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Physics in Perspective

Paul Villard and his Discovery of Gamma Rays

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The discovery of gamma rays by the relatively unknown French physicist Paul Villard is described in its historical context. From the beginning Villard gave a correct interpretation of the new rays, but his discovery was largely overlooked by the scientific community. A major reason for the small interest in gamma rays at the time was that they apparently did not fit into the picture that contemporary scientists had on the material nature of atomic radiations.

Key words: Gamma rays; discovery; Paul Villard.

Introduction

Radiation physics and chemistry flourished at the *fin de siècle*. Wilhelm Conrad Röntgen's sensational discovery of X rays in 1895 was soon followed by Henri Becquerel's discovery of radioactivity and by J. J. Thomson's proof of the independent existence of negative electrons of small mass. Marie and Pierre Curie discovered the radioactive elements polonium and radium, and Paul Villard observed a new kind of extremely penetrating rays, later called gamma rays.

Paul Villard is almost forgotten today by the scientific community. He is given credit for having discovered gamma rays, but his discovery is almost never discussed in any detail. He stands, one might say, in the shadow of the giants Becquerel and the Curies. The year 1998 marks the centenary of Marie and Pierre Curie's discovery of polonium and radium, and many publications commemorate them. My goal is to call attention to the relatively unknown Paul Villard and to present his discovery of gamma rays in its historical context.

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Biographical Sketch[1]

Paul Villard was born in 1860 in a village near Lyon, France. In 1881 he entered the *École Normale Supérieure* in Paris. After his *agrégation*, which gave him the license to teach at any secondary school financed by the government, Villard taught at various lycées in the province, and finally at the Lycée of Montpellier. Here he established contact with the local university. He developed a strong predilection for

Fig. 1. Paul Villard. (Courtesy of the *Archives de l'Académie des Sciences*, 23, Quai de Conti, 75006 Paris, France.)

scientific research and made frequent use of a small laboratory that the faculty placed at his disposal. However, he soon felt that he had to work in Paris, which was the center for physical science in France. Having a small fortune that was sufficient for his needs, he asked for leave from his teaching position. He went to Paris where he enjoyed the hospitality of chemistry professor Henri Debray and his successors at the *École Normale*. Villard now devoted himself exclusively to science, spending the rest of his professional life in the chemistry department of the *École Normale* in *rue d'Ulm*. In 1904, chemistry professor and director Robert Lespieau granted Villard the use of a small laboratory of his own.

Villard preferred independent research, and most of his papers are single-authored. He also had little concern for fame. Nevertheless, the *Académie des Sciences* awarded him its Wilde prize in 1904 and its La Caze prize in 1907. In 1908 he succeeded physicist Eleuthère Mascart as a member of the Academy. During the last years of his life, Villard was forced to spend extended periods of time outside of Paris because of his deteriorating health. He died in Bayonne on January 13, 1934.

Research Interests

Villard's earliest studies were in the field of physical chemistry, where he investigated the combination of water with various gases under pressure, forming hydrates of them. He published his first papers in the *Comptes rendus des Séances de l'Académie des Sciences* in 1888 together with Robert Hippolyte de Forcrand. They repeated, with improved accuracy, some earlier studies on gaseous hydrates, but Villard soon reported on a further series of completely new hydrates, which were considerably more difficult to produce. This work formed the basis for his doctoral thesis. In connection with his studies of gases under pressure, Villard constructed a widely-used manometer. His work on hydrates culminated in 1896, when he successfully combined the rare gas argon with water. Argon had been discovered by Lord Rayleigh and William Ramsay only two years earlier, in 1894.

In 1897 Villard gained access to a Crookes tube and started publishing a long series of papers on cathode rays and X rays.[2] He was particularly interested in the action of a magnetic field on the path of a beam of cathode rays. He also studied chemical reactions caused by cathode rays and X rays. He invented an osmotic method for admitting hydrogen into an X-ray tube, thereby lowering its resistance. In radiography, his name became linked to a particular exposure effect, now long-forgotten.* Villard's publication rate peaked in the years 1898–1900. During this period he published about ten major papers each year, including his two papers on radium radiation in 1900.

* The so-called Villard effect is an anomalous summation of the effects of X radiation and normal light on a photographic plate.

Prelude

In February 1896 Henri Becquerel discovered the radioactivity* of uranium. His search, literally in the dark, for the nature of the uranium rays can be followed in a series of papers presented to the Paris *Académie des Sciences* between February and May of 1896. Becquerel found that the element uranium spontaneously emits invisible radiation that can penetrate black paper and even metal sheets. The radiation affected a photographic plate like visible light, and discharged electrified bodies. Later, Ernest Rutherford showed that uranium rays ionize gases in the same way as X rays and cathode rays, thereby causing an enhanced electrical conductivity.

