HISTORY AND HERITAGE

ROENTGEN'S INVESTIGATION DETERMINING THE CHARACTERISTICS OF X-RADIATION

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Abstract—**Following the discovery of a "new kind of rays," to be named by him as x-radiation, and others as Roentgen's rays, Dr. Roentgen embarked on an intense investigation in a series of innovative experiments to determine its properties and characteristics and how it compared to other known radiations, specifically light and cathode rays. He demonstrated that the radiation produced fluorescence and exposed photographic plates. The revolutionary discovery was that it penetrated normally opaque objects and produced shadow images of things within. It was these characteristics alone that were the foundation of x-ray imaging that soon changed and enhanced the practice of medicine around the world.**

For additional experiments he developed a variety of test devices that continue to be used by physicists for evaluating the performance of x-ray equipment and devices. These included a pinhole camera, step wedge, and an innovative device to become known as a penetrameter. A major focus of his work was investigating the penetration of the radiation through a variety of objects and materials. He demonstrated, and often documented with photographic images, that penetration related to both characteristics of the material (thickness and density) and the x-ray beam itself (pressure within the tube, the associated electrical voltage, and filtration of the beam). Having observed the effect on electrical charges in the vicinity of the x-ray apparatus he developed a series of experiments to demonstrate the direct ionization in air. Within just a few months of intense research he discovered, evaluated, and documented virtually all of the properties and characteristics of x-radiation as we know them today.

Keywords— **Roentgen, x-rays, discovery, investigate, properties.**

I. INTRODUCTION

It is well known that a "new kind of rays," to be named x-rays or Roentgen's rays, were discovered by Wilhelm Roentgen while experimenting with cathode rays on the evening of November 8, 1895. What is less known and appreciated within the physics community is the extensive investigations he conducted following the discovery to determine and document the properties and characteristics of this radiation.

Through a series of innovative and carefully conducted experiments he demonstrated most of the major properties of x-radiation even as we know it today. The results were published in three articles that are the source of information and references for this article.

Here his observations and findings are quoted along with illustrations added by the author. The illustrations represent the author's understanding of the experiments based on the published descriptions.

Fig.1. An imaginary conversation between Dr. Roentgen and the author

That was actually a question by a writer for a magazine preparing an article on his discovery. His answer is very significant. It illustrates his recognition that it was necessary that he determine the properties and characteristics of this new kind of radiation before publishing or discussing it with others.

II. THE DISCOVERY

Before the time of the discovery physicists in various institutions were experimenting with partially evacuated glass tubes connected to high-voltage sources of electricity. It had been determined that streams of accelerated electrons, or cathode rays, were produced within the tubes. If a tube had a sufficiently thin window, some of the cathode rays penetrated into the surrounding air. Roentgen was experimenting with cathode rays coming from a tube when he made the discovery. Typically the tubes would glow because of the ionization of the air that remained in the tube. This light was interfering with Dr. Roentgen's experiment of observing fluorescence produced by the cathode rays close to the tube. To produce a dark environment he enclosed his glowing tube with an opaque cover. It was in this darkness that he noticed light being emitted from a fluorescent material at some distance from the tube--a distance much greater than the range of cathode rays in air.

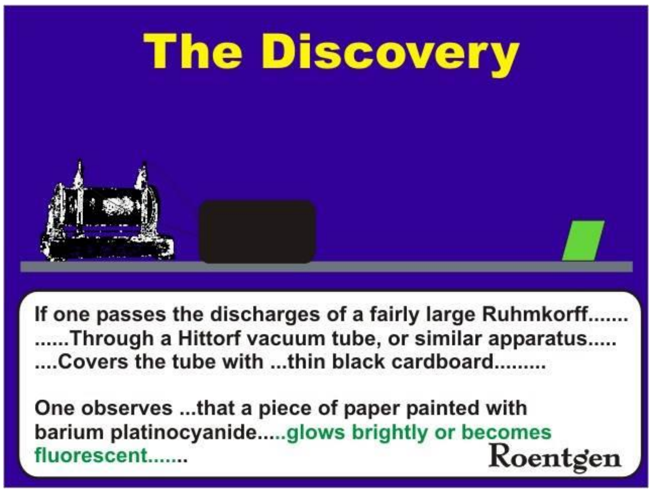

Fig. 2. The equipment that produced the x-radiation leading to the discovery

After associating the fluorescence with an invisible radiation from the tube he determined it would penetrate a variety of normally opaque materials and produce shadows. When holding an object, perhaps a piece of metal, he saw a shadow of the bones within his hand as illustrated below.

