictures as it moves. With the addition of computer technology, CT images can now be manipulated and the "slices" can even be "put back together" to create more 3-dimensional images.

Still, the growth of managed care as an alternative to traditional medical practice has driven many patients—and their doctors and hospitals—into controlled patterns. One result has been a reduction in the volume of medical services, including radiology, delivered to managed-care plan patients. Much of the reduction in imaging comes as a loss to physicians who self-refer procedures on their own patients. And questions arise: will managed care plans pay for more expensive procedures, if management decides the simpler ones are less expensive, and are adequate?

And with impending cutbacks in federal health spending and downward pressures on costs by private payers, the broader question is whether or not the nation wants and will pay for newer and better technologies. A good example is positron-emission tomography (PET), in which a very short-lived injected isotope is used as the energy source for cross-sectional imaging rather than X rays. PET has proved itself as a research tool. But its acceptance for clinical applications is proving more dependent on cost factors than scientific ones.

Ever since X rays were discovered by a physicist, the growth of radiology has been dependent on the contributions of that discipline, as well as the contributions of engineers, biologists, computer scientists, radiologic technologists, and a broad industrial base. Without these contributions, many of radiology's most important clinical advances would never have occurred. Clearly, radiology has earned a vital place in modern medicine. It may well be that the circumstances in which it will be practiced are uncertain—but then, so are most other things about modern health care.

Historic Whole Body Radiographs

A whole body radiograph of a dead soldier (page 25, left), was taken, in nine sections, by Ludwig Zehnder at the University of Freiburg in 1896 and measures 1.84 meters in height. The exposure time was approximately 5 minutes per film. The faint writing, with an arrow pointing towards the forehead, reads "small arms projectile located in the facing temple at a distance of 20 cm from the dry plate." The second radiograph (page 25, right) is a single-exposure whole body image taken by a Dr. Mulder in Bandung, Java, about 1900, presumably of a living person, wearing knee-length boots, with bunches of keys attached to an unseen belt.
(Courtesy Deutsches Museum, Munich, and Bob Batterman, Cornell University).

- Thrombolysis, which dissolves clots in blood vessels by delivering thrombolytic (clot breaking) drugs to the site or into the vascular system, is introduced by Dr. Charles Dotter. Using a thin catheter, a dose of a thrombolytic agent such as streptokinase is injected into the clot, dissolving it. One drawback of streptokinase is that it can induce allergies with repeated use over time. Later, synthetic thrombolytics that do not appear to induce allergic reactions will be used.
- Swiss physician Dr. Andreas Gruntvig, later in the United States, invents balloon angioplasty. A tiny deflated balloon is placed at the end of a catheter and threaded on a guidewire into a plaque-clogged section of blood vessel. The balloon is inflated, and the plaque is pushed to the sides of the vessel. Then the balloon is deflated and removed. The first applications of balloon angioplasty are all in arteries in the arms or legs. Balloon angioplasty is an instant success, in part because it can be used to open smaller, more fragile arteries.

1980–Today

- MRI (magnetic resonance imaging; also referred to as MR)—the marriage of a strong magnet and a computer—is introduced. Instead of X-ray's ionizing radiation, MR uses a magnetic field around the body and a radio signal to create images. MR works by having a patient lie in a large magnetic tube, which forces the hydrogen atoms in the body to "line up" in a polar formation. Then a strong radio signal bombards the atoms, and protons spinning in the hydrogen atoms are momentarily knocked off course. When the radio signal is turned off and the atoms return to their normal orbit, they emit a faint radio signal, which is used by a computer to measure the speed and volume by which they return to orbit. MR "sees" hydrogen atoms in the body—present in all tissues—and thus is exceptional at imaging both hard and soft tissue.
- Pulsed fluoroscopy reduces radiation exposure by using short bursts of high-intensity X-ray beams (up to 1–2 seconds; anything longer would burn out the tube) alternated with lower intensity beams. The high-intensity beams "linger" on the video screen, allowing the physician to view the anatomy like slow-motion moving pictures.
- PET (positron emission tomography) begins to be used in clinical applications. It watches the way cells "eat" substances such as sugar. The substance is tagged with a short-lived radioisotope (unstable atoms that release stray particles that can be seen with gamma cameras), then injected into the body. The PET scanner watches as the radioactive material "lights up" in cells, identifying areas where cancer cells might be present. Cancer cells have a higher metabolism than normal, healthy cells.
- Teleradiology, the ability to send images through the "information superhighway," is introduced. Teleradiology uses information-networking capabilities to transmit images from one place to another. However, it is more difficult than sending a written document because the digitized, computer radiology image contains so much more information than the printed word.

Impact of Synchrotron Radiation on Materials Research

by ARTHUR BIENENSTOCK and ARTHUR L. ROBINSON

Synchrotron radiation has transformed the role of X rays as a mainline tool for probing the atomic and electronic structure of materials and their surfaces.

FROM THEIR DISCOVERY 100 years ago, X rays have tantalized scientists with their ability to see into solid objects. For 80 of those 100 years, they have also been our principal means of unraveling the positions of atoms in crystallized solids, from the comparatively simple structures in metals and semiconductors to the highly complex arrangements in biological molecules, such as proteins and DNA. During the last three decades, however, the growth of synchrotron radiation with its bright, wavelength-selectable X rays has markedly expanded the scope of investigation.

The result for materials research is a tool that can probe in minute detail the interior and surface of all manners of samples, large and extremely small, including noncrystalline and inhomogeneous materials.

STRUCTURE IS THE KEY

Equally applicable to semiconductors for miniaturized computer chips, superconductors to drive magnets in medical imaging machines, magnetic disks for digital data storage, metals and alloys for high-strength structures, ceramics for engines and turbines that can operate at elevated temperatures, polymers for lightweight parts for automobiles or aircraft, light-emitting materials for flat-panel video displays, biomaterials for prostheses, or any of a host of other things, the fundamental tenet of materials research is that structure determines function.* The practical corollary that converts materials research from an intellectual endeavor into a foundation of our modern technology-driven economy is that structure can be manipulated to construct materials with particular desired behaviors.

Most basically, structure means the positions of the atoms (atomic structure) and the behavior of the electrons around the atomic nuclei (electronic structure). The atomic structures of solid materials span the extremes from completely ordered with atoms arrayed around the points of a repeating lattice (long-range order) to completely disordered. Many materials, such as metals and semiconductors, have crystalline structures with long-range order but may exhibit features of disorder, such as random distributions of impurity atoms or of aggregations of atoms in the form of precipitates. In addition, the material may consist of a large number of crystalline grains with different orientations. Some materials are mixtures of grains representing different phases with distinct compositions and structures. Computer chips begin with silicon single crystals, whereas metals and alloys are typically polycrystalline. Glasses are the most familiar disordered materials.

As for the electronic structure of materials, the inner electrons are bound tightly to the atomic nuclei (core electrons) with quantum states that retain much of their atomic character, whereas the outer, more loosely bound electrons participate in chemical bonding between atoms (valence electrons), as well as other processes, such as conducting electricity. In treating the valence electrons, solid-state theorists have found it easiest to make quantum mechanical models in the case of ordered materials. In these models, a valence electron is not identified with any particular atom, but is characterized by a kind of momentum (crystal momentum) and by an energy E associated with each momentum vector k. Although the allowed energies are quantized, in practice they are quasi-continuous functions of momentum $E(k)$, giving rise to the term band structure. Band gaps refer to ranges of energies that are forbidden irrespective of momentum.

SYNCHROTRON RADIATION

X rays are particularly well suited for probing the structure-function relationship because of their ability to penetrate into materials and because of the ways they interact with the constituents once they get inside. There are two basic types of X-ray interactions, scattering and absorption, that give structural information.

The pattern of scattered radiation contains information about the spatial structure of the scattering object. Since scattering is most informative when the wavelength is somewhat less than the size of the scattering object, X rays with short wavelengths near one angstrom are ideal for investigating the positions of atoms, whereas X rays with longer wavelengths are more appropriate for larger features. X-ray absorption provides a way to study electronic structure because the energy range of X-ray photons nicely matches that needed to excite electrons from core to valence quantum states or from one band to another.** Dissipating the energy of the photoexcited electrons can have many consequences, such as the emission of electrons, photons (fluorescence), or ions from the surface, all of which give rise to spectroscopic techniques to monitor the electronic structure.

From its first systematic use as an experimental tool in the early

**The structure-function relationship applies equally well in the life sciences. See "Biological Applications of Synchrotron Radiation" in the Fall 1994* Beam Line, *pp. 19–28, for a review of protein crystallography.*

***The photon energy ε measured in electron volts is inversely proportional to the wavelength λ measured in angstroms according to ε [eV] = 12,398.5/λ [Å].*

1960s, synchrotron radiation has vastly enhanced the utility of pre-existing and contemporary techniques, such as X-ray diffraction and X-ray photoelectron spectroscopy (photoemission), respectively, and has given rise to scores of new ways to do experiments that would not otherwise be feasible, or even possible. Generated by electrons (or positrons) circulating for many hours at the speed of light in accelerators called storage rings, synchrotron radiation is, in the newest facilities, one billion times brighter than the light from conventional X-ray tubes. Moreover, the wavelength can be selected over a broad range to match the needs of particular experiments. Together with additional features, such as controllable polarization (both linear and circular), laser-like collimation, and pulsed time structure, these characteristics make synchrotron radiation the X-ray source of choice for such a wide range of materials research that the following examples can only give a flavor of its impact on the field.

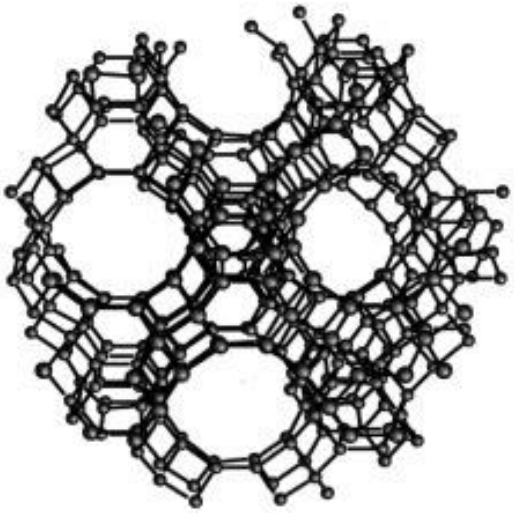
Materials research using X rays tends to be grouped into techniques carried out at high X-ray photon energies (hard X rays) and at low X-ray photon energies (soft X rays).

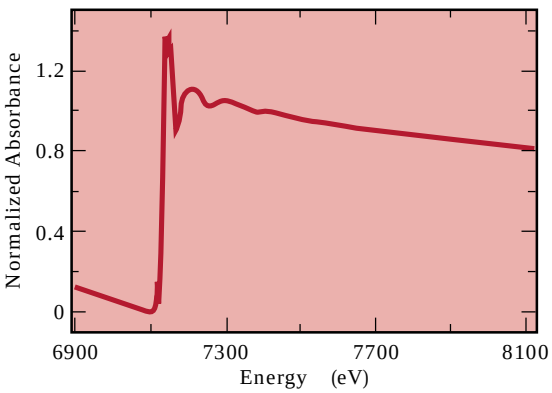
HARD X-RAYS

X-ray Crystallography in Two Dimensions

Since W. L. Bragg's first determination of a crystal structure (rock salt) in 1913 by measuring the intensities of X-ray beams diffracted by the NaCl crystal, researchers have made remarkable advances in their understanding of atomic arrangements in three-dimensional crystalline solids. The high brightness of synchrotron radiation made it possible for scientists from AT&T Bell Laboratories to extend X-ray crystallography to surfaces in 1979 experiments at the Stanford Synchrotron Radiation Laboratory (SSRL). In their technique, grazing-incidence X-ray scattering (GIXS), the X-ray beam strikes the sample surface at angles close to the critical angle for total reflection. (Total reflection occurs when the angle between the incident beam and the surface is very small if the X-ray index of refraction is less than unity, as it is for most solids.) Depending on the angle of incidence, the X-ray beam penetrates from about two nanometers to several micrometers below the surface. The beam is only diffracted by the material it penetrates, so that the structures of the first few layers of a thick material or those of thin films can be determined. First applied to ordered interfaces and then to surfaces whose structures differ from that of the interior (reconstructed surfaces), the technique is now used extensively in materials research to determine the structure of oxide layers in semiconductors and magnetic materials, as well as that of thin amorphous (non-crystalline) films.

Aerial view of the Stanford Synchrotron Radiation Laboratory at SLAC.





Zeolites are essential to modern industry with numerous applications, including use as ion exchanges, sorbents, separation media, and hydrocarbon conversion catalysts. They are aluminosilicates whose structures have pores and channels of molecular dimensions, as shown in the top figure. Their catalytic properties can be modified by incorporation of transition metal ions, such as Fe^{+3}. The bottom figure shows the X-ray absorption coefficient versus photon energy near the absorption edge of Fe^{+3} in iron zeolite, which was measured to determine the Fe coordination. (From work of C. M. Stanfel, K. O. Hodgson, I. J. Pickering, G. N. George, and B. Hedman of Stanford/SSRL plus D. E. W. Vaughan and K. G. Strohmaier, Exxon Research and Engineering Co.)