Further progress in the new field of radioactivity was of a chemical nature and was due to the work of Marie and Pierre Curie. They discovered in 1898 two new radioactive elements, which they named polonium and radium. From the beginning, the Curies felt obliged to place their newly discovered and prepared radioactive compounds at the disposal of contemporary scientists, in particular Becquerel. Later, radioactive materials became commercially available in France and Germany. Rapid progress in the investigation of the physical properties of the new kinds of radiation was now possible, because the activity of radium is more than a million times stronger than that of uranium. Radioactivity research also was stimulated by the remarkable results that were obtained simultaneously on the nature of cathode rays. In two famous papers of 1897 and 1899, J. J. Thomson demonstrated the existence of the negatively charged electron** and measured its charge and mass.

Radioactivity was a hot topic in Villard's day, and its investigation was pursued vigorously by a number of prominent scientists. Rutherford wrote in a letter to his mother in January 1902:

> I am now busy writing up papers for publication and doing fresh work. I have to keep going, as there are always people on my track. I have to publish my present work as rapidly as possible in order to keep in the race. The best sprinters in this road of investigation are Becquerel and the Curies in Paris, who have done a great deal of very important work in the subject of radioactive bodies during the last few years.[3]

Transmission experiments indicated that the radiation emitted by radioactive bodies was heterogeneous. Rutherford named two distinguishable types of radiation alpha and beta rays:

> there are present at least two distinct types of radiation – one that is very readily absorbed, which will be termed for convenience the α radiation, and the other of a more penetrative character, which will be termed the β radiation.[4]

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* The name "radioactivity" was coined by Marie Sklodowska Curie in 1898.

** Thomson called his subatomic particle "corpuscle," but it has since become known as "electron," a term coined in 1891 by the Irish physicist George Johnstone Stoney to represent the unit of electricity.

At this time β rays were more often studied than α rays because of their higher penetrating power and marked photographic action. At the weekly Monday session of the *Académie des Sciences* on December 11, 1899, Becquerel demonstrated that radium β rays are affected by a magnetic field.[5]* This brought out their strong resemblance to cathode rays. Later, it was shown that β rays, having different velocities, are dispersed by a magnetic field in much the same way as different colors of visible light are dispersed by a prism. These experiments constituted a sort of magnetic-spectrum analysis of β rays.

At the Monday session of the *Académie des Sciences* on January 8, 1900, Becquerel presented two notes by the Curies. Using his sensitive electrometer based on a piezoelectric crystal, Pierre Curie had demonstrated that radium radiation consists of two distinct types: rays that are deviable in a magnetic field (β rays), and rays that are non-deviable in a magnetic field (α rays).[6] Transmission experiments by Marie Curie had verified that the non-deviable rays are much less penetrating than the deviable rays.[7] At this time, α rays were believed to be non-deviable by a magnetic field. Therefore, the two kinds of radiation, α and β, were initially distinguished as non-deviable and deviable in a magnetic field.

Considering the progress achieved, Becquerel and the Curies drew up an ambitious plan to study some important issues. The predictable identification of the deviable rays (β rays) with cathode rays (electrons) required two more verifications. It was necessary to demonstrate that β rays carry a charge of negative electricity, and that they are deflected by an electrostatic field. By comparing the magnetic and electrostatic deflections, it should be possible to deduce the velocity of the particles in the deviable β rays. By measuring the charging rate of the rays and using the charge-to-mass ratio of the particles as determined from the deflection experiments, it should be possible to calculate the flux of material and, finally, the kinetic energy per second of the emitted particles. These data ought to give important clues to the as yet unanswered question of the source of energy in radioactive substances. That the emission from a given radioactive body is continuous and without any noticeable weakening was considered a great puzzle by contemporary scientists.

On March 5, 1900, the Curies reported that the deviable radium rays impart a negative charge to an insulated conductor.[8] In this case air would not act as an insulator because of the ionization due to the radiation. The Curies got around this difficulty by insulating a conductor with a thin layer of wax over its surface. They then exposed it to radium radiation and found that it became negatively charged. As corroboration they insulated some of the radium salt in the same manner with wax, and found that it became positively charged.

Becquerel on his part took care of the electrostatic deflection. It was a difficult task. Becquerel had estimated that to get a measurable deflection, it would be necessary to apply at least 20,000 volts between two plates 1 cm apart. This would exceed the electric strength of air. On March 26, 1900, Becquerel reported successful results.[9]** Finally, β rays were definitely identified with cathode rays, *i.e.*, it was

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* During the course of his work, Becquerel learned that Stefan Meyer and Egon Ritter von Schweidler as well as Friedrich Giesel had made similar observations.

** Ernst Dorn independently reported similar results on the electrostatic deflection.

proved that they are streams of rapidly moving, negatively charged electrons. For the velocity of the β particles Becquerel got an astounding figure, between one-half and two-thirds of the velocity of light. Thus, it was shown that β particles are emitted with velocities far exceeding those obtainable for electrons in a cathode-ray tube.

