GRAPHICAL REPRESENTATION OF THE THEORY AND PRACTICE OF X RAYS

Charles T. Knipp, University of Illinois

Practically the whole development of electrical science has taken place within the lifetime of many of us. True, the fundamental discoveries of Faraday in England, and Joseph Henry in America were before our time; they were advance signals, as it were, of what was soon to follow. Even in the seventies little or nothing was known of what we today consider the absolute necessities of life —the telegraph, the telephone, the electric light. The dynamo was an uncertain machine, and induction as used in our present lighting systems was undreamed of. Nevertheless, the scientific spirit was among physicists and chemists, and enthusiasm ran high with the result that the world was about to enter upon a new era of practical achievements based upon scientific investigation. Maxwell in England and Helmholtz in Germany were leaders in pure science, and we may consider Edison and Graham Bell in America as the leaders in making practical applications. Maxwell in the seventies, by intuitive and unparalleled mathematical reasoning, arrived at the now famous "Maxwellian equations" in which he enunciated that light waves are a manifestation of a universal, and almost unlimited in extent, phenomena ranging in wave length from, say, one hundred thousandths of a centimeter up to many kilometers, and what we call visible light consists simply of a small portion, about one octave, of this gamut of wave lengths. This was indeed a startling enunciation and required experimental proof before it was even universally adopted among physicists and mathematicians. It came at the time, or rather, shortly before the dynamo was invented, the telegraph was perfected, and the transmission of speech over wires to distant points was being utilized practically. Nor was the experimental proof that light waves are electromagnetic waves long in coming. Heinrich Hertz, a brilliant young German physicist, was the first to show experimentally that electrical energy could be transmitted to a distant point without the intervention of wires. His experiments, made in the middle eighties, formed the inception of our modern radio, though it was not until about ten or fifteen years later that wireless telegraphy assumed commercial proportions in the hands of Lodge, Marconi, Fleming, and others.

Electrical science made rapid strides following the experiments of Hertz. The direct current dynamo was perfected, the telephone was no longer a toy, and the underlying principles of alternating current generators and the transmission of power was being worked out. Greater advance was recorded along electrical lines during the twenty years prior to 1895 than had been made in two hundred years previous to 1875. All centers of learning were imbued with the desire to do research; yet the feeling arose generally among physicists the world over in the early nineties, and became more insistent, that practically all of the great discoveries had been made, that little more could be expected than greater refinement in making measurements; in short, all that the scientific world could expect to do was to polish off the fourth and fifth decimal places. This pessimistic outlook upon the future of science has been completely shattered by the brilliant sequence of discoveries that have been made since 1895. The discoveries of the last thirty years are unprecedented in the world's history. Nor are we at the end in this the year 1925. Not again will it be said that the great discoveries have all been made, not so long as the lure of scientific discovery and invention is uppermost in the minds of the earnest horde that make up the research fraternity of the present age.

Let us enumerate briefly some of the really great discoveries of the last thirty years. On the year following the period of scientific depression, referred to above, was made one of the greatest discoveries of them all, the discovery of X rays by Professor Roentgen of Berlin. Then came the brilliant work of J. J. Thomson and his associates on the discharge of electricity through gases, in which the "electron", now almost a household term, was isolated and its properties determined, followed in 1909 and 1910 by the first of that striking and important series of experiments on positive rays which at the present time, in modified form in the hands of Aston of Cambridge, England, and Dempster, of America, is yielding results which in no small degree are furnishing inside information on that perplexing problem of the ultimate structure of matter. Another discovery of the greatest importance was that of radio-activity by Becqueral of Paris.