Sometimes, the sample itself is only one or two molecules thick, so that it is in effect a two-dimensional system where behavior can differ from that usually observed. Among the most exciting two-dimensional phenomena to be analyzed are melting and crystallization. In three dimensions, crystallization is a first-order transition with a latent heat and a well-defined melting temperature at which the material transforms from highly disordered liquid to a well-ordered crystal. But, in two dimensions, the liquid-solid transformation can be continuous over a range of temperatures. As the liquid is cooled, the maximum size of ordered regions within the liquid grows until it covers the entire sample (i.e., the range of order diverges) at the "melting" temperature. Experimental understanding of this process at the microscopic level has come primarily through the use of synchrotron radiation whose high intensity is necessary to obtain a strong signal from the extremely small number of scattering atoms and whose collimation (high angular resolution) is required to observe the divergence of the order range.

Disordered Materials and X-ray Absorption Spectroscopy

A very large portion of the matter in our world is not in the two- or three-dimensional crystalline form studied by crystallographers. Much of it is amorphous or liquid. Because such materials lack the periodicity that makes the description of crystals relatively simple, they must be described in different ways. The most important way is to determine the average environment of each atomic species in the material. For example, how many nearest neighbors, next nearest neighbors, and so on does that atom have? What species are the neighboring atoms, and what are the distances to those neighbors?

High-accuracy X-ray absorption spectroscopy, made practical by the intensity and wavelength tunability of synchrotron radiation, has provided major advances in our ability to obtain such descriptions. In this approach, one measures the X-ray absorption coefficient as a function of photon energy near an X-ray absorption edge. (An X-ray absorption edge is the energy required to knock an electron out of an atomic quantum state; each atom has a unique set of edges, some of which occur at hard X-ray and some at soft X-ray photon energies.) As shown in the illustration on the left, the X-ray absorption coefficient drops relatively smoothly with increasing photon energy until the absorption edge is reached, then it rises markedly and begins an overall decrease with increasing photon energy. Oscillations are, however, superimposed on this decrease. The sharp features closest to the edge are known as X-ray absorption near-edge structure (XANES or NEXAFS), while those oscillations continuing to about 1000 eV above the edge are known as extended X-ray absorption fine structure (EXAFS). Both reflect the influence of the atoms surrounding the absorbing atom on the absorption coefficient, although in quite different ways, so that, even in a very complicated material, one can obtain the average environment of the specific atomic

species whose absorption edge is being studied. In the same way, one can determine the average environments of the individual atomic constituents of an amorphous material.

Since XANES and EXAFS are linked to the excitation process, the photon-energy dependence of any process directly associated with the excitation can yield the fine structure and the local environmental information. Thus, the fluorescence given off by the absorbing atom (whose photon energy depends on which absorption edge is excited and, hence, is unique to each atomic species) can be used as the signal, and, with a detector that discriminates against all other photon energies, an enormous increase in signal-to-noise is obtained. This enhancement is particularly valuable when the species of interest is present in very low concentrations, such as dilute impurities in semiconductors or proteins in solution. Similarly, measurements of the photon-energy dependence of the number of electrons photoemitted from the solid are used to analyze the environments of atoms on the surfaces of materials.

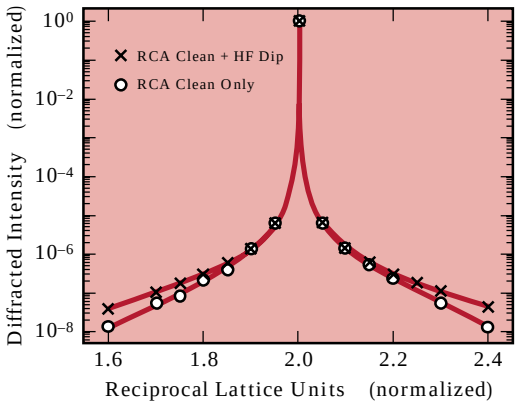
High-Sensitivity Chemical Analysis and Microcontamination

X-ray fluorescence can also be used for nondestructive chemical analysis of materials; in fact, it is the second most common use of X rays for materials research. Analysis of the photon energies at which fluorescence is emitted yields the sample's composition. With synchrotron radiation, the sensitivity of this technique has been increased markedly because of the high-intensities and wavelength tunability. At SSRL, its first application was in response to a claim that superheavy elements were present in some minerals. This claim had enormous significance, since the elements have higher atomic number than any that had been created in accelerators., but scientists from Oak Ridge National Laboratory detected no signal at all, thereby demonstrating that the concentrations had to be far below those claimed, if the super heavy elements were present at all.

The semiconductor industry presently uses a variant of this technique called total reflection X-ray fluorescence (TXRF) to screen the surface of polished silicon wafers for unwanted metallic and light-element impurities before microcircuit fabrication begins. Grazing incidence is used to obtain surface sensitivity, as in GIXS, and the fluorescent radiation is detected. TXRF with a conventional X-ray source is now used almost routinely, but about one hundred times greater sensitivity is required to aid in the development of fabrication processes for the high-density integrated circuits planned for the first decade of the next century, according to the Semiconductor Industry Association's (SIA) "National Technology Roadmap for Semiconductors."

Over the past two years, a collaboration of scientists from Hewlett-Packard, Intel and SSRL, with assistance from Kevex and Lawrence Berkeley National Laboratory (LBNL) staff, have achieved a fifty-fold sensitivity increase using synchrotron radiation as the X-ray source. Detector and other improvements are likely to yield the remaining factor

X-ray diffraction intensity measured over eight orders of magnitude for two silicon wafers which had previously been subjected to different cleaning procedures. Small differences in the wings of the peak, where the intensity of the diffraction is a consequence of the crystal being terminated by a surface, are being used to develop methods to characterize the effect of the procedures on the wafer surfaces. (Courtesy of A. Munkholm and S. Brennan, SSRL)



of two. Their TXRF experimental station at SSRL has now been tested by several other major semiconductor companies. This successful demonstration has resulted in TXRF with synchrotron radiation being placed on the Metrology Roadmap, a supplement to the SIA roadmap. Efforts are now under way to transform the approach from one suitable for the research laboratory to a routinely usable, consistently reliable technique. Doing so will likely also require coordination of operating schedules at two or more synchrotron sources, so that at least one is running when the other is down for maintenance.

Dynamic Processes in Solids

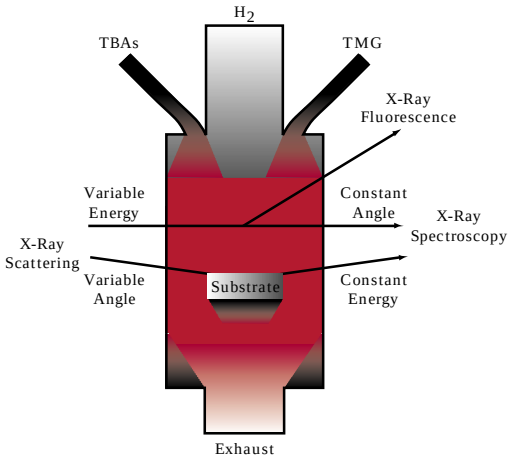
Synchrotron radiation beams are sufficiently bright that both scattering and X-ray absorption data can be acquired rapidly enough to follow processes as they occur in real time. For example, materials scientists are increasingly using these techniques to study dynamic processes in materials, such as the evolution of a material's structure as it undergoes physical or chemical changes, including the growth of semiconductor wafers or films prior to device fabrication and the transformation from one solid phase to another that occurs when metal alloys are heat-treated to improve their strength or ductility.

A team comprising researchers from AT&T Bell Laboratories, the IBM Research Division, and SSRL has collaborated on in-situ studies of the growth of compound semiconductors by the commercially important organometallic vapor-phase epitaxy method. Compound semiconductors, such as gallium arsenide, offer important advantages over silicon for high-speed devices and for combining electrical and optical functions in one device.

A Stanford University/SSRL group has provided the first microscopic in-situ observations of sputtering, a common method of depositing films of myriad types. These observations made it possible to understand the relationships between sputtering parameters and the structure of the sputtered film. Scientists from the Lawrence Livermore National Laboratory (LLNL) and the University of New Mexico have observed welding-induced solid-state phase transformations using time-resolved X-ray diffraction. Depending on the situation, such transformation may be beneficial or harmful. The ability to study the dynamics of process in solids potentially represents one of the most important impacts of synchrotron radiation on materials research.

X-Ray Microtomography

Imaging has been the most important use of X rays since their discovery. Among the most dramatic recent developments in this field is computer-aided tomography (CT), in which three-dimensional images are reconstructed mathematically from absorption radiographs taken at various angles with respect to the sample. The most familiar CT application to most of us is medical diagnostic radiology, where spatial resolution is of the order of 500 micrometers. With the use of synchrotron radiation, high-resolution CT, or microtomography, is becoming



Schematic of chamber used to perform dynamic, in-situ X-ray studies of the organometallic vapor phase epitaxy production of thin gallium arsenide (GaAs) films. Organometallic vapors of gases containing arsenic (TBAs) and gallium (TMG) carry these elements to the heated substrate, where the GaAs is formed. Hydrogen transports the vapors and prepares the substrate surface. Grazing-incidence X-ray scattering is used to study the substrate and film, while the vapors are studied with X-ray spectroscopy. (Courtesy of P. Fuoss)

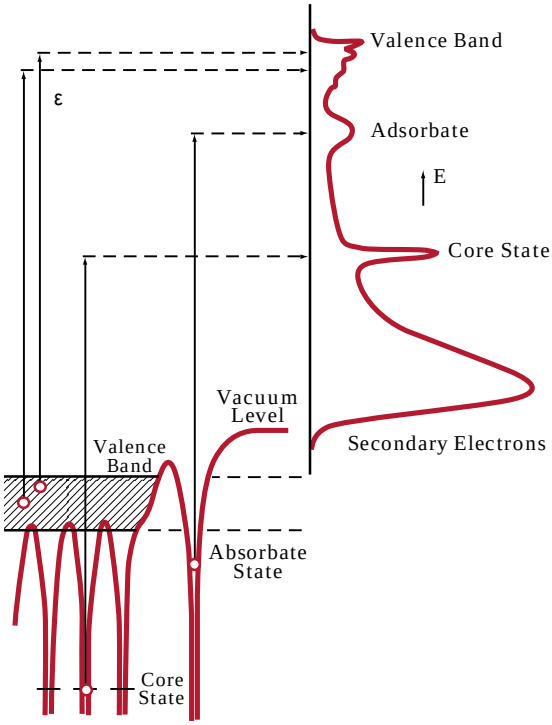
increasingly effective as a materials research tool, largely due to pioneering efforts by two teams, one from LLNL, Sandia National Laboratories, and the University of Dortmund and the other from Exxon. The technique now provides images with spatial resolution of the order of a few micrometers in samples with diameters less than one centimeter. One of the attributes of synchrotron radiation most critical to this improved capability is the natural collimation of the radiation, which leads to the resolution improvement. Another is the ability to select a single photon energy that is absorbed by the material of interest, which maximizes the ratio of signal to noise. These improvements have allowed detailed studies of failure in metal-matrix composites, as well as studies of the progression of osteoporosis in rats.

SOFT X RAYS

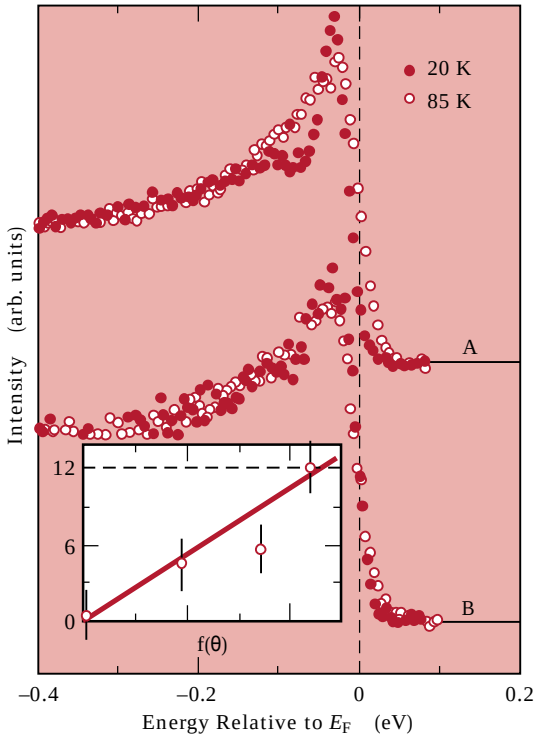
Angle-Resolved Photoelectron Spectroscopy

The starting point for determining many of a material's properties is its band structure. Photoelectron spectroscopy has been a particularly useful way to probe the band structure of solids. Based on the photoelectric effect explained by Einstein in 1905 but developed as a useful tool only in the 1960s with the advent of ultrahigh-vacuum technology, photoelectron spectroscopy is the measurement of the spectrum of kinetic energies of photoelectrons emitted from a material after absorption of a photon (see diagram on the right). To study the band structure, one excites the loosely bound valence electrons with low-energy ultraviolet or soft X-ray photons. An important feature of band structure that is accessible to photoelectron spectroscopy is the variation of the number of valence states with energy (the density of states). A major advance came in the mid-1970s when synchrotron-radiation researchers from AT&T Bell Laboratories developed angle-resolved photoelectron spectroscopy at the University of Wisconsin Synchrotron Radiation Center. The idea is that the momentum of the photoelectron is related to the momentum of the valence state. Measuring the direction as well as the kinetic energy gives the momentum and, hence, a way to "map" the band structure and thereby test theoretical calculations.