As a side-line Becquerel investigated the transmission of β rays through thin foils of various materials. He noticed that the most deviable rays were the most absorbable ones. Screens of sheet metal were found to act as sieves for the rays, cutting off the less penetrating rays and allowing the more penetrating ones to go through. Becquerel also made a curious and unexplained observation that the absorption apparently depended on whether the screen was situated close to the radioactive source or at some distance from it.[10] These experiments were criticized by Villard, who interpreted them in analogy with his own results for cathode rays.[11]

At the Academy session on November 20, 1899, Becquerel presented a note by the Curies, who had observed some chemical effects produced by radium rays.[12] They had found that the rays emitted by highly radioactive salts of barium are capable of converting oxygen into ozone. They also had observed a coloring action of the rays on glass and on barium platinocyanide commonly used for fluorescent screens. These results evoked Villard's interest. At the following meeting, one week later, he pointed out that he had made similar observations, although he had not yet ventured to publish them.[13] It was well known that when a Crookes tube had been used for some time, the glass of the bulb acquired a violet tint on the side struck by X rays and diffuse cathode rays. Villard had blocked the cathode rays by an aluminium foil and found that the violet coloration was definitely due to X rays. Villard had alluded to this phenomenon at the Easter meeting of the *Société de physique*, saying that strictly speaking it was possible to obtain a radiograph by using a simple glass plate for the sensitive medium. Moreover, according to Villard, his results established an important analogy between X rays and the rays emitted by radioactive substances.

Villard's interest in radioactivity was now aroused. It is not clear whether he initiated the radium experiments, or if they were suggested to him by Becquerel or the Curies. In any case, Villard gained access to some milligrams of a weakly radioactive sample. He wanted to compare the reflection and refraction properties of cathode rays and β rays. As it turned out, he would make an unpredictable discovery.

Discovery

Paul Villard presented his paper, "Sur la réflexion et la réfraction des rayons cathodiques et des rayons déviables du radium," at the Monday session of the Paris *Académie des Sciences* on April 9, 1900.* It follows from the title that Villard originally set out to study the deviable rays (β rays) but his work led to his

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* The papers at the sessions of the *Académie des Sciences* for the *Comptes rendus* are normally read by titles and authors only. They are published in full in the journal.

discovery of a new kind of penetrating rays. His description of his experiment is hard to follow without a diagram, but none is supplied. Villard addressed himself to a few scientists who were familiar with his experimental methods. Thus he considered a verbal description as perfectly adequate.

Villard emphasized that the deviable rays (β rays) behave in all respects like cathode rays. He measured the refraction of these rays as follows: A small quantity of barium chloride containing radium, enclosed in a glass ampoule, was placed in a lead tube. At the end of the tube, a cone of rays emerged with an opening angle of about 20°. In front of the tube an aluminium foil was mounted, inclined at 45° to the axis of the tube. The aluminium foil, 0.3 mm thick, intercepted half of the emergent beam. The entire arrangement was placed on a photographic plate, which was wrapped in light-tight black paper, in such a way that the plate received the emergent beam at grazing incidence. The exposed plate showed that the half-beam intercepted by the aluminium foil no longer was symmetrically equivalent to the non-intercepted half-beam. It had undergone an apparent refraction that was accompanied by a strong diffuse scattering. According to Villard, the transmitted radiation formed a fan of rays, the symmetry axis of which was normal to the surface of the metal foil. Villard pointed out that he had observed the same phenomenon for cathode rays, albeit with a much thinner foil.

During the course of his work, Villard noticed that in almost every experiment the photographic plate revealed traces of a non-refracted beam, which obviously had been propagating in a straight line. This beam was superimposed on the refracted beam, making it difficult to interpret the photographs. Next, Villard tried to deflect the non-refracted rays in a magnetic field, but they were unaffected. Moreover, these rays were penetrating enough to affect the photographic plate protected by several layers of black paper as well as an aluminium foil. The rays were even able to traverse a 0.2-mm thick lead foil when placed in the beam. Said Villard:

> I think that this effect is due to the presence of non-deviable rays, which are less absorbent than the ones [α rays] that have been described by Mr. Curie. . . . It follows from the facts presented above that the non-deviable rays emitted by radium contain some very penetrating radiations, capable of traversing metal foils and affecting a photographic plate.[14]

The Curies kindly placed a much stronger radium sample at Villard's disposal, and three weeks later he presented new and more detailed results on the radium rays to the *Académie des Sciences*. His comparative study of the penetrating power of β rays and his new type of rays, "Sur le rayonnement du radium," was read by Academy member Jules Violle at the Monday meeting on April 30, 1900.

Villard's experimental arrangement was about the same as in his first radium experiment but without the aluminium foil. The radiation from the radium sample was collimated by a long groove in a lead block and sent consecutively through two photographic plates stacked on top of each other. The deviable rays were bent in a magnetic field before hitting the photographic plates.

