Epilogue

The discovery of the X-rays in 1895 was "in the air". Wilhelm Conrad Röntgen was the one who had the knowledge and skills to observe and find the new rays. He is regarded as the founder or father of radiology, when he made the basic X-ray picture of the hand of his wife. In medicine a new era started, and Röntgen is appreciated more in medicine than in any other fields. Hitherto hidden parts of the body could be examined by the rapid development of X-ray technology. In the past 125 years, radiology evolved by using new kind of energies as there are ultrasound and magnetic resonance. Nowadays, by applying computer technology, the radiologist has acquired a central place in medical practice. In a poll organised by the British Science Museum in 2009, the British public voted for the X-rays as being the most important modern discovery prior to Penicillin and the DNA double helix.

The years 1895, the year of Röntgen's discovery, up to 1915 are called the "heroic phase" of physics. This term is coined by John D. Bernal (1901–1971), the Irish scientist and writer of history of science. Indeed, the technical and physical knowledge, which lead to the discovery of the X-rays, developed in the nineteenth century. The discovery of the X-rays paved the way for the future physics, represented by the Curies, Ernest Rutherford, Max Planck, Albert Einstein, Max von Laue, and Niels Bohr.

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Annex 1. On a New Kind of Rays

Preliminary Communication[1]

1. A *discharge* from a large induction coil is passed through a Hittorf's vacuum tube or through a well-exhausted Crookes' or Lenard's tube. The tube is surrounded by a fairly close-fitting shield of black paper; it is then possible to see, in a completely darkened room, that paper covered on one side with barium platinocyanide lights up with brilliant fluorescence when brought into the neighbourhood of the tube, whether the painted side or the other is turned towards the tube. The fluorescence is still visible at 2 meters distance. It is easy to show that the origin of the fluorescence lies within the vacuum tube.
2. It is seen, therefore, that some agent is capable of penetrating black cardboard which is quite opaque to ultraviolet light, sunlight, or arc light. It is therefore of interest to investigate how far other bodies can be penetrated by the same agent. It is readily shown that all bodies possess this same transparency but in very varying degrees. For example, paper is very transparent; the fluorescent screen will light up when placed behind a book of a thousand pages; and printer's ink offers no marked resistance. Similarly, the fluorescence shows behind two packs of cards; a single card does not visibly diminish the brilliancy of the light. So, again, a single thickness of tinfoil hardly casts a shadow on the screen; several have to be superposed to produce a marked effect. Thick blocks of wood are still transparent. Boards of pine 2 or 3 centimeters thick absorb only very little. A piece of sheet aluminum, 15 mm. thick, still allowed the X-rays (as I will call the rays, for the sake of brevity) to pass but greatly reduced the fluorescence. Glass plates of similar thickness behave similarly; lead glass is, however, much more opaque than glass free from lead. Ebonite several centimetres thick is transparent. If the hand be held before the fluorescent screen, the shadow shows the bones darkly, with only faint outlines of the surrounding tissues.

   Water and several other fluids are very transparent. Hydrogen is not markedly more permeable than air. Plates of copper, silver, lead, gold, and platinum

[1] Published in: Science 14 February 1896:227–31. From the translation in Nature by Arthur Stanton from the "Sitzungsberichte der Würzburger Physik.-medic. Gesellschaft", 1895.

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also allow the rays to pass, but only when the metal is thin. Platinum 0.2 mm. thick allows some rays to pass; silver and copper are more transparent. Lead 1.5 mm. thick is practically opaque. If a square rod of wood 20 mm. in the side be painted on one face with white lead, it casts little shadow when it is so turned that the painted face is parallel to the X-rays but a strong shadow if the rays have to pass through the painted side. The salts of the metal, either solid or in solution, behave generally as the metals themselves.