High-temperature superconductors provide a contemporary illustration of the usefulness of angle-resolved photoelectron spectroscopy, although the strong Coulomb and magnetic interactions in these materials make the application of conventional band structure problematic. Metallic superconductors known before the 1986 discovery of the high-temperature ceramic superconductors owe their behavior to an interaction between the valence electrons that is mediated by vibrations of the crystal lattice. The interaction usually results in a small energy gap between the superconducting and normal states that is symmetrical (i.e., the gap is the same for all momentum directions). The interaction responsible for superconductivity in the new superconductors that can operate at temperatures up to 125 Kelvin or so remains



Schematic diagram of the quantum states in a crystalline solid and the photoelectron spectrum for a photon energy ε. Shown are core states in potential energy wells, the portion of a valence band occupied by electrons (cross-hatched), and a state in a potential energy well associated with the surface. The vacuum level is the minimum energy needed for a photoelectron to escape the solid. Peaks in the photoelectron spectrum occur at kinetic energies equal to the excess above that needed for the photoelectron to escape the surface. The large peak in the photoelectron spectrum at low kinetic energies is due to secondary electrons that lose energy during collisions on the way to the surface (Courtesy N. V. Smith, LBNL, and F. J. Himpsel, IBM T. J. Watson Research Center)



Angle-resolved photoelectron spectra for the superconducting compound $Bi_2Sr_2CaCu_2O_8$ in the superconducting (20 K temperature) and normal (85 K temperature) states for two directions of the momentum (A and B). In the superconducting state, the appearance of an energy gap shifts the photoelectron spectrum near the Fermi energy (E_F) to lower energies in direction A but not in direction B (i.e., the gap is anisotropic). The inset shows the variation of the gap with direction in the surface plane as represented by an angular function f(θ) chosen for ease of comparison with theory. (From work of Z.-X. Shen, W. E. Spicer, and D. M. King, Stanford University; D. S. Dessau, SSRL; and B. O. Wells, Massachusetts Institute of Technology)

controversial, but recent angle-resolved photoelectron spectroscopy measurements reported only last year by a Stanford University group working at SSRL have now shown that the energy gap is strongly anisotropic, thereby narrowing the theoretical options (see figure at left).

Photoemission From Surfaces and Interfaces

X rays can penetrate deeply into a solid before being absorbed, so that a putative photoelectron has some distance to travel in order to escape from the surface. The probability of escaping with no energy losses depends on the kinetic energy of the photoelectron, reaching a minimum of a few angstroms. Experimenters using synchrotron radiation can therefore tune the X-ray photon energy to produce photoelectrons from very near the surface or deeper in the bulk, a feature that turns photoelectron spectroscopy into a surface-sensitive technique. However, while clean surfaces prepared in the laboratory often have long-range order, surfaces in the "real-world" may by design or otherwise be harder to characterize. Photoelectron spectroscopy from core states is well suited for probing short-range order and local properties (e.g., atomic coordination and oxidation states) that can be studied in these circumstances. Of particular interest, the energy of core states has a simple relation with chemical properties, such as the type of chemical bond, that depend on the local environment.

An important example is analysis of the processing of computer chips, which involves complex surface chemistry. Patterns in advanced integrated circuits are etched into a silicon surface by the process of plasma etching. In this process, a fluorocarbon plasma removes silicon fluoride moleclules from the surface. There are many process parameters that have been optimized empirically, but the physical reasons for choosing them are unclear. In the mid 1980s, researchers from the IBM T. J. Watson Research Center investigated the interaction of fluorine atoms with well-prepared and characterized silicon surfaces in experiments at the National Synchrotron Light Source (NSLS). The group demonstrated that removal of the molecule silicon trifluoride is a bottleneck in the etching reaction, independent of crystallographic orientation and other parameters, a fact that was not known before this work (see diagram on next page). They have since extended their use of core-state photoelectron spectroscopy to investigate how silicon dioxide forms on silicon surfaces, another crucial process in chip manufacture.

Spectroscopic Imaging

Inhomogeneity is a fact of life for materials that aspire to work in the real world. Materials scientists deliberately mix in additives, which may be distributed unevenly, to improve the performance of metals and alloys, superconductors, permanent magnets, and ceramics. Even computer chips based on single crystals of silicon have circuit patterns made of other materials imprinted on them. To examine materials on a local scale rather than measuring an average over the entire sample, it is

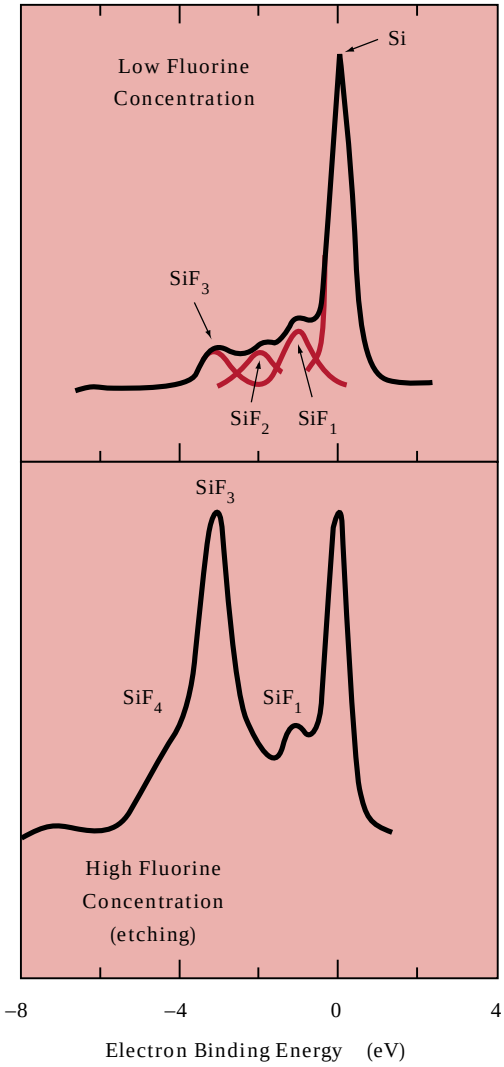
necessary to have spatial resolution. With focused synchrotron radiation it is possible to direct enough photons into a small area of the sample to generate a useful signal. The most intuitive means of obtaining spatially resolved spectra is by rastering the spot across the sample (or the sample through the spot). Most of the usual photon and electron spectroscopies can be done in this way with a spatial resolution limited by the spot size. Alternatively, larger sample areas can be illuminated and imaging achieved by photon or electron optics. In either the scanning or the imaging mode, the new terms spectromicroscopy and spectroscopic imaging have been coined to describe this capability.

Polymer blends are a case in point. Designed in the hope of obtaining the high performance of expensive materials at a lower cost, blends often exist in discrete domains or phases with different compositions. Morphological features, such as domain size, presence of inclusions, and interparticle distances, are important determinants of the mechanical properties of polymer blends. Experiments in 1992 with a scanning X-ray microscope at the NSLS provide dramatic evidence for a new and direct means for investigating the morphology of polymer blends. With spatially resolved near-edge X-ray absorption spectroscopy (micro-XANES) involving chemically sensitive core states, the researchers were able to image the structure of polymer blends, including the visualization of domains several micrometers in diameter corresponding to regions of different composition and various other features, such as inclusions and holes. More recent experiments have extended the technique to still smaller structures in other types of polymers. The ultimate spatial resolution has not been reached but may eventually be better than 100 angstroms in newer facilities.

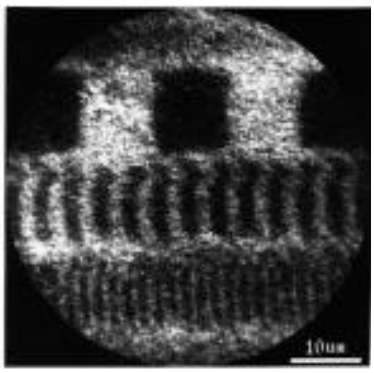
Circular Polarization

The use of circularly polarized synchrotron radiation is now at the cutting edge of research on properties that are dependent on electron spin, such as the magnetic properties of solids and thin films, a subject not only of academic interest to solid-state physicists and materials scientists but also of considerable economic importance to the magnetic recording industry. Spin-dependence is at the core of understanding magnetism on a microscopic scale. For magnetic materials, the opportunities range from development of a basic understanding that can have the same impact on the development of magnetic materials as band theory has had on semiconductors, to applications-oriented areas associated with the properties of magnetic memory and recording devices. Magnetic circular dichroism (MCD) spectroscopy, which is essentially the difference between the absorption of left- and right-handed polarized photons by a sample in a magnetic field, is the key for probing magnetic materials.

Although MCD experiments based on core-state X-ray absorption were reported first in Germany in 1987, effective use of soft X rays for the investigation of magnetic materials containing transition metals



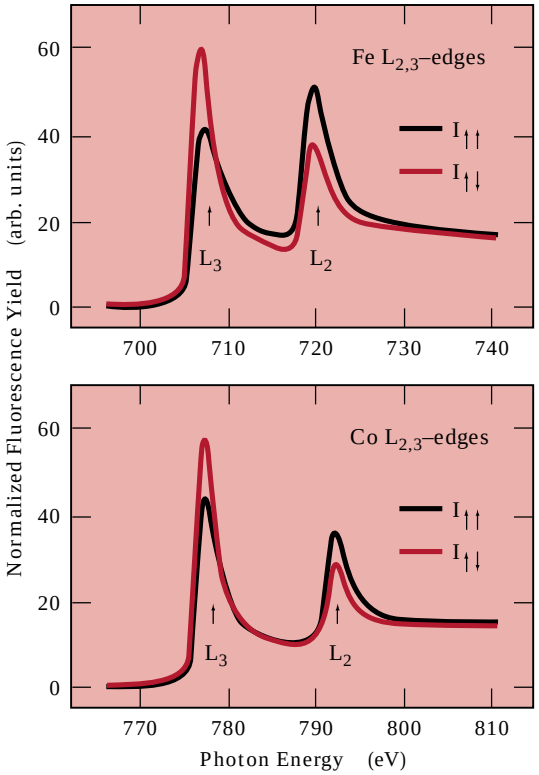
Photoelectron spectra for silicon exposed to a low and a high concentration of fluorine. The energy of the silicon peak depends approximately linearly on the number of fluorine atoms bound to silicon at the surface. The large peak due to silicon trifluoride in the spectrum for high fluorine exposure, which simulates a plasma etching environment, indicates that removal of this molecule from the surface is the bottleneck of the etching reaction. (From the work of F. R. McFeely, J. F. Morar, G. Landgren, F. J. Himpsel, and N. D. Shinn, IBM T. J. Watson Research Center)



A magnetic image of an area on a data-storage disk made of a cobalt-platinum-chromium alloy containing domains of 10 by 10, 10 by 2, and 10 by 1 square micrometers. To obtain the highest resolution, the image was made by subtracting an image obtained at the cobalt L_3 peak (see bottom figure on this page) from the reverse-contrast image obtained at the L_2 peak. (From the work of J. Stöhr, Y. Wu, B. D. Hermsmeier, M. G. Samant, and G. R. Harp, IBM Almaden Research Center; and S. Koranda, D. Dunham, and B. P. Tonner, University of Wisconsin, Madison)

(particularly iron, cobalt, and nickel) was pioneered by an AT&T Bell Laboratories group. Thin films containing multiple layers of magnetic and non-magnetic elements, which are under intense investigation as candidates for future high-density magnetic storage materials, illustrate the usefulness of MCD. By tuning the photon energy to the element(s) of interest in each layer, the researcher can select which layer to probe. The AT&T group and its collaborators, for example, reported in 1993 experiments at the NSLS the ability to measure separately the magnetization of each layer as a function of applied magnetic field (hysteresis curves), as well as detect interactions between layers not observable by conventional techniques (see bottom illustration). Hysteresis curves are the most fundamental characterization of a magnetic material, yielding the magnetic moment giving rise to the magnetization and other information.

Spatially resolved MCD spectroscopy is called magnetic imaging. A group including researchers from the IBM Almaden Research Center and the University of Wisconsin Synchrotron Radiation Center working at SSRL graphically demonstrated the virtues of magnetic imaging in 1993 experimenters on a commerical magnetic recording disk, basically a cobalt-platinum-chromium alloy covered with a thin protective layer of carbon and lubricant. Using MCD from core states in the cobalt to provide the contrast for a microscope using electron optics to image electrons from the surface, the experimenters made images of the pattern of magnetic domains (bits) on the data-storage disk (i.e., domains magnetized in one direction had a large positive MCD signal, whereas the domains magnetized in the opposite direction had a large negative signal).