Villard reported that the first photographic plate showed traces of two distinct beams. One had been deflected by the magnetic field and broadened. The other had propagated along an absolutely straight line and produced a sharp impression. On the second plate there was only one trace, that from the non-deflected beam. It produced an impression that was as sharp and intense as on the first plate. It was even more visible because of the lower background radiation on the second plate. The plates were made of glass, and because of the grazing incidence the non-deflected beam had traversed 1 cm of glass before reaching the second plate. It followed that the non-deflected rays were able to penetrate at least 1 cm of glass without any noticeable attenuation. Even a lead foil, 0.3 mm thick, was found to attenuate the rays only slightly. Villard appeared already to have associated the penetrating radiation with X rays. He concluded that the "X rays" emitted by radium have a considerably larger penetrating power than the deviable rays (β rays).[15]

Less than three weeks later, Villard expressed himself more boldly. At the Friday meeting of the *Société francaise de physique* on May 18, 1900, he demonstrated that radium emits rays that are non-deviable and extremely penetrating. These new rays, said Villard, were different from the radium rays observed so far. He went on to suggest that the extremely penetrating rays, discovered by him, were indeed a kind of X rays. Furthermore, as he pointed out, the readily absorbed radium rays (α rays) were analogous to the non-deviable cathode rays (positive ions or *Kanal-strahlen*) previously observed by J. J. Thomson, Wilhelm Wien, and others. The deviable rays (β rays) had already been shown by Becquerel to be identical to a stream of electrons. Villard concluded that "on retrouverait ainsi les trois rayonnements des tubes de Crookes,"[16] *i.e.*, the three kinds of radiation (ions, electrons and X rays) known from experiments with cathode-ray tubes were all present in radium rays. Thus, from the beginning, Villard gave a correct interpretation of the three components of radium rays. Unfortunately, his discovery was largely overlooked by his contempories.

Impact

Villard performed his radium experiments under the watchful eyes of Becquerel. In fact, both men reported on transmission experiments with radium radiation at the April 9, 1900, session of the *Académie des Sciences*. Becquerel found it necessary to repeat Villard's experiment, and he delivered his comments three weeks later at the April 30 meeting. He disputed the apparent refraction of β rays. Regarding the very penetrating rays, he simply denied their presence. He argued that

> the existence of these rays could not possibly have escaped attention in the experiments of Mr. and Mrs. Curie, nor in my own experiments. . . .[17]

This must be considered a very negative statement. Gradually, however, Becquerel had to accept the experimental facts. At the Academy session on June 11, 1900, he said:

> The radiation of radioactive bodies is composed of two distinct groups: one, consisting of cathode rays, is deviable by a magnetic field and by an electric field; the other one, whose nature is as yet unknown, is non-deviable and apparently composed of rays having various penetrating powers through metals and opaque bodies.[18]

Thus, Becquerel still hesitated to accept a third distinct kind of radiation. The nature of the non-deviable rays was unknown at this time, and according to Becquerel there were just two types of radiation: deviable and non-deviable radiation, the latter admittedly with an unusually large range of penetrating powers. In a review paper, published in *Nature* on February 21, 1901, Becquerel mentioned Villard's results only briefly:

> I might add that recently Mr. Villard has proved the existence in the radium radiation of very penetrating rays which are not capable of deviation.[19]

This is a remarkably modest announcement of Villard's discovery of a new type of radiation with extraordinary properties. The Curies seemed to treat Villard's findings with more interest. As mentioned above, they placed a stronger radium source at his disposal, thus enabling him to produce more detailed and reliable observations. They also supported Villard's interpretation of the penetrating rays as a kind of X rays.

Contrary to common belief, Villard did not introduce the designation "gamma rays." It is characteristic of the weak contemporary interest in these penetrating rays that they went unnamed for nearly three years. The name gamma rays was probably invented by Rutherford, but I have been unable to determine where they are explicitly named. Rutherford still used the descriptive form "rays nondeviable in character, but of very great penetrating power" in the January 1903 issue of the *Philosophical Magazine*,[20] but in the subsequent February issue, the trio α, β and γ appeared:

> Radium gives out three distinct types of radiation:
> 1. The α rays, which are very easily absorbed by thin layers of matter, and which give rise to the greater portion of the ionization of the gas observed under the usual experimental conditions.
> 2. The β rays, which consist of negatively charged particles projected with high velocity, and which are similar in all respects to cathode rays produced in a vacuum-tube.
> 3. The γ rays, which are non-deviable by a magnetic field, and which are of a very penetrating character.[21]

Marie Curie noted in her doctoral thesis that "one can distinguish between three types of radiation, which I will denote by the letters α, β and γ, following the notation of Rutherford."[22]

At first sight, it seems surprising that no one apparently took much care in 1900 and the following years of Villard's new kind of very penetrating rays. Rutherford