3. The preceding experiments lead to the conclusion that the density of the bodies is the property whose variation mainly affects their permeability. At least no other property seems so marked in this connection. But that the density alone does not determine the transparency is shown by an experiment wherein plates of similar thickness of Iceland spar, glass, aluminum, and quartz were employed as screens. Then the Iceland spar showed itself much less transparent than the other bodies, though of approximately the same density. I have not remarked any strong fluorescence of Iceland spar compared with glass (see below, No. 4).
4. Increasing thickness increases the hindrance offered to the rays by all bodies. A picture has been impressed on a photographic plate of a number of superposed layers of tinfoil, like steps, presenting thus a regularly increasing thickness. This is to be submitted to photometric processes when a suitable instrument is available.
5. Pieces of platinum, lead, zinc, and aluminum foil were so arranged to produce the same weakening of the effect. The annexed table shows the relative thickness and density of the equivalent sheets of metal.

	Thickness	Relative thickness	Density
Platinum	·018 mm	1	21.5
Lead	·050″	3	11.3
Zinc	·100″	6	7.1
Aluminum	3.500″	200	2.6

From these values it is clear that in no case can we obtain the transparency of a body from the product of its density and thickness. The transparency increases much more rapidly than the product decreases.

6. The fluorescence of barium platinocyanide is not the only noticeable action of the X-rays. It is to be observed that other bodies exhibit fluorescence, e.g. calcium sulphide, uranium glass, Iceland spar, rock salt, & c.

   Of special interest in this connection is the fact that photographic dry plates are sensitive to the X-rays. It is thus possible to exhibit the phenomena so as to exclude the danger of error. I have thus confirmed many observations originally made by eye observation with the fluorescent screen. Here the power of the X-rays to pass through wood or cardboard becomes useful. The photographic plate can be exposed to the action without removal of the shutter of the dark slide or other protecting case, so that the experiment need not be conducted in darkness. Manifestly, unexposed plates must not be left in their box near the vacuum tube.

It seems now questionable whether the impression on the plate is a direct effect of the X-rays or a secondary result induced by the fluorescence of the material of the plate. Films can receive the impression as well as ordinary dry plates.

I have not been able to show experimentally that the X-rays give rise to any calorific effects. These, however, may be assumed, for the phenomena of fluorescence show that the X-rays are capable of transformation. It is also certain that all the X-rays falling on a body do not leave it as such.

The retina of the eye is quite insensitive to these rays; the eye placed close to the apparatus sees nothing. It is clear from the experiments that this is not due to want of permeability on the part of the structures of the eye.

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 aluminum, 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 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 a body more transparent than its walls exhibits the middle brighter than the edge.

8. The preceding experiments, and others which I pass over, point to the rays being incapable of regular reflection. It is, however, well to detail an observation which at first sight seemed to lead to an opposite conclusion.

   I exposed a plate, protected by a black paper sheath, to the X-rays, so that the glass side lay next to the vacuum tube. The sensitive film was partly covered with star-shaped pieces of platinum, lead, zinc, and aluminum. On the developed negative, the star-shaped impression showed dark under platinum, lead and, more markedly, under zinc; the aluminum gave no image. It seems, therefore, that these three metals can reflect the X-rays; as, however, another explanation is possible, I repeated the experiment with this only difference that a film of thin aluminum foil was interposed between the sensitive film and the metal stars. Such an aluminum plate is opaque to ultraviolet rays but transparent to X-rays. In the result the images appeared as before, this pointing still to the existence of reflection at metal surfaces.

If one considers this observation in connection with others, namely, on the transparency of powders and on the state of the surface not being effective in altering the passage of the X-rays through a body, it leads to the probable conclusion that regular reflection does not exist but that bodies behave to the X-rays as turbid media to light.

Since I have obtained no evidence of refraction at the surface of different media, it seems probable that the X-rays move with the same velocity in all bodies and in a medium which penetrates everything and in which the molecules of bodies are embedded. The molecules obstruct the X-rays more effectively as the density of the body concerned is greater.

9. It seemed possible that the geometrical arrangement of the molecules might affect the action of a body upon the X-rays, so that, for example, Iceland spar might exhibit different phenomena according to the relation of the surface of the plate to the axis of the crystal. Experiments with quartz and Iceland spar on this point lead to a negative result.

10. It is known that Lenard in his investigations on cathode rays has shown that they belong to the ether and can pass through all bodies. Concerning the X-rays the same may be said.