X-ray absorption spectra from iron and cobalt core states in a multilayer sample of iron, cobalt, and copper. The spectra for each element show two peaks (L_3 and L_2) corresponding to absorption by two different core states. The red curves are spectra for the case of anti-parallel electron spin and photon spin (helicity), whereas the black curves are for parallel spins. The difference between the two curves is the magnetic circular dichroism, which has opposite signs for the L_3 and L_2 peaks. (From work of C. T. Chen, H.-J. Lin, and G. Meigs, AT&T Bell Laboratories; Y. U. Izerda, A. Chaiken, and G. A. Prinz, Naval Research Laboratory; and G. H. Ho, University of Pennsylvania)

NEW CONSTRUCTION DEMONSTRATES IMPACT

If there were any doubts about the value of synchrotron radiation, the current worldwide spurt in building new facilities—including in the U.S. the Advanced Light Source at LBNL and the Advanced Photon Source at Argonne National Laboratory with a combined cost exceeding $900 million—should put them to rest (see "Third-Generation Synchrotron Light Sources" in the Spring 1994 *Beam Line*, Vol. 24, No. 2, pp. 17–28). Even with dozens of beamlines guiding synchrotron radiation simultaneously to as many waiting experiments at each facility, the demand for beam time shows no sign of leveling off. In the more distant future, there is the possibility of using electron linear accelerators to make XP-ray lasers that generate very powerful coherent beams.

The X-Ray Universe

by WALLACE H. TUCKER

X-ray images of the Universe are strikingly different from the usual visible-light images.

WILHELM ROENTGEN'S INITIAL DISCOVERY of X-radiation in 1895 led immediately to practical applications in medicine. Over the next few decades X rays proved to be an invaluable tool for the investigation of the micro-world of the atom and the development of the quantum theory of matter. Almost a century later, telescopes designed to detect X-radiation are indispensable for understanding the structure and evolution of the macro-world of stars, galaxies, and the Universe as a whole.

THE BIRTH OF THE FIELD

X-ray astronomy emerged with the space age, because X-ray observatories could now be positioned above earth's X-ray-absorbing atmosphere. This may seem strange, since X rays pass right through our flesh, which is much denser than the atmosphere. Even though the atoms in the atmosphere are widely spaced, the total thickness of the atmosphere is so great that an X ray has a neg-ligible chance of getting to the ground. (The lower-energy visible-light photons interact weakly with the atmospheric atoms and pass through with little absorption.)

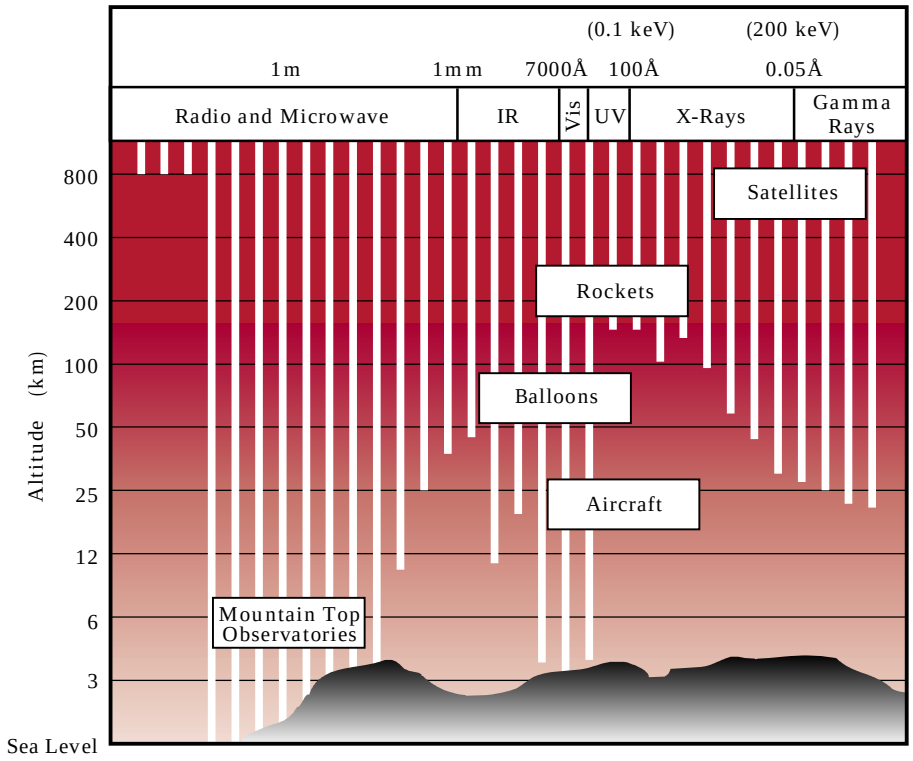
In September 1949 a team led by Herbert Friedman of the Naval Research Laboratory was the first to detect X-ray emission from the solar corona, the hot outer layers of the sun's atmosphere. Their experiment consisted of a collection of small Geiger counters aboard a captured German V-2 rocket. The observed X-ray emission was weak, amounting to only one millionth of the total energy radiated at all wavelengths by the sun.

The low X-ray output from the sun led many astronomers and astrophysicists in the late 1950s and early 1960s to think that efforts to build larger detectors and telescopes to observe X rays from sources outside the solar system would be fruitless. Fortunately, a group led by Riccardo Giacconi at American Science & Engineering (AS&E) did not listen to the pundits. Instead they followed the example set by Roentgen, who when asked what he thought when he first observed X rays in his laboratory, replied, "I did not think: I investigated." Undeterred by NASA's rejection of a proposal to search for cosmic X-radiation, Giacconi persuaded the Air Force to fund the project with the understanding that its primary goal was to look for X rays from the moon.

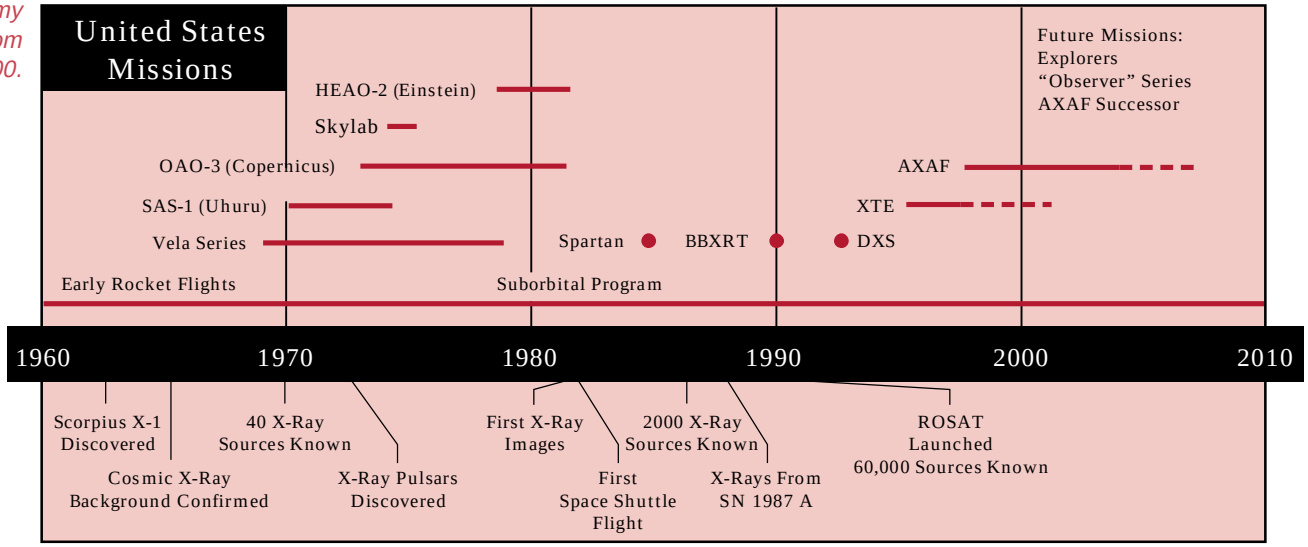
The AS&E team's first two X-ray astronomy rocket flights failed. The third try, in June 1962, was a success. During an observation period that lasted just over five minutes, Geiger counters a hundred times more sensitive than any used before detected a strong source in the constellation of Scorpius, as well as a smooth background glow. Within a year these results were verified by the AS&E group and confirmed by Friedman's group at the Naval Research Laboratory. A new field of astronomy had been born. As a historical footnote, X-ray emission from the moon was not detected until 1990 by the Roentgen Satellite X-ray observatory (ROSAT).

THE X-RAY SATELLITES

By 1967 there were a dozen or more groups involved in X-ray astronomy, and more than thirty sources had been found. Major advances in the field began in the 1970s with the use of satellites



The absorption of X rays by the earth's atmosphere restricts ground-based observations to radio, near infrared, and visible wavelengths. X rays are absorbed high above the earth.



X-ray astronomy missions, from 1960–2000.

equipped with X-ray detectors. The first of these, Uhuru, was launched in 1970. In 1978, NASA's Einstein X-ray observatory was the first large focusing X-ray telescope to be placed in orbit. The Einstein X-ray telescope produced high-resolution images and accurate locations for thousands of cosmic X-ray sources. This and later missions have observed X rays from ordinary stars, white dwarf stars, neutron stars, black holes, interstellar shock waves produced by stellar explosions, the nuclei of galaxies, and hot gas in intergalactic space.

The X rays detected by X-ray astronomers, like those put to use in industry, medicine, and laboratory research, must be produced by high-energy particles. It is not surprising, then, that an X-ray image of the sky can look markedly different from an optical image. In essence, X-ray images reveal hot spots in the universe: regions where particles have been energized or raised to very high temperatures by phenomena such as strong magnetic fields, violent explosions, or intense gravitational forces. The temperatures inferred are typically several orders of magnitude higher than those on the surfaces of stars. Where do such conditions exist? In an astonishing variety of places, ranging from the vast spaces between galaxies to the bizarre warped space around neutron stars and black holes.

The ROSAT mission, an international collaboration involving Germany, the United Kingdom, and the United States, launched in 1990, has the most sensitive detector so far for low-energy X rays of the type emitted by stars similar to the sun. The source of X rays from these stars is a hot gaseous upper atmosphere, or corona, that has been heated to temperatures of millions of degrees Celsius.

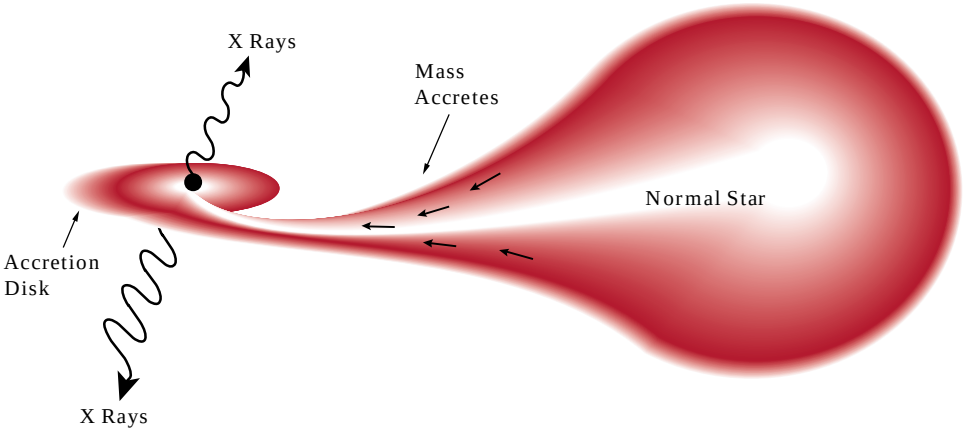
Young stars less than a hundred million years old are observed to have an X-ray output a thousand times more than that of the sun. This suggests that the X-radiation from the young sun could have been much stronger than it is today. How did this enhanced radiation affect the evolution and chemistry of the primordial atmosphere of the earth? X-ray observations should help to answer this vital question.

THE STRONGEST X-RAY SOURCES

The brightest X-ray sources in the sky are associated with the end phases of stellar evolution: the remnants of supernova explosions as well as neutron stars and black holes formed in the violent final seconds of a massive star's normal existence. The X-ray emission from these collapsed stars is billions of times greater than that from the sun.

The launch in 1970 of the Uhuru X-ray satellite by NASA made it possible to monitor X-ray stars for prolonged periods of time. It was discovered that the X-ray emission from these stars undergoes rapid, intense, and sometimes periodic variations. Combined observations with optical and X-ray telescopes have demonstrated that these X-ray sources are members of binary systems in which matter streams from a normal star onto a nearby collapsed star with an intense gravitational field.

In most X-ray binary star systems, the collapsed star is a neutron star. Neutron stars are the end products of the evolution of stars approximately ten times more massive than the sun. These stars undergo a supernova explosion in which most of the star is expelled into space at very high speeds. A shock wave analogous to a immense sonic boom spreads through space, heating interstellar gas to temperatures of millions of degrees. X-ray observations study these shock waves for clues about the origin of all of the heavy elements from carbon on up.



Cross section of an accretion disk of a neutron star.

Left behind is the rapidly spinning, highly magnetized, compressed core of the star—a core so dense that the electrons have combined with the protons to form an object composed mostly of neutrons. A sample of neutron star material the size of a sugar cube would weigh one billion tons. Most neutron stars appear to have a mass about equal to that of the sun compressed into a ball about twenty kilometers in diameter. The strong magnetic field on the surface of the star can funnel the infalling matter, resulting in a hot spot which manifests itself as a regularly pulsing X-ray source.