Fig. 3 An illustration of what Roentgen saw. Shown here is the author's hand in a recreation.

III. EXPERIMENTS

What followed these initial observations was a period of intense experimentation to investigate and determine the characteristics and properties of the "new kind of rays". Some of the major experiments are now described.

Transparency of objects to the new kind of radiation: This appears to be one of the first characteristics that were investigated with several experiments. One was the penetration of the radiation through a book.

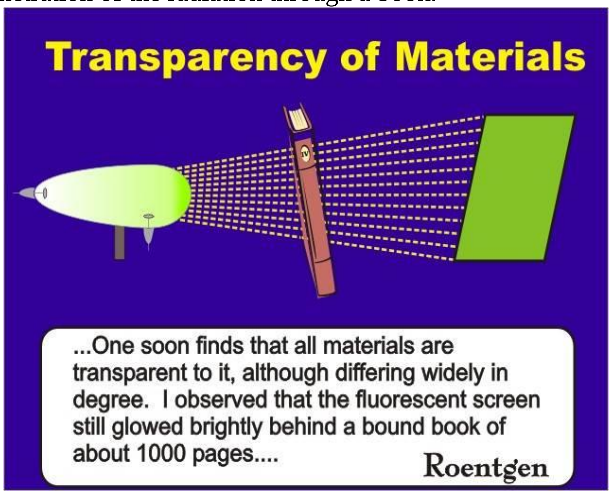

Fig. 4. A thick book was one object that was penetrated by the radiation.

***Propagation in straight lines (like light*)**: In the investigation of the characteristics of the new radiation it would have been logical to consider how it compared to other known radiations at that time such as light and cathode rays or electrons. A pinhole camera was used to verify the straight line propagation, demonstrating it shared some properties with light.

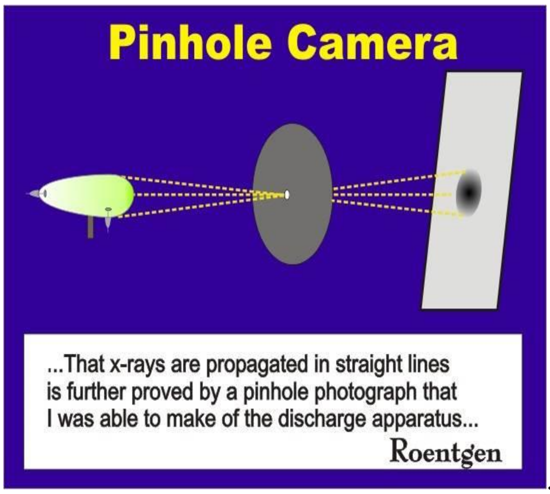

Fig. 5. Using a pinhole camera to compare characteristics to those of light.

The pinhole camera was used in several experiments. It produces an image of the actual x-ray source. This is the technique that has now been used by physicists to determine the actual size and distribution of radiation for x-ray tube focal spots.

***Reflection (like light)*:** The question is whether x-rays are reflected from surfaces as light is reflected.

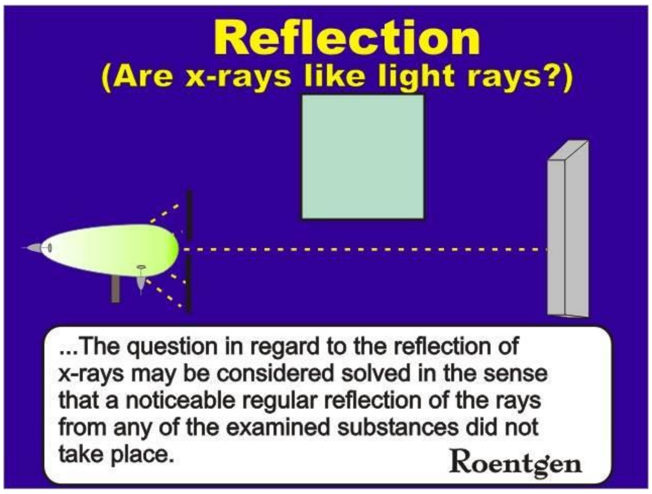

Fig. 6. Reflection of x-rays from a variety of materials was not observed.