In his latest work, Lenard has investigated the absorption coefficients of various bodies for the cathode rays, including air at atmospheric pressure, which gives 4.10, 3.40, and 3.10 for 1 cm, according to the degree of exhaustion of the gas in discharge tube. To judge from nature of the discharge, I have worked at about the same pressure but occasionally at greater or smaller pressures. I find using a Weber's photometer that the intensity of the fluorescent light varies nearly as the inverse square of the distance between screen and discharge tube. This result is obtained from three very consistent sets of observations at distances of 100 and 200 mm; hence air absorbs the X-rays much less than the cathode rays. This result is in complete agreement with the previously described result that the fluorescence of the screen can be still observed at 2 meters from the vacuum tube. In general other bodies behave like air; they are more transparent for the X-rays than for the cathode rays.

11. A further distinction, and a noteworthy one, results from the action of a magnet. I have not succeeded in observing any deviation of the X-rays even in very strong magnetic fields.

The deviation of cathode rays by the magnet is one of their peculiar characteristics; it has been observed by Hertz and Lenard that several kinds of cathode rays exist, which differ by their power of exciting phosphorescence, their susceptibility of absorption and their deviation by the magnet; but a notable deviation has been observed in all cases which have yet been investigated, and I think that such deviation affords a characteristic not to be set aside lightly.

12. As the result of many researches, it appears that the place of most brilliant phosphorescence of the walls of the discharge tube is the chief seat; whence the X-rays originate and spread in all directions; that is, the X-rays proceed from the front where cathode rays strike the glass. If one deviates the cathode rays within the tube by means of a magnet, it is seen that the X-rays proceed from a new point, i.e. again from the end of the cathode rays.

    Also for this reason the X-rays which are not deflected by a magnet cannot be regarded as cathode rays which have passed through the glass, for that passage cannot, according to Lenard, be the cause of the different deflection of the X-rays. Hence, I concluded that the rays are not identical with the cathode rays but are produced from the cathode rays at the glass surface of the tube.

13. The rays are generated not only in glass. I have obtained them in an apparatus closed by an aluminum plate 2 mm thick. I propose later to investigate the behavior of other substances.

14. The justification of the term "rays," applied to the phenomena, lies partly in the regular shadow pictures produced by the interposition of a more or less permeable body between the source and a photographic plate or fluorescent screen.

    I have observed and photographed many such shadow pictures. Thus, I have an outline of part of a door covered with lead paint; the image was produced by placing the discharge tube on one side of the door and the sensitive plate on the other. I have also a shadow of the bones of the hand [...], of a wire wound upon a bobbin, of a set of weights in a box of a compass card and needle completely enclosed in a metal case, of a piece of metal where the X-rays show the want of homogeneity, and of other things.

    For the rectilinear propagation of the rays, I have a pinhole photograph of the discharge apparatus covered with black paper. It is faint but unmistakable.

15. I have sought for interference effects of the X-rays, but possibly, in consequence of their small intensity, without result.

16. Researches to investigate whether electrostatic forces act on the X-rays are begun, but not yet concluded.

17. If one asks, what then are these X-rays, since they are not cathode rays, one might suppose, from their power of exciting fluorescence and chemical action, them to be due to ultraviolet light. In opposition to this view, a weighty set of considerations presents itself. If X-rays be indeed ultraviolet light, then that light must possess the following properties.

    (a) It is not refracted in passing from air into water, carbon bisulphide, aluminum, rock salt, glass, or zinc.
    (b) It is incapable of regular reflection at the surfaces of the above bodies.
    (c) It cannot be polarized by any ordinary polarizing media.
    (d) The absorption by various bodies must depend chiefly on their density.

That is to say, these ultraviolet rays must behave quite differently from the visible, infrared, and hitherto known ultraviolet rays.

These things appear so unlikely that I have sought for another hypothesis.

A kind of relationship between the new rays and light rays appears to exist; at least the formation of shadows, fluorescence, and the production of chemical action point in this direction. Now it has been known for a long time that, besides the transverse vibrations which account for the phenomena of light, it is possible that longitudinal vibrations should exist in the ether and according to the view of some physicists must exist. It is granted that their existence has not yet been made clear, and their properties are not experimentally demonstrated. Should not the new rays be ascribed to longitudinal waves in the ether?