BLACK HOLES

For a few binary X-ray star systems, the mass of the collapsed object is deduced to be greater than three times the mass of the sun. These objects are presumably the end products of stars even more massive than those that produce neutron stars. The theory of dense matter and Einstein's theory of general relativity require that such an object would collapse in on itself to form a warp in space called a black hole. A black hole does not have a surface in the normal sense of the word. It is more like a whirlpool with a critical range of influence. The critical distance from a black hole is called the gravitational horizon. Anything that falls within the horizon—matter, light, X rays or other forms of electromagnetic radiation—is pulled inexorably inward by the gravity of the black hole and cannot escape.

No unique X-ray signature of a black hole has yet been discovered. In general, successful black hole candidates meet two requirements: (i) they are luminous X-ray sources that exhibit large, rapid, and sometimes quasi-periodic (a stable period would indicate a neutron star) fluctuations on a time scale of milliseconds; and (ii) optical observations of the primary star indicate that it has an invisible companion with a mass greater than three times the mass of the sun, the theoretical upper limit for the mass of a neutron star.

To date, a half dozen such systems have been discovered. The best estimates of the black holes in these systems are about 10 solar masses. Observations by future missions such as the X-ray Timing Explorer, scheduled to be launched by NASA in August of 1995, are expected to expand this list.

GALACTIC BLACK HOLES

Black holes of much larger mass are thought to lie at the center of many and perhaps all galaxies. These supermassive black holes, which could contain the mass of as many as a billion suns, are thought to form when a stellar-mass black hole swallows enormous quantities of interstellar gas that has accumulated in

the central regions of galaxies. As gas falls inward, it is accelerated to high energies. This energized matter produces copious amounts of electromagnetic radiation over a wide range of wavelengths.

If the black hole is extremely massive and the rate at which it is pulling in matter is large, the energy release can be stupendous. This is apparently what is happening in quasars. They radiate as much energy per second as a thousand or more normal galaxies from a region about the size of our solar system. It is as if a small flashlight produced as much light as all the houses and businesses in the entire Los Angeles basin.

In black hole models for quasars, matter approaching the gravitational horizon radiates predominantly energetic X-ray and gamma-ray photons. A study of the intensity and variability of the X- and gamma-radiation from quasars can then provide information on the size of the black hole, the rate at which it is accreting matter, and other factors that are crucial to understanding the inner workings of these violent maelstroms.

INTERGALACTIC GAS AND DARK MATTER

The matter around black holes radiates intense X-radiation because it is highly compressed and exceedingly hot. Extreme temperatures can also be found in the near vacuum of intergalactic space. In contrast to the gas spiraling into black holes, the intergalactic gas is hot because it is spread out. Its low density makes it easy to heat and difficult to cool.

It seems certain that an understanding of the nature of dark matter could change our theories of the formation of stars and galaxies, the nature of subatomic particles, and the evolution of the Universe.

Ordinarily this would also preclude it from producing any appreciable X-ray emission. However, in certain regions of space thousands of galaxies have clustered together. The amount of gas associated with these clusters of galaxies may have a mass equivalent to a hundred trillion suns. The only direct way to study this gas is through the X-radiation it emits. X-ray observations have shown that the mass of the gas in clusters of galaxies is considerable—comparable to the mass of all the stars in all the galaxies.

Unless we are seeing a cluster of galaxies at a very special time when gas is exploding out of the cluster, the pressure of the hot gas must be balanced by the gravity of the cluster. X-ray observations indicate that the hot gas in clusters cannot be confined by the combined gravitational force of gas and galaxies. An additional, as yet unobserved form of matter, called dark matter, must be postulated. The implied amount of dark matter is enormous, about three to ten times as much as that of the observed gas and galaxies.

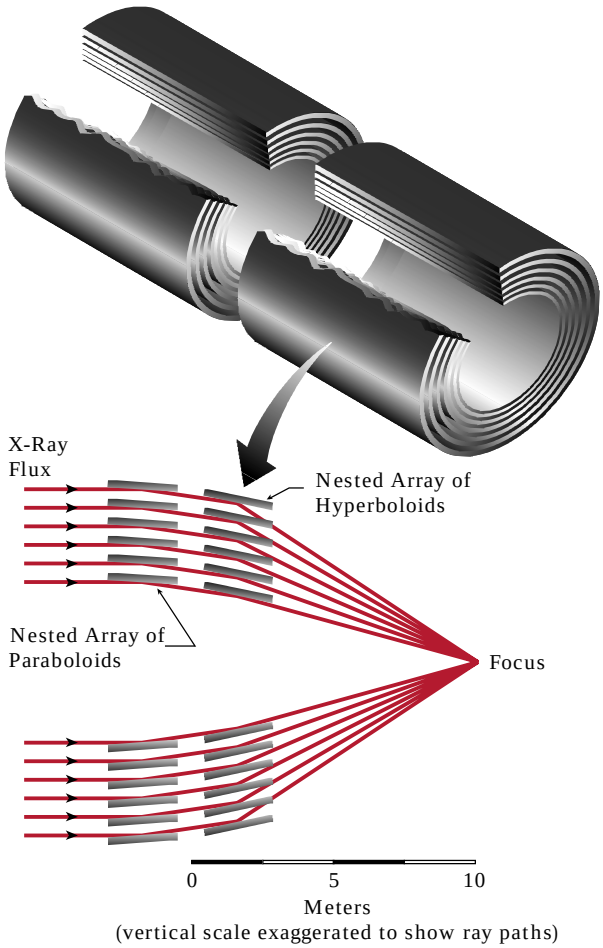
If the conclusions drawn from observation of clusters of galaxies so far can be generalized to the universe as a whole, then dark matter is the predominant component of our Universe.

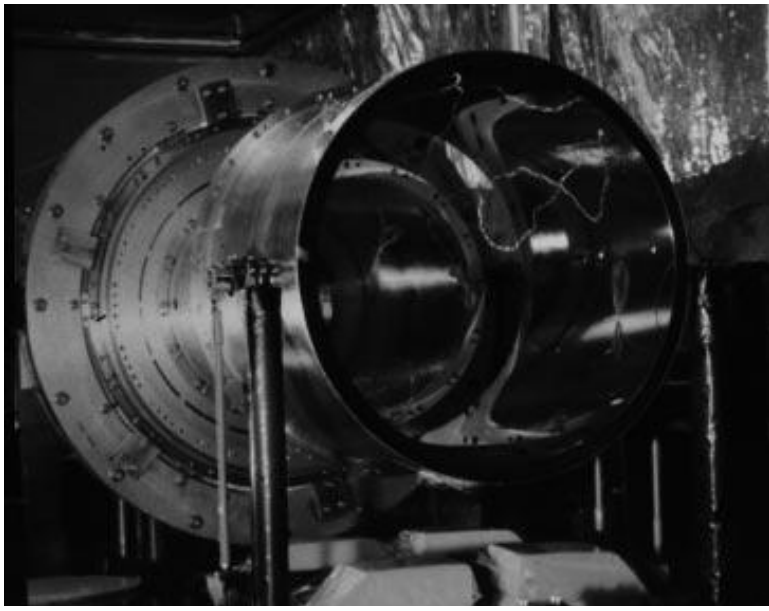
Is the dark matter composed of dim stars, planets, or black holes? Or does it consist of subatomic particles that interact with ordinary matter only through gravity? We do not know. But it seems certain that an understanding of the nature of dark matter could change our theories of the formation of stars and galaxies, the nature of subatomic particles, and the evolution of the Universe.

X-RAY BACKGROUND RADIATION

Other important clues to the evolution of the universe are found in the X-ray background radiation. One of the first discoveries of X-ray astronomy was an unexpectedly strong and uniform background glow of X-radiation. The uniformity of the radiation suggests that it is not coming from nearby galaxies, but from a distance so great that all the individual sources merge into a smooth background, just as the lights of a distant city appear as a uniform glow.

The current opinion is that the X-ray background radiation must have been produced about ten billion years ago. Sometime between a million and a few billion years after the hot Big Bang phase from which our Universe is thought to have evolved, the universe made a dramatic transition from a smooth, featureless state to clumps of galaxies. The X-ray background radiation must have been produced during this transitional period. Radiation from quasars and the bright nuclei of galaxies appear to be capable of producing a significant portion of the





Above right: Photograph of the largest AXAF mirror.
Above: Schematic of nested pairs of grazing-incidence mirrors which permit the precise focusing of X rays. (Courtesy Harvard-Smithsonian Center for Astrophysics, Marshall Space Flight Center, Hughes Optical Systems, and Eastman Kodak).

X-ray background, but it is still unclear if they can produce all of it.

THE FUTURE

What is clear is that future X-ray missions will probe ever more deeply into space with ever more sensitive and versatile instruments. The most important X-ray astronomy mission of the coming decade will be NASA's Advanced X-ray Astrophysics Facility (AXAF), which is scheduled for launch in 1998. This observatory, with its four sets of nested mirrors, will be the X-ray equivalent of the Hubble Space Telescope. AXAF and other future missions will provide scientists with opportunities for deeper insight into black holes, dark matter, the X-ray background, and the events that led to the formation of the elegant galaxies and colossal clusters and superclusters of galaxies that constitute our Universe.

"It's hard to waste 10^8 dollars."
—Philip Morrison (1975)

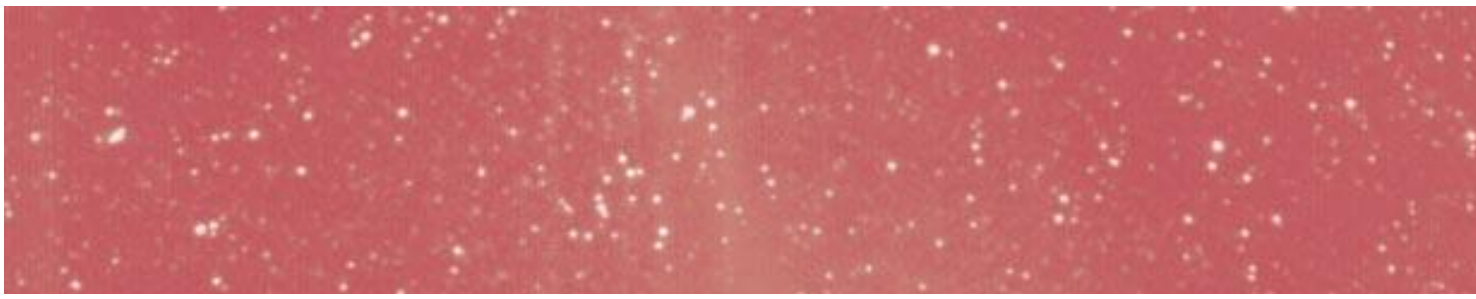
On Beyond X

by VIRGINIA TRIMBLE

Astrophysics in the Gamma Ray, Neutrino, and Gravitational Radiation Regimes

"But, unfortunately, no longer impossible."
—Virginia Trimble (1995)

X-RAY ASTRONOMY began in a blaze of glory with extra-solar-system sources brighter than anyone could rationally have expected. I except, of course, the pioneers, working with Bruno Rossi and Herbert Friedman, who built the first rockets—such people are necessarily irrational or nothing new would ever get done.



In contrast, the field of gamma ray astronomy saw generations of rationally-motivated detectors come and go before the photons outnumbered the people writing about them. The sagas of neutrino and gravitational radiation astronomy are even stranger.

I have tried elsewhere to draw some profound conclusion from these very different histories, and failed. Readers are therefore cordially invited to propose answers to the question "And the moral of that is?" provided they keep in mind that most of the founders of all four fields are likely to be out there surfing the net.

GAMMA RAY ASTRONOMY

Gamma rays were part of the astrophysical inventory from 1920 to 1929, because cosmic rays were erroneously so identified. Correlations with the earth's magnetic field cast early doubts, but the critical measurement was one of cosmic ray penetrating power. The paper, by Bothe and Kohlhorster, is still exciting reading, even (or perhaps especially) if you don't know German. The first sentence mentions "Gammastralung" and the last "Korpuskularstrahlen," and in between are three centimeters of plumbium. Limits on real cosmic gamma rays dropped to 1% of the particle flux in the post-war era of flights of V2 rockets and clones.

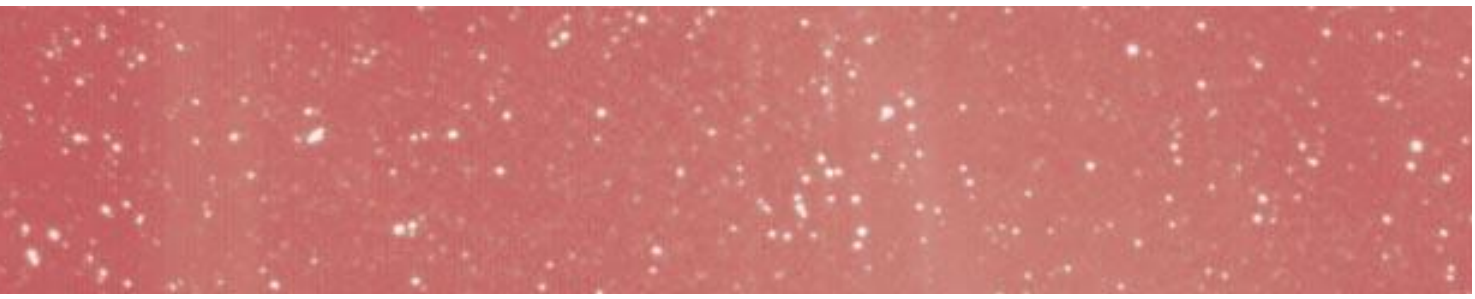
Theorists began advertising detectable sources in the 1950s—first, annihilation gamma rays that, according to Geoffrey Burbidge and Fred Hoyle, should be coming from the radio source Cygnus A if its energy source was the collision of a galaxy with an anti-galaxy; and second nuclear decay gamma ray lines expected from supernovae if their light curves were powered by the Californium-254 source advocated by Burbidge, Burbidge, Fowler, and Hoyle. The classic 1958 previews, written by Philip Morrison and Satio Hayakawa, popularized these and other, less exotic, potential sources. Promised fluxes ranged as high as $0.1-1\gamma/cm^2$–sec in the MeV range.