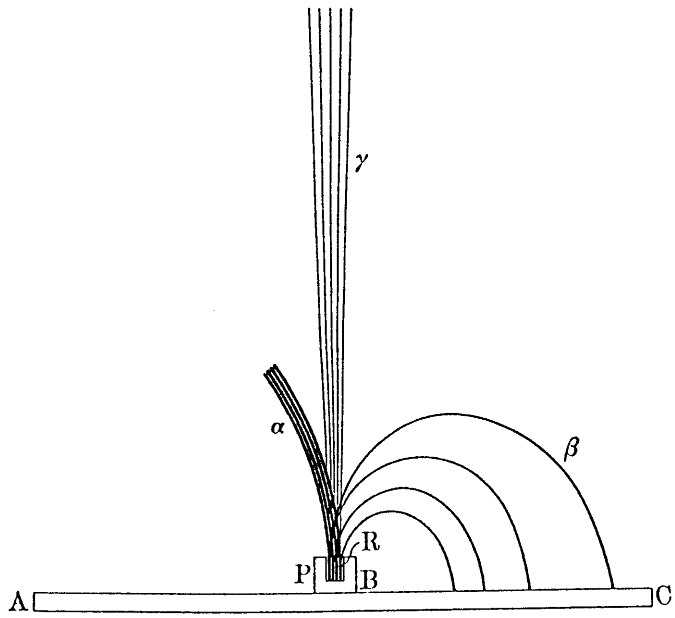

Fig. 2. Marie Curie's *Gedankenexperiment* to distinguish the three kinds of radioactive radiation. R = radium source, P = lead block, ABC = photographic plate. (From ref. 23, reprinted with permission from the publishers: ESME, 23, rue Linois, 75724 Paris cedex 15, France, and Friedr. Vieweg & Sohn, 65048 Wiesbaden, Germany.)

measured the absorption of γ rays in various materials, but for the time being did not pay much attention to these new rays. R. J. Strutt determined the ionization produced by γ rays in various gases. With respect to their ionization properties, γ rays at first sight seemed to be more similar to cathode rays than to X rays. However, A. E. Eve and R. K. McClung showed that the ionization power of X rays varies with the hardness of the radiation, and that the ionization properties of hard X rays approach those of γ rays.

Rutherford discovered the electric and magnetic deviability of α rays. Their deflection is in the opposite sense to β or cathode rays. Thus α rays were proved to consist of positively charged particles projected with great velocity. From measurements of their charge-to-mass ratio, the α particles were provisionally identified as positive ions of hydrogen or helium. They finally were established as helium ions.

Marie Curie has described a *Gedankenexperiment* (Fig. 2) to distinguish the three types of radiation.[23] A small piece of radioactive material (R) is placed at the bottom of a long groove in a lead block (P) situated on a photographic plate (ABC). The entire apparatus is highly evacuated. A strong magnetic field is applied at right angles to the plane of the diagram. A collimated bundle of rays emerges from the groove, and the three types of radiation are dispersed in the magnetic field. From a knowledge of the direction of the magnetic field, one concludes that one type of radiation is positively charged (α particles), one is negatively charged (β particles), and one is electrically neutral (γ rays). In practice, as pointed out by

Curie, the experiment cannot be performed in the simple way described above. Each type of radiation had to be studied separately using its own experimental arrangement.

Rutherford recognized that the α particles, since their mass is much larger than the mass of the β particles, carry virtually all of the energy released in radioactive processes. He pointed out that

> for uranium about 1/1000* of the total energy radiated is carried off in the form of electrons. The ratio is still smaller for thorium and radium. It thus appears that in the permanent radioactive substances the electrons driven off represent only a small fraction of the energy dissipated.[24]

Rutherford was of the opinion that α rays represent the most important type of radiation from radioactive bodies, and he regarded β and γ rays as comparatively of much less significance. Consequently, he concentrated his research on the investigation of α particles. His studies culminated in the transformation theory of Rutherford and Frederick Soddy of 1903, and in the α-scattering experiments by Hans Geiger and Ernest Marsden, which led Rutherford to postulate the existence of the atomic nucleus in 1911.

Although studies of α rays yielded remarkable results, β rays continued to attract considerable interest. Becquerel's numerical result for the charge-to-mass ratio of the β particle was adequate for its interpretation as an electron and, if not at first very accurate, was soon improved upon by other experiments. Walter Kaufmann was even able to show that its mass increases with increasing velocity.