I must confess that I have in the course of this research made myself more and more familiar with this thought and venture to put the opinion forward, while I am quite conscious that the hypothesis advanced still requires a more solid foundation.

Continuation[2]

9 March, 1896

Since my work must be interrupted for several weeks, I wish to present at this time some new phenomena which I have observed:

18. At the time of my first publication, I knew the X rays are able to discharge electrified bodies, and I suspect that in Lenard's experiments it was also the X rays and not the cathode rays, which transmitted unchanged by the aluminum window of his apparatus, that produced the effects described by him upon electrified bodies at a distance. However, I have waited until I could present incontestable results before publishing my experiments.

    These can be obtained only if the observations are made in a space that is not only protected completely from the electrostatic forces emanating from the vacuum tube, from the conducting wires, from the induction apparatus, and so on, but it is also closed against air which comes from the region of the discharge apparatus.

    Accordingly, I had a chamber built of zinc plates soldered together, which is large enough to accommodate me and the necessary apparatus and which is completely airtight except for an opening which could be closed by a zinc door. The wall opposite the door is to a large extent covered with lead. At a place near the discharge apparatus, which is set up outside the case, an opening 4 centimeters wide is cut out of the zinc wall and its lead cover, and this opening is made airtight with a thin sheet of aluminum. Through this window, the X rays can enter the observation space.

    Now I observed the following phenomena:

    (a) Positively or negatively electrified bodies set up in air are discharged if they are irradiated with X rays. The more intense the rays are, the more rapid is

[2]Translated from: Ueber eine neue Art von Strahlen. II.Mittheilung. Würzburg 1897. In: Sitzungsberichte der Physik.-med. Gesellschaft zu Würzburg.1896:11–6. By W. Robert Nitske, The life of Wilhelm Conrad Röntgen. Discoverer of the X Ray, 318–21.

the discharge. The intensity of the rays was estimated by their effect upon the fluorescent screen or upon a photographic plate.

Generally, it is immaterial whether the electrified bodies are conductors or insulators. So far I have not been able to find a specific difference in behavior of different bodies with regard to the rate of discharge nor in the behavior of positive and negative electricity. Yet, it is not impossible that small differences may exist.

(b) If an electrified conductor is not surrounded by air but by a solid insulator, e.g. paraffin, the irradiation has the same effect as moving a grounded flame over the insulating cover.

(c) If this insulating cover is surrounded by a tight-fitting grounded conductor, which like the insulator must be transparent to X rays, the radiation exerts upon the inner electrified conductor no effect detectable with the available apparatus.

(d) The observations cited under (a), (b), and (c) indicate that air which is irradiated with X rays has acquired the property of discharging electrified bodies with which it comes in contact.

(e) If this is really the case and, in addition, if the air retains this property for some time after being exposed to X rays, it must be possible to discharge electrified bodies that themselves are not directly irradiated by X rays simply by conducting irradiated air to them.

One can be convinced of the validity of this conclusion in different ways. I should like to describe one experimental method, although it is perhaps not the simplest one.

I used a brass tube 3 centimeters wide and 45 centimeters long. A few centimetres from one end of the tube part of its wall was cut away and replaced with a thin sheet of aluminum. Through the other end a brass sphere, fastened to a metal rod and insulated, was sealed airtight into the tube. Between the sphere and the closed end of the tube, there was soldered a little side tube, which could be connected to an exhaust apparatus. When suction was applied, air that passed the aluminum window on its way through the tube flowed around the brass sphere. The distance from window to sphere was over 20 centimeters.

I arranged this tube inside the zinc chamber so that the X rays could enter through the aluminum window of the tube perpendicularly to its axis. The insulated sphere lay in the shadow beyond the range of these rays. The tube and zinc case were connected to each other, and the sphere was connected to a Hankel electroscope.

It was then observed that a charge, either positive or negative, given to the sphere was not influenced by the X rays as long as the air remained at rest in the tube but that the charge instantly decreased considerably if irradiated air was drawn past the sphere by strong suction. When a constant potential from a storage battery was applied to the sphere, and when irradiated air was continuously drawn through the tube, an electric current was produced just as if the sphere had been connected to the tube wall by a poor conductor.