An off-the-shelf nuclear emulsion stack, flown on an Italian balloon, quickly cut these numbers by 100. Thomas Cline built the first detector deliberately designed for astronomical gamma ray sources in 1961 and pushed the limits down to about $10^{-3}\gamma/cm^2$–sec. The extraordinary efforts required to beat down backgrounds and extract signals shine through the bland 1962 remark of Bill Kraushaar and George Clark that "the remaining 22 events, which come from a variety of directions in space, are gamma rays." Jim Arnold, piggy-backing on Ranger 3 in the same year, defined the diffuse background, while balloon and rocket-borne detectors pushed sources down to near $10^{-4}\gamma/cm^2$–sec, interrupted by one 1966 false alarm at about the same level, in the general direction of Cygnus. A 1967 review by Giovanni Fazio pointed out that the ratio of papers to confirmed extra-solar-system photons above 100 keV was still infinity (but his discussion of the likely radiation processes has held up well).

Gamma ray photons coming from the galactic center direction and from the Crab Nebula finally appeared in 1967–68. The Crab photons were pulsed and, having been collected in 1967 by Richard Haymes and his colleagues, provide the earliest measurement we have, or will ever have, of the pulsar period.

SAS2, the first satellite optimized for gamma rays, went up in 1972 and quickly increased the photon number count to 10^4 or so, though the number of identified sources hovered at a handful. COS B returned 2×10^5 photons in the 1970s, leading to a catalog of a couple dozen sources, nearly all unidentified. Balloons and rockets continued to fly, and it was a balloon package that first spotted the cobalt-56 decay line from supernova 1987A.

The modern era began with the spring 1991 launch of the Compton Gamma Ray Observatory (CGRO). The source inventory now includes pulsars, X-ray binaries and transients, supernova(e), the centers of many active galaxies and of the Milky Way, the interstellar medium (both diffuse and patchy), a diffuse isotropic background of somewhat uncertain origin, and, of course, the sun. All the processes advertised in the early reviews have been seen—nuclear decay lines (of aluminium-26,

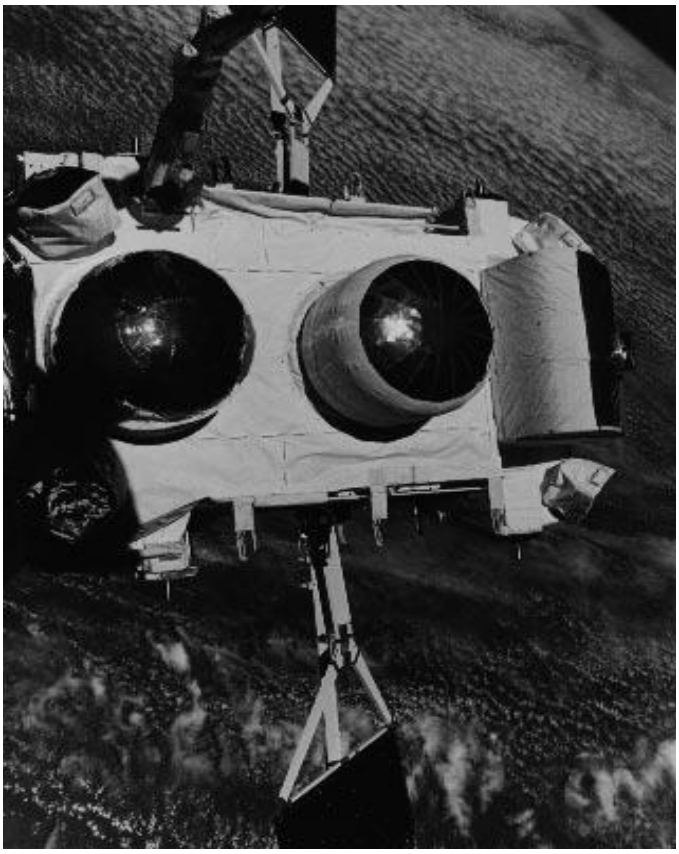


cobalt-56, cobalt-57, excited carbon and oxygen, but not californium-254!), electron-proton annihilation, pion decay, bremsstrahlung, inverse Compton scattering, and probably synchrotron radiation, though the experts are still sometimes arguing about which process goes with which source.

Most gamma ray astronomy has been done at energies of 0.5–100 MeV. One CGRO instrument(EGRET) records photons up to 30 GeV. There is then a decade or so nearly unprobed. By the time you reach TeV and PeV energies, a single photon entering the earth's atmosphere will give you a shower of relativistic particles sufficient to make a Cerenkov light flash or even an extensive air shower (EAS), happily distinguishable from that of a real cosmic ray.

Astronomy at installations sensitive to these has a checkered history. Reports of positive TeV and PeV detections (of the Crab Nebula, Cygnus X-3, Hercules X-l, and several others) surfaced in the early 1980s. Most probably deserve the Scotch verdict of not proven. The exceptions are TeV fluxes from the Crab Nebula (unpulsed) and the nearby, BL Lac type active galaxy Markarian 421, both seen by the Cerenkov installation at the Whipple Observatory. Limits in the range 40 TeV to 1 PeV, even for the Crab, have been the main product so far of the Cygnus EAS array near Los Alamos. The next step in this direction will augment the Cygnus scintillation detectors with water Cerenkov detectors to produce an EAS array reaching down to about 1 TeV and to fluxes well below the current $10^{-11}/cm^2$–sec limits. Will Milagro expand the source inventory beyond two? Will primordial black holes finally show up? Morrison's theorem says yes.

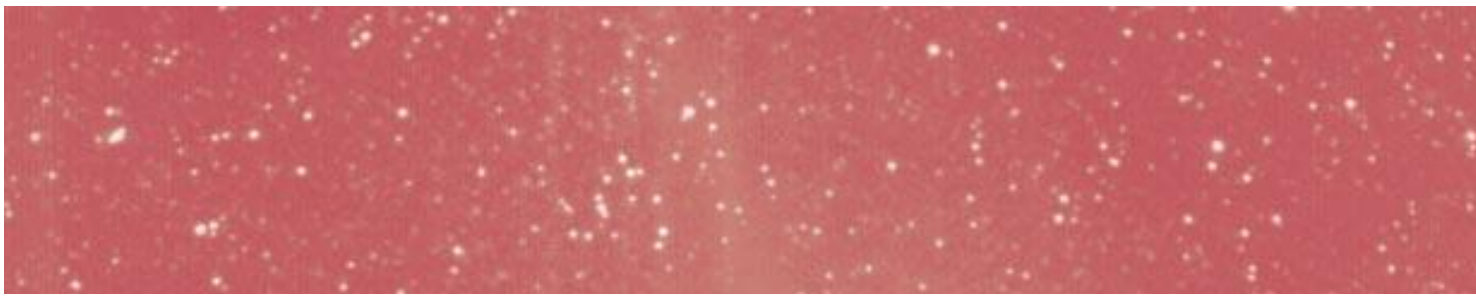
And then there are the gamma ray bursters. Two sorts were predicted (shock break out in supernovae triggered by the collapse of stellar cores to neutron stars; evaporation of mini black holes) and two sorts have been seen (many of one type and three soft gamma repeaters). But they are not the same sorts. Supernovae are no longer supposed to do this sort of thing, because the emerging shock is less explosive and radiates mostly ultraviolet, and the limits on black hole gamma rays are still not very constraining.



NASA

The Compton Gamma Ray Observatory, launched in April 1991, carries four instruments. Each of them provides some information about gamma ray arrival times, energies, and directions of travel. But EGRET specializes in the highest energies (to 30 GeV), while the others are most efficient around an MeV, and COMPTEL concentrates on locations and imaging, OSSE on spectral information, and BATSE on accurate arrival times, especially for bursts and variable sources.

The bursters we have were accidental discoveries, made in the data collected by the American Vela satellite series starting in 1969 and, at about the same time, by the Soviet Cosmos satellites, and announced in 1973–74. What the satellites were supposed to do was



LANL

One of the VELA satellite series, originally launched to look for neutrons and gamma rays from terrestrial events (nuclear bombs). They began seeing celestial events (gamma ray bursters) in about 1969 and the data became generally available a few years later. The author has never even had a "company confidential" clearance and knows nothing whatever more about the satellites.

look for gamma rays from illegal atmospheric bomb tests carried out by "the other side." Neither series ever saw any illegal tests,* but they did discover the bursters. This is the context in which Morrison originally made the remark about the difficulty of wasting 10^8 dollars. His other example was the seismic array, aimed at illegal underground tests, whose primary discovery was the tracing out of tectonic plate boundaries by microseisms.

The first gamma ray burst paper reported 16 events over three years, each depositing something like 10^{-3} erg/cm^2 at the top of the atmosphere. Data from later astronomical satellites, some with purposeful burst detectors, others with active anti-coincidence shielding, increased the inventory to a hundred or so, picked up fluxes down to 10^{-5} erg/cm^2, and revealed spectral features suggestive of cyclotron resonances in magnetic fields of about 10^{12} gauss, the same as ordinary pulsar fields.

We spent whole meetings assuring each other that this was all perfectly explicable in terms of hiccups in nearby, old neutron stars. The "nearby" part was needed to account for isotropy of the events over the sky and the relationship between numbers and fluxes that implied homogeneous distribution in space. All participants firmly expected that, with lower flux limits, we would begin to see both the edges of the galactic plane and the concentration of bursts within it.

Notoriously, this is not what happened. CGRO has increased the burst inventory to well above 1000 (growing at the rate of about one per day) and lowered the detectable fluxes to about 10^{-7} erg/cm^2. Sure enough, we are now seeing the edge of the distribution (in the form of a relative sparcity of the faintest detectable events). But the distribution on the sky remains isotropic. Somehow, we are in the middle of the source population, but we see the edge, and this has not been a popular astronomical position since the time of Copernicus.

Although a tiny subset of three sources (soft gamma repeaters) now seem to belong to neutron stars in young supernova remnants, the theoretical situation is otherwise A Mess. Potential for sorting it out with additional statistics or more detailed gamma ray spectra and light curves seems limited. What we need is optical or radio counterparts that last more than a second or so, which may well not exist at brightnesses we can see. Meanwhile, a follow-on gamma ray satellite called

**A test by a country that has not signed the nuclear non-proliferation treaty cannot reasonably be called illegal!*

INTEGRAL is rapidly pushing the 10^9 dollar barrier in its estimates.

NEUTRINO ASTRONOMY

And the Lord spoke to Pauli and said, "Speak unto the children of Rutherford and tell them that, wherever a proton is converted to a neutron or a neutron to a proton, there also shalt thou have a neutrino (or antineutrino) to make the spins and energies come out even." This illustrates that the Lord, who may indeed be an engineer, a biologist, and a mathematician, is primarily a bookkeeper. As with any other sort of particles, you can also make them pairwise, neutrino plus anti-neutrino, under appropriate (hot, dense) conditions.

Suitable environments for neutrino production occur in bombs, reactors, the early universe, and stars. For two of the four, the products have not yet been seen. Fredrick Reines and Clyde Cowan originally proposed their experiment as a way to "see the neutrinos coming out of a bomb," but applied it to reactors (successfully, of course). Detecting the cosmological sea of neutrinos that ought to correspond to the 2.7K sea of photons (cosmic background radiation) remains the sort of problem that experimental physicists dream about solving on their way to Stockholm.