As usual, the scientific staff at the Cavendish Laboratory, Cambridge, England, took up the cue and Ernest Rutherford, a native of Australia, made astonishing discoveries as to the properties of the radio-activity emitted from radio-active material. A contributor in this line of research second only to Rutherford is Mme. Curie of Paris. The discovery of radio-activity gave to science a powerful tool in the further study of the ultimate structure of matter. Radium, for instance, emits three types of radiation known as alpha, beta, and gamma rays (so named by Rutherford). The alpha rays are electrically charged atoms,—atoms of helium. They are thrown off continuously from, say, radium, and in spite of their minuteness (it would take about 500,000,000 alpha particles placed side by side to make one centimeter) it is possible to make the effect of a single alpha particle visible. In the hands of Rutherford this effect revealed itself as a flash of light when an alpha particle struck a willemite screen. Shortly after this C. T. R. Wilson, by the aid of his cloud experiments, was able to show the presence of the alpha particle by a line of condensation of water vapor left in the wake of its path. These alpha-ray tracks, as they are now called, may be, under favorable conditions, three or four centimeters long and can be produced by exceedingly simple apparatus. The discoveries arising out of the discovery of the electron by Thomson and of X-rays by Roentgen formed the starting point of manifold industrial developments. The modern triode vacuum tube and the unbounded success of radio of today resulted from Thomson's work of a quarter of a century ago. "We come nearer knowing what electricity really is from the study of the discharge of electricity through gases than from the flow of electricity through metals or through electrolytes." The discovery of X-rays in 1895 took the world by storm. Every physics laboratory having Crookes vacuum tubes in its possession at once tested these for X-rays. Nor were their efforts disappointing, for many of them made 10 or 15 years before were found on testing to give X-rays. Marked enthusiasm in X-ray research followed. Many workers were attracted by the practical aspects, and we have at the present day X-ray outfits for every possible need,—the surgeon, the dentist, the shop merchant, the manufacturer in the testing of materials, and the bacteriologist as well. Others, possibly with no thought of the utilitarian, sought, for the pure joy of discovery, to use the X-ray as a possible means of attack in the solution of that ever fundamental problem of the ultimate structure of matter. They are being rewarded. We now know definitely what X-rays really consist of.

They might more appropriately be called Roentgen rays in honor of their discoverer, though it seems that the term X-rays even yet stands in better favor.

Earlier in their history physicists were perplexed by not being able to reflect, diffract, refract, and polarize X-rays in the same manner that light rays are reflected, etc. Many attempts were made without success, when about fifteen years ago Professor Laue of Munich, Germany, made the brilliant prediction after an involved mathematical analysis of the subject that X-rays, if they are a wave phenomenon, should be reflected, refracted, and indeed diffracted by a crystalline substance where, as crystallographers tell us, the molecules of the crystals are in definite layers and therefore the interfaces should be smooth, infinitely smoother than the fines polished glass surface, and the X-rays falling on these surfaces should be regularly reflected. This was at once put to test and confirmed. The scientific world, as if by magic, turned to this new discovery of Laue. Theories of X-rays irrelevant to this were dropped. The Braggs in England, and Hull in America led the way, and now investigations based upon the wave theory of X-rays are in progress in almost every research laboratory of note. It is as common to speak of X-ray spectra now as it was of light a few years ago. By means of these spectra new substances are being discovered, and the relationship to the order of an element in the periodic table—Moseley's law—was established.

The theory of Laue so beautifully confirmed by experiment suggests at once the extreme shortness of the wave length of X-rays. The highest polished glass surface is as a surface of shot in comparison to the wave lengths falling upon it in the form of X-rays. It is for this reason that the reflection and refraction of X-rays so long eluded the most painstaking research. It is also because of the extreme shortness of the wave length that X-rays are so penetrating.

It is interesting in this connection to study the wide range of electromagnetic waves. Fig. 1 is a graphical representation.[1] The entire gamut is shown, from the longest Hertzian waves to the shortest gamma waves—a range of over 48 octaves. This graph reveals many interesting features. For instance, that portion of Hertzian waves that is used in wireless and radio covers a range of but 4 or 5 octaves, while the Hertzian waves of all lengths occupy about 23 octaves. Heat waves occupy 8.5 octaves, and the visible light spectrum but one. It should be noticed that between the Hertzian waves and the heat waves is a region of 3 octaves that has as yet not been explored. This is because the wave lengths are too short to be measured by wireless apparatus and too long to be measured by the present designed methods for measuring heat wave radiations. Beyond the visible spectrum comes the ultra violet region of one octave, and a region beyond which until recently was unexplored,—but now is known to be the upper limit of the X-ray region. In other words, it is definitely known that X-ray waves now begin in the ultra violet region and extend to the end of the graph—the gamma rays shown (one octave) are the short X-rays emitted by radio-active material. It is of interest to note the relative position that the seven octaves of the ordinary piano occupy on this scale of wavelengths. Of course sound waves are not electromagne ic waves as is explained in a footnote on the graph.