(f) The question arises in what manner the air can lose the property given to it by the X rays. It is still unsettled whether in time it loses the property itself, that is, without coming in contact with other bodies.

However, it is certain that a brief contact with a body that has a large surface, and is not necessarily electrified, may render the air ineffective. If, for example, one placed a sufficiently large stopper of cotton wadding so far into the tube that irradiated air must pass through the cotton before it reaches the electrified sphere, the charge of the sphere remains unchanged, even while suction is applied.

If the stopper is placed in front of the aluminum window, one obtains the same results as without the cotton, proof that dust particles cannot possibly be the cause of the discharge observed.

Wire screens have an action similar to cotton; however, the screen must be very fine, and many layers must be placed on each other if the irradiated air passing through them is to be made ineffective. If these screens are not grounded, as has been assumed so far, but are connected to a source of electricity of a constant potential, the observations have always been what I expected. However, these experiments have not yet been completed.

(g) If the electrified bodies are placed in dry hydrogen instead of air, they are also discharged by the X rays. It seemed to me that the discharge in hydrogen proceeded somewhat slower; however, this is still uncertain because of the difficulties of obtaining equal intensities of the X rays in a series of consecutive experiments.

The method of filling the apparatus with hydrogen precludes the possibility that the layer of air originally present on the surface of the bodies could play an important role in the discharge.

(h) In highly evacuated spaces, the discharge of a body struck directly by the X rays proceeds much more slowly—in one case about seventy times more slowly—than in the same vessels when they are filled with air or hydrogen at atmospheric pressure.

(i) Experiments have been started on the behavior of a mixture of chlorine and hydrogen under the influence of X rays.

(j) Finally, I should like to mention that one must often accept with great caution the results of experiments on the discharging effects of X rays in which the influence of the surrounding gas has not been considered.

19. In many cases it is advantageous to insert a Tesla apparatus (condenser and transformer) between the discharge apparatus which furnishes the X rays and the Ruhmkorff induction coil. This arrangement has the following advantages: firstly, the discharge tubes are less liable to be punctures and heat up less; secondly, the vacuum, at least so far as my self-constructed apparatus is concerned, keeps for a longer time; and thirdly, many discharge tubes produce more intense rays under these conditions. Some tubes that were evacuated too little or too much to work satisfactorily on the Ruhmkorff coil alone, functioned satisfactorily with the use of the Tesla transformer.

The question arises immediately—and I should like, therefore, to mention it without contributing anything to its solution at present—whether X rays can also be produced by a continuous discharge from a source of constant potential, or whether fluctuations of the potential are essential and necessary to produce the rays.

20. It is stated in paragraph 13 of my first communication that X rays can be produced not only in glass but also in aluminum. In continuing the investigations along these lines, no solid body could be found that was not able to produce X rays under the influence of cathode rays. There is also no reason known to me why liquids and gaseous bodies may not act in the same manner.

However, quantitative differences in the behavior of different bodies have appeared. For example, if one lets cathode rays fall upon a plate, one half of which consists of a 0.3 millimeter platinum sheet and the other half of a 1 millimeter aluminum sheet, one observes on the photograph of this double plate taken with a pinhole camera that the platinum emits considerably more X rays from the front side where it has been struck by the cathode rays than the aluminum emits from the same side. From the rear side, however, hardly any X rays are emitted from the platinum but relatively many from the aluminum. In the latter, rays have been produced in the front layers of the aluminum and have penetrated through the plate.

One can easily arrive at an explanation of this observation, but it might be advisable to learn first about some other properties of the X rays.

However, it should be mentioned that the observed facts also have a practical significance. According to my experience up to now, platinum is best suited for the production of X rays of highest intensity. For several weeks I have used with good success a discharge tube with a concave mirror of aluminum as cathode and a platinum foil as anode, which has been placed in the focus of the cathode and inclined 45 degrees in relation to the axis of the mirror.

21. In this apparatus X rays are emitted from the anode. From experiments made with apparatus of various shapes I must conclude that, insofar as the intensity of the X rays is concerned, it does not matter whether these rays are produced at the anode or not.