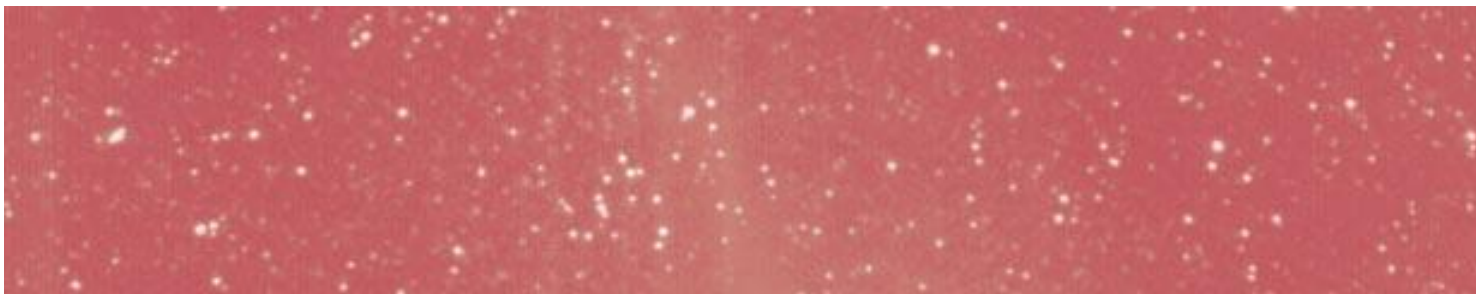
This leaves us with stars. Neutrino radiation by the sun and other hydrogen fusers is implicit in the reactions for the proton-proton chain and CN cycle as written down by Hans Bethe in 1938–39, though he himself did not actually show them in the reaction equations. Counting this particular sort of bean obviously did not seem so important in those days when the neutrino was thought probably to be its own antiparticle, the way the photon is. Soon after, Gamow and Schoenberg pointed out that much more copious neutrino emission might occur in evolved, denser stars, both from one-way conversion of $p + e$ to $n + \nu$ en route to neutron-rich conditions ("deleptonization" is the modern word) and from cycling between p's and n's, with energy loss at each cycle (the Urca process, named by them for the Rio de Janiero casino where money similarly vanishes at every exchange).

AMANDA is the Antarctic Muon and Neutrino Detector Array. It makes use of the extreme clarity of polar ice (from which bubbles have been squeezed by the weight of ice above). Thus flashes of Cerenkov light from high-speed particles passing hundreds of meters away can be seen by the widely-spaced phototube detectors.

Calculations of the various pair production processes (bremsstrahlung, synchrotron, plasmon, Compton, and annihilation neutrinos) followed hard upon the description by Feynman and Gell-Mann of the universal Fermi interaction which revealed their possibility. The recognition of neutral currents, permitting the production of mu and tau neutrinos (pairwise) under stellar conditions, triggered a third round of calculations in the 1970s. Round four, invoking rotations or oscillations among the neutrino types, is by no means over, the knock-out punch necessarily awaiting further experimental/observational results.*

The first experiments were gedanken ones. Bruno Pontecorvo and Luis Alvarez wondered in the 1940s what would happen if you exposed a sufficiently large quantity of some substance with a large cross-section

**Baby astronomers are taught to call themselves observers; baby physicists experimenters. The distinction blurs most thoroughly in cases like gamma rays, neutrinos, and gravitational radiation, where you have no idea whether your telescope/detector will see anything at all until you have built and debugged it. Galileo never had this problem.*



The interior of the Kamiokande detector. (Courtesy Yoji Totsuka, University of Tokyo).

for induced beta or inverse beta decay to the sun. Their answer was "nothing." Solar neutrinos would not be energetic enough. Rather, they proposed chlorine-37 as a trapper of reactor (anti) neutrinos, still believing the particle and anti-particle to be the same.

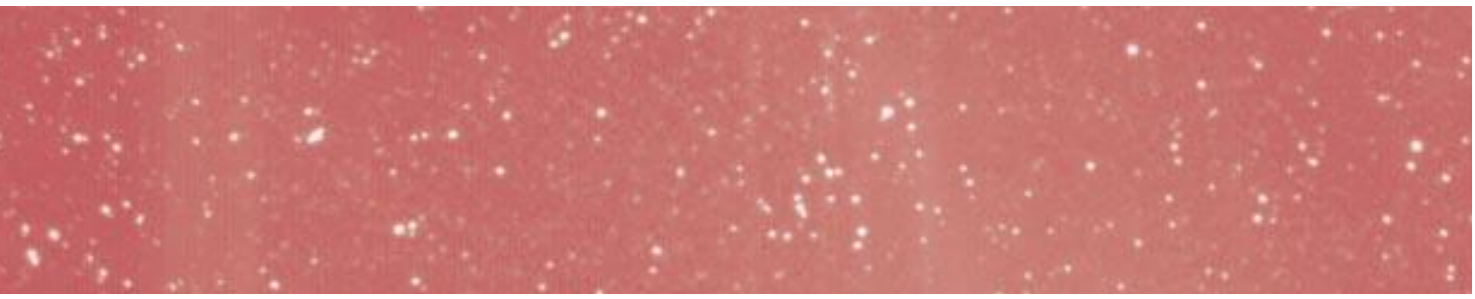
It is against this historical background that Raymond Davis, Jr. buried his first chlorine tank in the ground near Brookhaven in 1954, though he also took the trouble to report a solar upper limit (about 10^4 times the current best value). Incidentally, Ray assures us that he does not have a middle initial. The journal habit of name inversions (so that he appears in references lists as Davis, R., Jr.) is responsible for the ghost R.J. Davis. Similar practices have produced ghost papers by Einstein & Preuss, Einstein & Silbst, etc.

The solar experiment came to seem possible in 1958, with a large increase in the laboratory cross section for $He^3 + He^4$ producing Be^7, which would, in turn, capture either a proton or an electron, with a beta-unstable product above the energy threshhold for transformation of Cl^{37} to A^{37}. Davis began serious search for a mine deep enough and large enough to contain a 100,000 gallon tank of C_2Cl_4 (perchlorethylene, or cleaning fluid) in 1963. Even as theorists continued to throw scurrilous SNUs (solar neutrino units) at each other, the tank was built, filled, and instrumented, and data collected.

Davis's 1968 upper limit of about a third of the expected high-energy neutrino flux eventually became a detection at about the same level, and there things have sat for 27 years. Kamiokande (a water Cerenkov device that began life as the Kamioka Nucleon Decay Experiment and matured into the Kamioka Neutrino Detection Experiment) has recorded the very highest energy neutrinos at about half the expected rate and shown that they indeed come from the direction of the sun. SAGE and GALLEX (where gallium transmuting to germanium signals the passage of even quite low energy neutrinos) report that the flux of neutrinos from $p + p$ making deuterium + positron + neutrino (the main solar reaction) is about half of what standard models predict. And we are not going to reconcile the various discrepancies in this paragraph!

The tale of Supernova 1987A is more coherent, according to most tale-tellers. On February 22/23, 1987, there were operating at least four detectors with possible sensitivity to supernova neutrinos above thresholds of 5–18 MeV. Two were large volumes of liquid scintillator (in the Mt. Blanc tunnel and in the Soviet Baksan Neutrino Observatory) and had been deliberately constructed to look for explosive astronomical events. The other two were large water Cerenkov counters (IMB in the Morton salt mine and Kamiokande, mentioned above) and had been constructed—also, of course deliberately, but to look for proton decay, as predicted by some grand unified theories of particle physics.

The Mt. Blanc group were monitoring their data in real time and quickly became aware of a cluster of five above-threshold events within a time interval of a few seconds, the largest such grouping in 2.5 years of operation. They promptly issued an IAU telegram and circular, reporting that a burst of neutrinos had arrived eight hours before the first photons from the supernova. This report sent the Kamioka group rootling in their data to find, eventually, 12 above-threshold events within 12.4 seconds, but 4.7 hours later than the Mt. Blanc ones. The



IMB group, who had previously supposed that their energy threshold was too high for supernova neutrinos with kT ≈ 5 MeV to produce visible flashes, then examined their data, finding 8 events above 19 MeV within a six-second period, less than a minute or two from the Kamioka event time. Finally, Baksan weighed in with five events also within a few seconds, not more than a few minutes apart in time from the IMB and Kamioka clusters. Only IMB and Mt. Blanc were using accurate clocks, and none of the other groups has ever reported anything above their thresholds at the time of the Mt. Blanc event.

The majority of reviewers have dealt with this by believing in the IMB and Kamioka neutrinos and their simultaneity, disbelieving the Mt. Blanc ones, and ignoring the Baksan ones. Then they can say that the flux, temperature, time scale, and so forth were just what should have come from a core-collapse (type II) supernova, and that there is no evidence for neutrinos having unexpectedly large mass, magnetic moment, coupling constants, or any other anomalies.

The Baksan and Mt. Blanc experimenters have, both independently and in collaboration, found correlations among the "below threshold" data streams of all four detectors during a two hour period around the time of the Mt. Blanc burst. Signals recorded by the two gravitational radiation antennas operating at the time also show statistically significant correlations with each other and with the neutrino detector data streams during this period. The results have been reported in several journals and at least four conference proceedings, but remain essentially unnoticed by the community.

Looking ahead, designs, proposals, and some preliminary data exist for an assortment of detectors and arrays focused on higher energy neutrinos and lower flux events from astrophysical sources. In addition to supernovae and merging neutron-star pairs, plausible sources include the annihilation or decay of dark matter particles in the galactic halo and production in association with very high energy cosmic rays in active galaxies or elsewhere. The active substances to be used include water (e.g., Superkamiokande), deuterated water (Sudbury Neutrino Detector), and ice (Antarctic Muon And Neutrino Detector). All seem to be in the 10^8 dollar class, and at least the ones just mentioned are going forward more or less as planned. Keep your window cleaner handy!

GRAVITATIONAL RADIATION ASTRONOMY

Gravitational radiation comes from wiggling massive particles in much the same way as electromagnetic radiation comes from wiggling charged particles. And you can detect them because they, in turn, will wiggle other particles with mass or charge. Why then are the production and detection of gravitational radiation still challenges when we have been radiating infrared and seeing optical photons since the time of the coelenterata or thereabouts? Mostly (as you know perfectly well) because gravitation is the weaker force. Thus, even for entitities moving at (nearly) the speed of light, the ratio of radiated powers is $GM^2/q^2 \approx 10^{-36}$, where G is G, M is mass, and q is electric charge (in God's units or cgs).

To make things worse, the lowest non-zero order of radiation is a dipole for the electromagnetic case and a quadrupole for the gravitational case. This happens because the former force is carried by a spin one particle (photon) and the latter by a spin two particle (graviton).* It costs you two extra powers of (v/c) for systems in slow motion. As a result, the earth in its orbit will lose more energy in 31.7 nHz electromagnetic radiation than in 63.7 nHz gravitational radiation if there is as much as a tenth of a Coulomb of excess charge hanging around. The corresponding ratio for orbiting neutron stars or black holes with $v \approx c$ is one electron per Teragram, and the radiated frequencies will be kilohertz (the range in which most detectors are designed to operate). And, other things being equal, whatever sort of detector you might think of constructing is correspondingly more sensitive to electromagnetic than to gravitational disturbances, not to mention acoustic noise, microseisms, changes in local g, and massive visitors tilting the floor. That the moon overhead raises tides rather

The connection has been explained to me on a number of occasions in ways that seemed to make perfect sense at the time.

Joe Weber with aluminum cylinder gravitational antenna. (Courtesy Joe Weber)

than hair is only because it (like most macroscopic objects) is so nearly electrically neutral.

As if all this weren't sufficiently offputting, for about 30 years (1925–55) many general relativists doubted whether gravitational radiation had any physical reality at all. Their doubts came from defective choices of viewpoint and sign errors (in odd numbers of places) and surely delayed serious consideration of this window on the universe.

Joe Weber, the one man who was apparently not discouraged, combined a background in radio engineering and electronic countermeasures with a knowledge of general relativity gained in late night reading to design (before 1960) and build (by 1965) a detector for gravitational radiation. Initial calculations by Freeman Dyson and John A. Wheeler of the radiation expected from binary neutron stars and supernovae date from the same period. Weber's first antenna used multi-ton aluminum bars as the energy collectors and piezoelectric crystals glued at their centers to turn mechanical energy of the oscillating bar into varying electrical currents of the sort radio amateurs had been amplifying and filtering for decades. At least one antenna of this design has been operating nearly continuously at the University of Maryland ever since. When supernova 1987A exploded, the only detectors on line were two Maryland bars and a similar one at the University of Rome. If supernova 1995N (or thereabouts) goes off, similarly close to us, as I write this, the same situation is quite likely to obtain.

Not that others haven't tried. The five years after the 1969 publication of the first positive results from Maryland saw about 10 room-temperature, single-mass detectors built, instrumented, and operated (as a rule only very briefly) by as many different groups. None was a precise copy of the Weber bars, and negative results outnumbered positive ones in the literature by so large a factor that most people in the field remain unaware of the latter.

Recognizing that ordinary thermal noise was a fundamental limitation, Weber's group cooled one of their bars to liquid helium temperatures in 1972. Others followed gradually (in Rome, Stanford, Western Australia, Louisiana State University, Japan and elsewhere). Efforts in this direction continue, using either aluminum or niobium (because it is a superconductor) bars, with a goal of operating or noise temperatures in the millikelvin range. The installations, like the first one, are so complicated that, so far, more has been learned from them about cryogenics than about relativity.