In Table I are tabulated some of the data listed in Fig. 1. In column two the wave lengths are expressed in centimeters, while in column three these same lengths

[1] Graph prepared by Professor F. R. Watson, Department of Physics, University of Illinois.

are expressed exponentially. It should be noted that the gamma rays and X-rays overlap; however, in the remaining rays the limits are distinct.

TABLE I.

Wave Lengths of Electromagnetic Radiations

Kind of wave	Wave length in cms.	Wave length in cms. Expressed exponentially
Hertzian waves........	2,000,000.0 to .2	2.0×10^{6} to .2
Unexplored	.2 to .031	.2 to .031
Infra red rays........	.031 to .000072	.031 to 7.2×10^{-5}
Visible light...........	.000072 to .00004	7.2×10^{-5} to 4.0×10^{-6}
Ultra violet rays......	.00004 to .000002	4.0×10^{-5} to 2.0×10^{-6}
X-rays	.000002 to .0000000006	2.0×10^{-6} to 6.0×10^{-10}
Gamma rays	.000000014 .0000000001	1.4×10^{-8} to 1.0×10^{-10}

NOTE.—The range covered from the longest Hertzian waves to the shortest gamma rays is about ten thousand million million fold! And the only break in this sequence is a small gap between the Hertzian waves and infra-red rays that have not as yet been explored.

Lastly, we have in Fig. 2 a graphical representation of the present status of X-rays. This graph does not claim to be complete; however, it is suggestive. Some of the more important properties of X-rays are set down, and the uses to which X-rays are put is included under two heads:—first, practical applications, and second, the study of the ultimate structure of matter. It is common observation that the most abstract investigation of today may result in the greatest practical importance to-morrow. An interesting phase under practical applications is "X-rays and industry". This is divided into two parts which may be styled X-ray crystallography and industrial radiography. Since the study of X-rays by means of crystals, introduced by Laue and the Braggs, a new field in the practical application of X-rays has been opened. We can now study the physical properties of

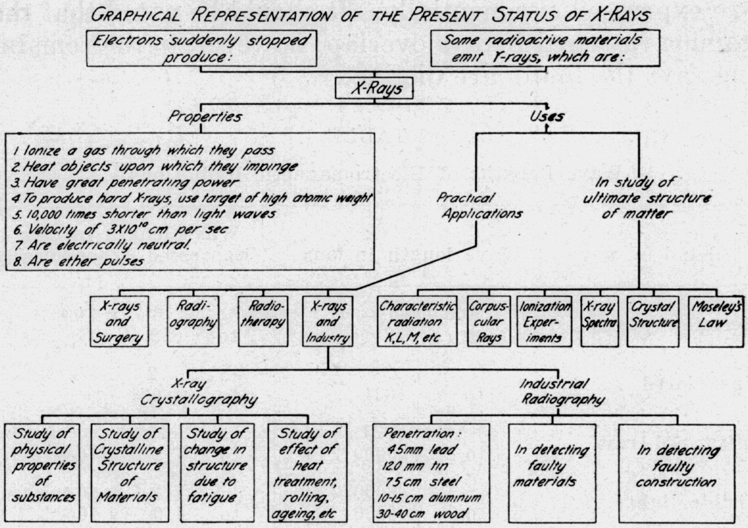

FIG. II.

substances, their crystalline structure, the change in structure due to fatigue, due to heat treatment, rolling, ageing, etc. Again, since the introduction of the Coolidge X-ray tube, industrial radiography has moved forward to an enviable position. The penetration that is now obtainable is nothing short of marvelous. With present day outfits X-rays become a menace to people across the street. Brick walls are readily penetrated, and photographic plates a block away (if in direct line of the radiation) may be fogged. With greater penetration came lesser time of exposure. Ordinary X-ray exposures require now but a fraction of a second.

The graph, while not complete, shows in a most striking way the wonderful scope the X-ray has assumed. In many lines the work has only been well begun. The practical applications seem to be without limit, and the theoretical and experimental studies with X-rays as a tool bid fair to soon solve that outstanding problem, what is the ultimate structure of matter?

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University of Illinois
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