A discharge apparatus was built especially for experiments with alternating currents from a Tesla transformer in which both electrodes are concave aluminum mirrors, whose axes form a right angle; in their common focus, a platinum plate is placed to receive the cathode rays. A report on the usefulness of this apparatus will appear later.

Annex 2. Dissertations and "Habilitation" Publication Supervised by Röntgen

Giessen

1881 Heinrich Heine	*Ueber die Absorption der Wärme durch Gase und eine darauf beruhende Methode zur Bestimmung des Kohlensäuregehaltes der atmosphärischen Luft.* Phil.Diss. Giessen 1881. Ann Physik 1882;252:441–81
1885 J. Fink	*Ueber den Einfluss des Druckes auf den electrischen Leitungswiderstand von Electrolyten.* Ann Physik 1885;262:481–517
1886 Jakob Schneider	*Ueber die Compressibilität von Salzlösungen.* Phil.Diss. Giessen 1886
1887 Ludwig Zehnder	*Ueber den Einfluss des Druckes auf den Brechungsindex des Wassers für Natriumlicht.* Phil.Diss. Giessen 1887

Würzburg

1893 Max Wien	*Über eine neue Form der Induktionswaage*. Habilitationsschrift
1893 Otto Stern	*Über den Einfluss des Druckes auf das elektrische Leitungsvermögen*
1897 Julius Hanauer	*Ueber die Abhängigkeit der Capacität eines Condensators von der Frequenz der benutzten Wechselströme*. Dissertation. Leipzig Barth. Ann Physik 1898;301:789–814

Munich

Date of PhD	Name	Title of dissertation	Remarks
18 November 1901	Peter Paul Koch	*Über eine neue Methode zur Untersuchung auf Pyroelektrizität*	
5 March 1902	Julius Wallot	*Die Verwendung des Aragoschen Keilcompensators zur Messung der Brechungsexponenten von Flüssigkeiten*	Ann Physik 1903;316(6):355–96
18 July 1902	Adolf Bestelmeyer	*Die Abhängigkeit der inneren Reibung des Stickstoffs von der Temperatur*	Ann Physik 1904:318(5):944–95

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(continued)

Date of PhD	Name	Title of dissertation	Remarks
11 June 1903	Nikolaus Schmidt	*Die empfindliche Flamme als Hilfsmittel der Bestimmung der Schwingungszahl hoher Töne*	Dissertation Munich
25 July 1903	August Leonhard Bernoulli	*Die Passivität des Chroms nach der Faradayschen Theorie*	Inaugural Dissertation, Universität München
27 November 1905	Ernst Wagner	*Metallmanometer als Hochdruckpräzisions-messer, geprüft mit dem Amagatschen Manometer*	(Auszug aus der Münchener Dissertation). Ann Physik 1904;320:906–53
27 November 1903	Ernst Schnorr von Carolsfeld	*Widerstandsmessung mit konstanten und Wechselströmen in und ausser dem Magnetfeld an Wismuth- und Antimondrähten*	
5 June 1905	Abram Fjodorovich Joffe	*Elastische Nachwirkung im kristallinischen Quarz*	Ann Physik 1906;325(10):919–80
19 July 1905	Ernst Angerer	*Bolometrische Untersuchungen über die Energie der Röntgenstrahlen*	Ann Physik 1906;326(11):87–117
19 July 1905	Alfred Magnus	*Über die durch elektrische Entladungen hervorgerufenen Gasabsorptien in Geisslerschen Röhren*	
1905	Emil Silbernagel	*Bewegung eines Punktes innerhalb einer nicht homogenen Staubmasse mit cylindrischen Flächen gleicher Dichtigkeit*	[First Promotor Hugo Hans von Seeliger]
6 March 1906	Rudolf Walter Ladenburg	*Über die innere Reibung zäher Flüssigkeiten und ihre Abhängigkeit vom Druck*	Ann Physik 1907;327(2):287–309
26 July 1906	Peter Pringsheim	*Versuche über das Minimumpotential von Spitzenentladungen und über den Einfluss erhöhter Temperaturen auf dasselbe*	Ann Physik 1907;329(11):145–63
17 July 1907	Walter Lissauer	*Die piezoelektrische Erregung des Quarzes und Turmalin bei der Temperatur der flüssigen Luft*	Dissertation München 1907
22 November 1907	John Patrick Donaghey	*Über das Spektrum des Stickstoffs in Geisslerschen Röhren die auf tiefe Temperaturen abgekühlt sind*	*The Spectrum of Nitrogen at Low Temperatures*
19 December 1907	Eugene Bassler	*Polarisation der X-Strahlen, nachgewiesen mittels Sekundärstrahlung*	Ann Physik 1909;333(4):808–84
12 July 1909	Gerhard Freiherr Du Prel	*Über den Einfluss allseitigen Druckes auf das magnetische Moment von Eisen, Nickel und Nickelstahl*	Doktorarbeit Universität München
24 July 1911	Walter Friedrich	*Räumliche Intensitätsverteilung der X-Strahlen, die von einer Platina Antikathode ausgehen*	Ann Physik 1912;344(12):377–430