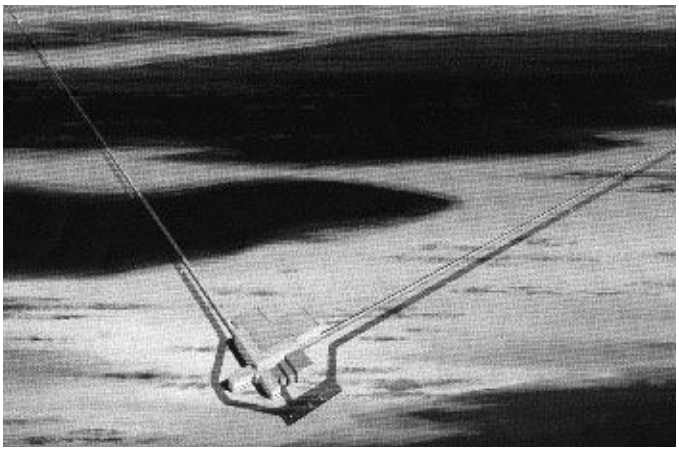
Present high-profile plans for the detection of gravitational radiation, like LIGO (the Laser Interferometer Gravity Wave Observatory) and its European counterpart Virgo, use a very different design. Two or more masses are suspended in isolation far apart and the distance between them monitored using laser light. The first device of this type collected data briefly at Hughes Research Laboratory in 1971. The builder was Robert L. Forward, who had been Weber's graduate student and says that at least the germ of the idea came from his teacher. Forward provided a stable base for his masses by mounting them at the ends of a large granite slab. Such slabs are more often used as raw materials for gravestones, which may be trying to tell us something.

The cost of such an installation with a baseline of 3 km, rather than 3 m, has predictably escalated from 1980s estimates of $60–$80 million to three or more times as much. Construction is underway for the two LIGO detectors, with initial operation expected in this

decade and sensitivity to known sources to be reached with an upgrade in the next.

Meanwhile, the existence and properties of gravitational radiation are being explored in a very different way, from its effects on the orbital evolution of known pairs of neutron stars (binary pulsars). For a couple of the pairs, the radiation is sufficient that the stars will merge in less than 10^8 years. Such events, in distant galaxies, are a leading candidate to produce gamma ray bursts, thereby taking us back to the first section.

So far, there has never been a counterexample to the cliches that "whenever you open a new window you see a new scene," and "it's hard to waste 10^8 dollars." Gamma ray astronomy has already passed through this stage, and the discovery of supernova neutrinos with the two installations looking for proton decay probably also qualifies. The conservative bet is, I suppose, that the clichés will continue to be true for the still more expensive gamma ray, neutrino, and gravitational radiation projects now on the drawing boards and in the tunnels. This may be the only context in which I am not an unmitigated conservative!



An artist's conception of one of the two LIGO sites. The two perpindicular arms of the site extend four kilometers to end buildings. LIGO will measure gravitational waves by sensing very small motions (on the order of 10^{-18} meters) of suspended mirrors at the ends of the two arms. Light from a stable laser in the building at the vertex of the two arms is split and sent down the two arms through vacuum pipes to the end mirrors. The end mirrors reflect the light beams back to the vertex where it is recombined and compared. (Courtesy of the LIGO project, the California Institute of Technology and the Massachusetts Institute of Technology.)

~For Further Reading~

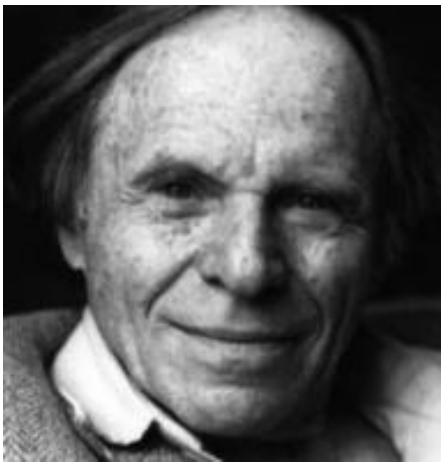
What else to read?

Gamma ray astronomy: The current situation is described in recent conference proceedings—**The Second Compton Symposium** ed. C.E. Fichtel, N. Gehrels, and J.P. Norris, AIP Conf. Proc. **304**, 1994 (which also has a bit more of the history), and the **Third Compton Symposium**, to appear in 1995 also in the AIP series.

Neutrino astronomy: The history and accomplishments up to 1988 are elegantly described by J.N. Bahcall in his **Neutrino Astrophysics**, Cambridge Univ. Press, 1989. Additional 1987A results and future detector plans appear in several volumes of proceedings of **Texas Symposia on Relativistic Astrophysics** (Annals of the NY Academy of Sciences), especially the 14th, ed. E.J. Fenyves. And for the latest word on solar neutrinos, see John Bahcall's fine article in the Fall/Winter 1994 *Beam Line,* Vol. 24, No. 3.

Gravitational radiation detection: Not even a short history that would be regarded as correct by all participants has yet been written, including this one.

CONTRIBUTORS



PHILIP MORRISON received his PhD in theoretical physics from the University of California, Berkeley, where his thesis supervisor was J. Robert Oppenheimer. He has served on the faculties of San Francisco State University, the University of Illinois, Cornell University, and MIT, where he is now Institute Professor (emeritus). During WWII he spent four years with the Manhattan Project, working first with Enrico Fermi at Chicago and then at Los Alamos with O. R. Frisch. He has written and spoken widely ever since against nuclear war and its preparations (see "Recollections of a Nuclear War," *Scientific American*, August 1995, p. 42). His current research interests are in active galaxies and cosmology.

Having published widely in aid of the broad public understanding of science and science education, Morrison's most recent books are *Powers of Ten*, written in conjunction with Phyllis Morrison, and *Nothing Is Too Wonderful to Be True.*

ALEXI ASSMUS is a lecturer in the Department of History at Princeton University. She received her PhD in the history of science from Harvard University as well as a master's degree in physics. She was an NSF postdoctoral fellow at the University of California at Berkeley, where she taught the history of 19th and 20th century physics and its associated technologies. She has written about U.S. physics between the two world wars. Her current work is on physicists during the Cold War.

OTHA W. LINTON is the Associate Executive Director of the American College of Radiology and the Executive Director of Radiology Centennial, Inc. He holds a Bachelor of Journalism degree from the University of Missouri and a Master of Science in Journalism from the University of Wisconsin. His work has been widely published, and he is a regular contributor to several journals, including *The American Journal of Roentgenology*, *Radiology*, and the *Journal de Radiologie* in Paris, France. He joined the American College of Radiology in 1961 and has served a key role in its growth.

As Executive Director of Radiology Centennial, Inc., a not-for-profit organization created by some 54 national radiation science societies and 76 companies which supply goods and services for radiology, he has coordinated efforts to commemorate the 100th anniversary of the discovery of the X ray and to celebrate a century of achievement in radiation science.

ARTHUR BIENENSTOCK received his BS and MS from the Polytechnic Institute of Brooklyn and his PhD from Harvard University. In 1963 he joined the faculty of the Division of Engineering and Applied Physics at Harvard as an assistant professor. He remained at Harvard until 1967, when he became a member of the faculty of Stanford University, where he holds a joint appointment as Professor in the departments of Materials Science and Applied Physics. In 1978 he became Director of the Stanford Synchrotron Radiation Laboratory.

Bienestock is a member of the American Crystallographic Association and the Materials Research Society, as well as a Fellow of the American Physical Society and the American Association for the Advancement of Science.

CONTRIBUTORS

A native of the San Francisco Bay Area, ARTHUR ROBINSON studied materials science at Stanford University as both an undergraduate and graduate student from 1959–1968. Following a tour with the U.S. Air Force at Wright-Patterson Air Force Base in Dayton, Ohio, he moved to Washington, DC in 1973 to become a reporter for *Science* magazine, where he covered developments in physical science and technology, including the rapidly expanding field of synchrotron radiation. Since 1987, Robinson has been a staff scientist with Lawrence Berkeley Laboratory's Advanced Light Source, where he has been able to continue a career combining writing and science.

WALLACE H. TUCKER has been involved in research in X-ray astronomy since 1965. His current research is concentrated on the X-ray emission from clusters of galaxies and the nature of dark matter. He is the co-author with Riccardo Giacconi of *The X-ray Universe* (Harvard University Press), and he and his wife, Karen Tucker, have written two popular books on modern astronomy: *The Cosmic Inquirers* (Harvard University Press) and *The Dark Matter* (William Morrow). He divides his time between the Harvard-Smithsonian Center for Astrophysics and the University of California, San Diego.

Regular readers of *Beam Line* need no introduction to VIRGINIA TRIMBLE, and probably don't want one. She first met astrophysical neutrinos as co-hostess of the first conference devoted to the solar neutrino problem at UC Irvine in January 1972 and as junior editor (with Fred Reines) of its proceedings. She met Joe Weber the same month, and they have been married for the last 23 years. The above picture was taken the year that Kraushaar and Clark counted their 22 residual gammas and Davis began thinking about a site for a large solar neutrino detector.

DATES TO REMEMBER

Oct 3–7 7th International Conference on the Structure of Baryons, Santa Fe, NM (Leonora Alsbrook, Baryons '95 Conference Coordinator, LANL, Protocol Office, MS P366, Los Alamos, NM 87545 or BARYONS@LAMPF.LANL.GOV).

Oct 11 Techniques in Macromolecular Crystallography: Cryocooling and Data Reduction/Analysis, Stanford, CA (Katherine Cantwell, SSRL, MS 69, Box 4349, Stanford, CA 94309-0210 or K@SLAC.STANFORD.EDU).

Oct 12–13 SSRL 22nd Annual Users Meeting (Katherine Cantwell, SSRL, MS 69, Box 4349, Stanford, CA 94309-0210 or K@SLAC.STANFORD.EDU).

Oct 15–20 Workshop on Beam Dynamics and Technology Issue for $\mu^+ \mu^-$ Colliders (MUMU '95), Montauk, NY (TUOHY@BNLCL1.BNL.GOV).

Oct 15–21 International Workshop on Single Particle Effects in Large Hadron Colliders, Montreaux, Switzerland (LHC95@CERNVM.CERN.CH).

Oct 16–20 National Synchrotron Radiation Instrumentation Meeting (SRI '95) (to be followed by the 7th Annual Users' Meeting for the Advanced Photon Source, 18–20 Oct., 1995), Argonne, IL (Linda Carlson, Advanced Photon Source, Argonne National Laboratory, Bldg. 431E, 9700 South Cass Ave., Argonne, IL 60439-4815).

Oct 17–20 7th Workshop on RF Superconductivity, Gif-sur-Yvette, France (B. Bonin, Centre d'etudes de Saclay, DAPNIA/SEA, BP 701, f-91 191 Gif-sur-Yvette Cedex, France or SRF@HEP.SACLAY.CEA.FR).

Oct 21–28 Nuclear Science Symposium (NSS) and Medical Imaging Conference (MIC), San Francisco, CA (Lynette Willard, Symposium Coordinator, PO Box 808, MS L-469, Livermore, CA 94550 or WILLARD2@LLNL.GOV).

Oct 23–26 Conference on Fundamental Interactions of Elementary Particles, Moscow, Russia (Organizing Committee, B. Cheremushkinskaya ul 25, ITEP, RU-117259, Moscow, Russia or AKSENOVA@VXITEP.ITEP.RU).

Oct 23–27 Institute for Theoretical Physics Conference on Unification: From the Weak Scale to the Planck Scale, Santa Barbara, CA (Prof. James S. Langer, Directory, Institute for Theoretical Physics, University of California, Santa Barbara, CA 93106-4030).

Oct 25–27 4th International Conference on Synchrotron Radiation Sources and 2nd Asian Forum on Synchrotron Radiation, Kyongju, Korea (Dr. Chinwha Chung, Secretary/Organizing Committee, PAL/POSTECH, Pohang, Korea 790-784 or CWCHUNG@VISION.POSTECH.AC.KR).

DATES TO REMEMBER

Oct 30–Nov 11	International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS '95), Chicago, IL (Peter Lucas, Chairman, ICALEPCS '95 Conference, Fermilab, MS 307, PO Box 500, Batavia, IL 60510 or LUCAS@ALMOND.FNAL.GOV).
Oct 30–Dec 1	ICTP School on Synchrotron Radiation in Science and Technology, Trieste, Italy (L. Fonda, ICTP School on Synchrotron..., PO Box 586, I-34100, Trieste, Italy or SMR877@ICTP.TRIESTE.IT).
Nov 6–9	40th Conference on Magnetism and Magnetic Materials (INTERMAG 40), Philadelphia, PA (Courtesy Associates, 655 15th Street NW, Suite 300, Washington, DC 20005).
Dec 3–8	Supercomputing '95 (SC '95), San Diego, CA (Supercomputing '95, San Diego Supercomputer Center, 10100 Hopkins Drive, La Jolla, CA 92093-0505 or SC95@SDSC.EDU).
Dec 13–16	3rd International Conference on Physics Potential and Development of $\mu^+\mu^-$ Colliders, San Francisco, CA (Melinda Laraneta, UCLA, Physics Department, 405 Hilgard Avenue, Los Angeles, CA 90024 or LARENTA@PHYSIC.UCLA.EDU).
Jan 15–26	US Particle Accelerator School, San Diego, CA (US Particle Accelerator School, c/o Fermilab, MS 125, PO Box 500, Batavia, IL 60510 or USPAS@FNALV.FNAL.GOV).

Watch for these Articles in Future Issues of Beam Line

IN WATER OR ICE? HIGH-ENERGY NEUTRINO ASTRONOMY
John Learned and Michael Riordan

THE DISCOVERY OF THE TOP QUARK
Paul Grannis and Bill Carithers

SUPERCONDUCTORS AND SUPERCOLLIDERS
Lance Dixon

LASER ELECTRON INTERACTIONS
Adrian Melissinos

SPIN PHYSICS
Emlyn Hughes

RARE K DECAYS
Jack Ritchie