Thus prominent and influential physicists and chemists were busy investigating α and β rays (particles), yet they paid little attention to Villard's discovery of γ rays. The available experimental possibilities for investigating γ rays were limited, and their nature was difficult to determine. In this connection, we recall that the nature of X rays was also unknown at this time. X rays, however, enjoyed great popularity in medical circles because of their striking uses in diagnosis and therapy. Consequently, rapid development in X-ray technology took place, resulting in improved X-ray tubes and associated equipment. Marie Curie, however, included a γ radiograph (Fig. 3) in her doctoral thesis,[25] thereby demonstrating a potential application of Villard's discovery. She noted the advantage of eliminating the accompanying β rays with a magnet, thus producing a sharper image with γ rays only. She also noted, however, the weak contrast between bone and soft tissue in γ radiographs, and the long exposure times required. It was much easier and faster to produce X-ray radiographs, and γ rays remained a scientific curiosity for many years.

At this time, there were only a few experimental techniques available to study the physical properties of the radiations emitted by radioactive substances. The rays produce luminosity on a fluorescent screen, and affect a photographic plate. They also produce ionization in gases. With respect to γ rays, the experimental possibil-

* Owing to an obvious slip of calculation, the number should be 1/100 instead of 1/1000, but the conclusion is still valid.

ities were exhausted, temporarily at least, and research came to a halt. In 1903, Rutherford and Soddy remarked:

> Radium, like thorium and uranium, emits two types of radiation, the α, or easily absorbed rays (deflectible in very intense magnetic fields), and the β, or penetrating rays, readily deviated in a magnetic field. It also emits some very penetrating rays, which, however, have not yet been fully investigated.[26]

Or again:

> In addition to the α and β rays the radio-elements also give out a third type of radiation which is extremely penetrating. . . . These rays have not been sufficiently examined to make any discussion possible of the part they play in radioactive processes.[27]

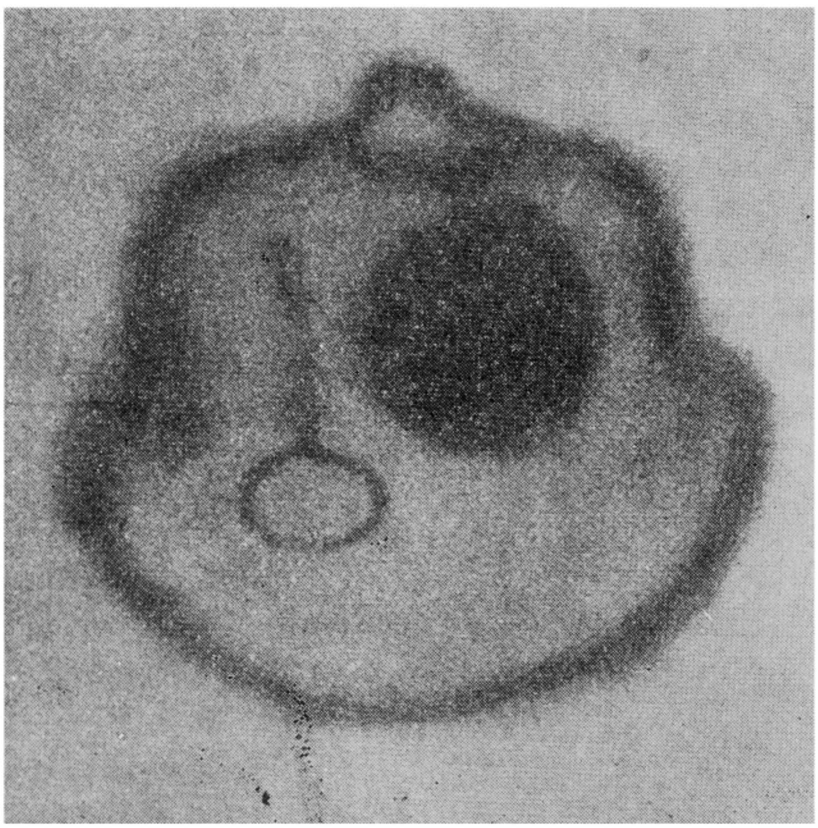

Fig. 3. Gamma radiograph of a *porte-monnaie* (purse) with coin and key by Marie Curie. (Courtesy of the *Association Curie et Joliot-Curie*, 11, rue Pierre et Marie Curie, 75248 Paris Cedex 05, France.)

Apart from the limited experimental techniques available, a major reason for the small interest in γ rays was that they apparently did not fit into contemporary views in radiation physics and chemistry. After J. J. Thomson's proof of the independent existence of the electron of small mass in 1897, and in particular after his measurements of its charge and mass in 1899, contemporary scientists focused much of their interest on the material nature of atomic radiations. The view that atomic radiations are material and particulate proved to be successful in interpretating the nature of cathode rays, and it continued to deliver remarkable results when applied to α and β rays. That picture was disturbed with γ rays, which did not seem to fit into this established view of radiation and matter. Rutherford thus made a half-hearted attempt to reconcile γ rays with the corpuscular view:

> The question at once arises as to whether these very penetrating rays are projected particles like kathode rays or a type of Röntgen rays. The fact that the penetrating rays are not deviable by a magnetic field seems, at first sight, to show that they cannot be kathode rays. . . . According to the electromagnetic theory, developed by J. J. Thomson and [Oliver] Heaviside, the apparent mass of an electron increases with the speed, and when the velocity of the electron is equal to the velocity of light its apparent mass is infinite. An electron moving with the velocity of light would be unaffected by a magnetic field.
>
> It does not seem at all improbable that some of the electrons from thorium and radium are travelling with a velocity very nearly equal to that of light . . . .
>
> The power of these rapidly moving electrons of penetrating through solid matter increases rapidly with the speed. From general theoretical considerations of the rapid increase of mass with speed, it is to be expected that the penetrating power would increase very rapidly as the speed of light was approached. Now we have already shown that these penetrating rays have very similar properties, as regards absorption and ionisation, to rapidly moving electrons. In addition, they possess the properties of great penetrative power and of non-deviation by a magnetic field, which, according to theory, belong to electrons moving with a velocity very nearly equal to that of light. It is thus possible that these rays are made up of electrons projected with a speed of about 186,000 miles per second.[28]

This model has two obvious flaws. First, it would imply a gradual transition from β to γ rays as the velocity of the electrons approached the velocity of light, whereas γ rays had been shown by Villard to be different from β rays. Second, there was the problem of the particle mass approaching infinity, which Rutherford also addressed. Later, he assumed correctly that "γ rays are very penetrating Röntgen rays, which have their source in the atom of the radioactive substance at the moment of the expulsion of the β or kathodic particle."[29] Soddy held a similar view, suggesting that "γ rays are in all probability X rays of high penetrating power which accompany the production of the β rays."[30]

William Bragg originally defended a corpuscular theory of X rays and γ rays.[31] The electromagnetic wave nature of X rays was firmly established, however, in 1912, when Max Laue* conceived the idea of employing a crystal as a space

* Later Max von Laue.

diffraction grating for X rays. The successful realization of this idea by Laue and his assistants, Walther Friedrich and Paul Knipping, opened up a wide field of research. In the hands of William and Lawrence Bragg, father and son, X-ray diffraction soon became a powerful tool for crystal-structure determination, but also for X-ray spectroscopy. In particular, experiments of the two Braggs and of Henry Gwyn Jeffreys Moseley and Charles Galton Darwin in 1913 showed that the reflection of X rays from crystals afforded a reliable method for studying the wavelength of X rays.

It would not be long before Rutherford applied crystal-diffraction techniques to confirm the wave nature of γ rays. He and E. N. da C. Andrade first determined the wavelength of relatively soft γ rays.[32] Later, they employed an ingenious transmission method to measure the small angles of reflection (about 1.5°) of harder γ rays.[33] Thus, it was finally established that γ rays as well as X rays are electromagnetic radiations of short wavelength. Meanwhile, high-voltage X-ray generators had made it possible to produce X rays with wavelengths in a range overlapping those of γ rays, the only distinction between the two types of radiation being their origin. A few years later, Arthur Holly Compton's studies of the scattering of X rays led to the concept of X rays acting as particles.[34] Thus, it was shown that X rays and γ rays can indeed be viewed as streams of particles or quanta moving with the velocity of light. These particles, however, are not massive electrons but light quanta (photons) of zero rest mass.

Epilogue

By 1901 there had been a sudden decline in Villard's publication activity. In that year he published only one major paper, and it dealt with a technical subject, a voltage-multiplying circuit to be used with an X-ray tube (Fig. 4).[35] In the Villard circuit, which still bears the name of its inventor, the transformer secondary is connected to the X-ray tube through two condensers, one at each pole. Across the X-ray tube is a rectifying valve (devised by Villard and called *soupape cathodique* by him). The sum of the condenser voltages is alternatively supplemented and reduced by the transformer voltage, so that the potential across the X-ray tube varies from 0 to 2V, where V is the peak potential delivered by the transformer. In 1911 Villard and Henri Abraham devised an influence machine that could yield a current of 3 mA at a voltage of 250 kV, the maximum voltage being 320 kV. Villard also devised a new form of alternator to provide high-frequency currents for wireless telegraphy.

After publishing his two papers of 1900 on his discovery of γ rays, Villard made no further studies of them. Was he disappointed by the little interest that his discovery aroused in the contemporary scientific community? In particular, was he disappointed by the reluctant acceptance of his results by Becquerel? Whatever the case may be, Villard decided to withdraw from the highly competitive arena of research in radioactivity and to devote his efforts to the more familiar cathode rays and X rays. Villard also developed an interest in the aurora borealis whose streamers are caused by the interaction between charged particles and molecules in