(continued)

Date of PhD	Name	Title of dissertation	Remarks
1911	Herman William March	*Über die Ausbreitung der Wellen der drahtlosen Telegraphie auf der Erdkugel*	(Auszug aus einer Münchener Dissertation). Ann Physik 1912;342(1):29–50
5 March 1912	Friedrich Beyer	*Über den Einfluss allseitigen Druckes auf die elastischen Eigenschaften, insbesondere auf die elastische Nachwirkung beim Kautschuk, Silber und Glas*	
18 November 1913	Karol Szlenker	*Über den elektrischen Widerstand des Kalkspates bei Wechselstrom*	
26 May 1913	Paul Knipping	*Über den Einfluss der Vorgeschichte auf verschiedene Eigenschaften des Bleies*	
26 May 1913	Anton Ernst Weber	*Über die Anwendung des rotierenden Sektors zur photographischen Photometrie*	(Auszug aus der Münchener Dissertation). Ann Physik 1914; 350(22):800–3
6 March 1914	Johannes Brentano	*Über den Einfluss allseitigen Druckes auf die elektrische Leitfähigkeit von Wismutdrähten außerhalb und innerhalb des transversalen Magnetfeldes für Gleichstrom und für Wechselstrom*	Ann Physik 1915;351(7):941–83
2 December 1914	Richard Glocker	*Interferenz der Röntgenstrahlen und Kristallstruktur*	Ann Physik 1915;352(11):377–428

Annex 3. Publications by Wilhelm Conrad Röntgen

Zurich

1. Röntgen WC. Studien über Gase. PhD thesis. Zurich: Zürcher & Furrer; 1869.

Strasbourg

2. Röntgen WC. Ueber die Bestimmung des Verhältnisses der specifischen Wärmen der Luft. Annalen der Physik und Chemie. 1870;141:552–66.
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Annex 4. Scientific Forefathers of W.C. Röntgen

Phenomena with an electrical or magnetic origin were already described in the antique world; however, during the Renaissance, the first steps directed to present-day science were made. The following tables show names of persons with their discovery or invention. These can be regarded as a chain of events making the discovery of the X-rays possible. The discoveries are in the fields of electricity and magnetism, evacuation production of vacuum, luminescence, discharge tubes, and photography.

Electricity and Magnetism

1600	William Gilbert (1544–1603) shows electrical phenomena by the rubbing of amber or other materials. Electricity is his concept. Father of electricity. "The earth is a magnet"
1703	Francis Hauksbee (1660–1713) builds the prototype of a generator. He observes electrical discharges in vacuum by shaking mercury
1729	Stephen Gray (1666–1736) differentiates between a conductor and an insulator. He conducts electricity from one body to another through a metallic wire
1747	Benjamin Franklin (1706–1790) defines positive and negative electricity, constructs a multiple plate capacitor. Constructs the lightning conductor
1748	Jean-Antoine Nollet (1700–1770) develops an electroscope for measurement of the amount of electricity
1800	Alessandro Volta (1745–1827) develops the voltaic pile, one of the first electrochemical cells. It consists of two electrodes, one of zinc, the other of copper. Electrolyte is usually sulphuric acid. Founder of electrochemistry
1820	Hans Christian Oersted (1777–1851) showed that an electric current produces a circular magnetic field as it flows through a wire. This is a proof for the relationship between electricity and magnetism
1822	André-Marie Ampère (1775–1836) publishes on the intensity of electric currents. Founder of the field of electrodynamics
1827	Georg Ohm (1789–1854) finds quantitative correlation between the voltage and the intensity of a current
1831	Michael Faraday (1791–1867) discovers electromagnetic induction, which forms the basis for electrostatic machines and for transformers. He coined the words anode and cathode
1851	Heinrich Daniel Rühmkorff resp. Ruhmkorff (1803–1877) develops the induction coil