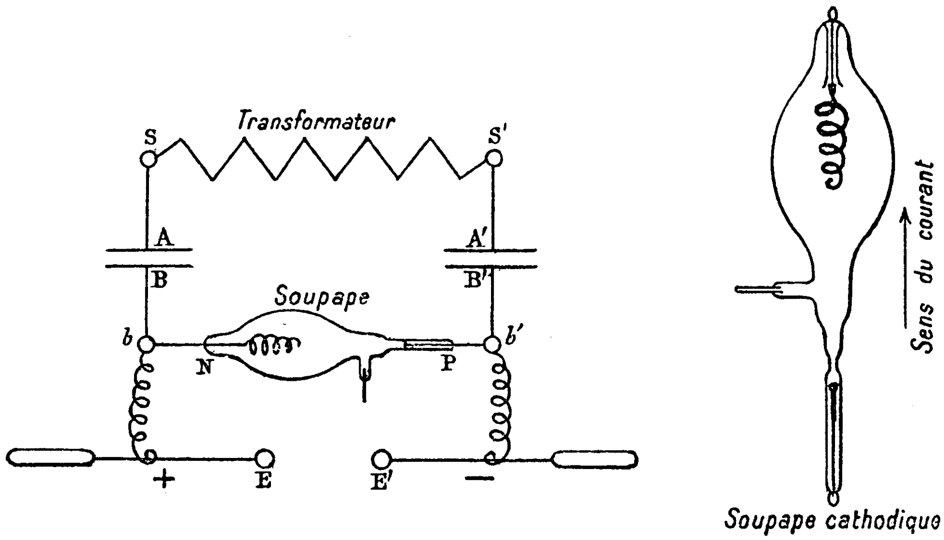

Fig. 4. Villard voltage-multiplying circuit. *Soupape cathodique* = rectifying valve. The X-ray tube is connected to E and E'. (From ref. 35.)

the upper atmosphere and have some bearing on the electric discharges in a rarefied gas in a cathode-ray tube.

By necessity, but also following his own inclination, Villard constructed all of his experimental equipment himself. He devised several instruments useful for practising radiologists. The idea of using the ionization of air as a measure of the output of an X-ray tube was suggested by Villard in 1908. In that year he invented an instrument (Fig. 5), which he used for directly determining the quality or penetrating power of X rays. Villard called his device a *radiosclérométre*.[36] The principle laid down by Villard became internationally recognized twenty years later, when the roentgen (r) unit of radiation exposure was recommended by the Second International Congress of Radiology in Stockholm in 1928.

Today, the name of Paul Villard has disappeared almost without a trace. Nevertheless, as I have shown here, Villard made important contributions to radiation science and technology. In particular, many of his practical inventions had a lasting impact. Villard also made a crucial contribution to radiation science when he discovered γ rays. However, the nature of these rays unfolded over several years through the work of several people. This clarifying process had to await the development of new theoretical concepts, such as the quantum theory of radiation and the existence of high-frequency electromagnetic waves.

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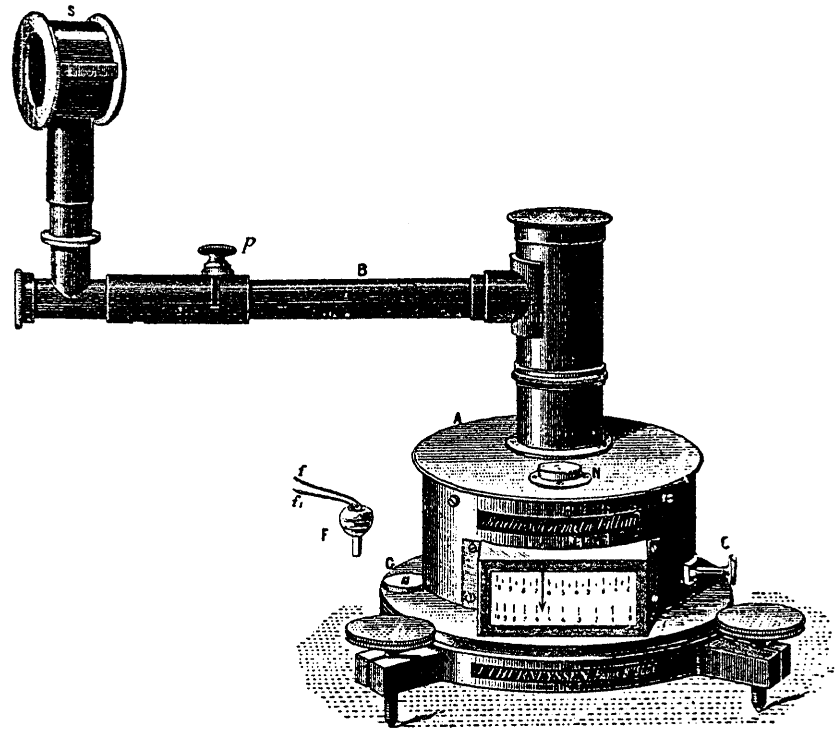

Fig. 5. The *radiosclérometre* devised by Villard for directly determining the quality or penetrating power of X rays. (From ref. 36.)

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