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(continued)

1857	Julius Plücker (1801–1868) observes cathode rays and their deflection by magnetism
1866	Werner von Siemens (1816–1892) discovered the dynamo-electric principle
1873	James Clerk Maxwell (1831–1879) publishes "A treatise on electricity and magnetism", wherein quantitative connections between electromagnetism and light are formulated
1876	Eugen Goldstein (1850–1930) studies discharge tubes and finds positive ions at the anode ("Kanalstrahlen")
1881	George Johnstone Stoney (1826–1911) introduces the word "electron", which he regards as the fundamental unit of electricity discharge
1888–1892	Heinrich Rudolf Hertz (1857–1894) discovers the transmission of cathode rays through thin aluminum sheets. Verifies Maxwell's theory of electromagnetic waves for light
1891	Nicola Tesla (1856–1943) develops the Tesla coil producing high voltages
1892	Hendrik Antoon Lorentz (1853–1928) finds a basis for a theory of the electrical and optical phenomena (electron theory)
1894	Philipp Lenard (1862–1947) investigates the cathode rays which have penetrated a thin aluminum window. He continues the studies of Hertz. Cathode rays are not visible, but their effects can be studied
1895	Jean Baptiste Perrin (1870–1942) shows that cathode rays have a negative charge
8-11-1895	W.C. Röntgen observes a strange phenomenon, which leads to the discovery of the X-rays

Evacuation of Tubes: Producing Vacuum

1643	Evangelista Torricelli (1608–1647) invents the mercury barometer with "Torricellian vacuum"
1654	Otto von Guericke (1602–1686) designs the vacuum pump
1855	Heinrich Geissler (1814–1879) introduces the mercury displacement pump to lower the gas pressure in the tubes
1891	August Raps (1865–1920) improves the pump of Geissler by automatic control of the mercury flow

Luminescence (Phosphorescence and Fluorescence)

1602	Vincentius Casciarolus (1571–1624) discovers the luminescence of barium sulphide
1852	George Gabriel Stokes (1819–1903) describes the fluorescence of certain materials (salts of calcium, barium, and strontium) when radiated with UV-light
1858	Julius Plücker (1801–1868) *o*bserves in his research on cathode rays fluorescence on the walls of the vacuum tube opposite to one of the electrodes

Discharge Tubes

1855–1860	Geissler and Plücker develop vacuum tubes, containing various gases. They observe different colours
1869–1879	Johann Wilhelm Hittorf (1824–1914) and William Crookes (1832–1919) produce tubes for a higher vacuum
1887–1893	Otto Schott (1851–1935) develops borosilicate glass with a high tolerance to heat and resistance to thermal shock and degradation

Photography

1802	Thomas Wedgewood (1771–1805) creates permanent pictures by capturing camera images on material (paper and white leather) coated with silver nitrate
1819	John Herschel (1792–1871) improves the photographic process; finds that thiosulphate dissolves solid silver chloride for fixation of an image. Coined the term photography in 1839
1822	Joseph Nicéphore Niépce (1765–1833) develops a process to produce photo etchings
1839	Louis Daguerre (1787–1851) develops the Daguerre process: a silver plated surface is sensitised by iodine vapour, developed by mercury vapour, and fixed with saturated salt water
1851	Frederick Scott Archer (1813–1857) invents the collodion process
1871	Richard Leach Maddox (1816–1902) discovers dry gelatine photographic emulsion. The plates could be used commercially. No preparation was necessary
1879	George Eastman (1854–1932) invents a machine to coat glass plates
1889	George Eastman uses nitrocellulose for the first flexible film; later the nitrate film was used for X-ray photography, but its flammability hazard was a problem

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