***Scattering of x-radiation**:* In an interesting experiment described here the observation was reported as reflections from several metals. This appears to be scattering or the production of secondary radiation from within the metal objects and not reflections from the surfaces, as light would be reflected.

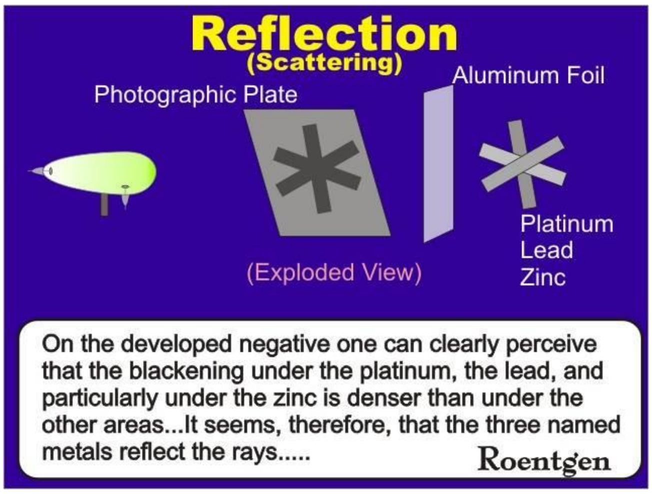

Fig.7. An experiment that apparently demonstrates the formation of a secondary radiation by different metals.

Refraction of x-radiation: A logical investigation was to determine if x-radiation undergoes refraction, a property that would be shared with light.

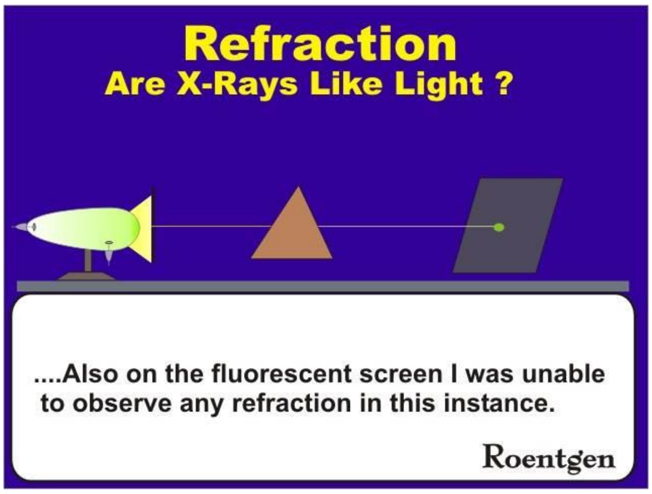

Fig.8. An experiment to investigate the possibility of refraction within a material.

Experiments were conducted using a variety of materials to determine if x-rays refracted, or changed direction, when moving from one material to another. There was no indication of this which suggested that x-rays could not be focused with a lens.

Do x-rays have magnetic properties? This was a continuation of experiments comparing x-radiation to known radiations--in this case, cathode rays.

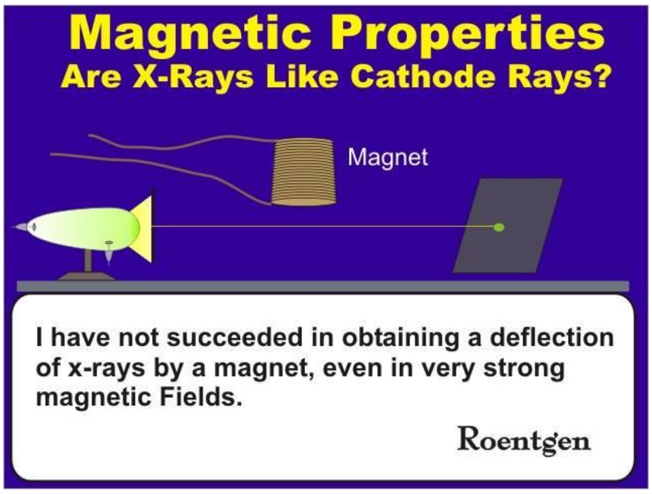

Fig.9. Cathode rays within a tube can be deflected with a magnet, but not x-rays emitted from a tube.

Effect of Object Thickness on Transparency**:** Having already observed that a variety of materials were transparent to x-radiation, attention was turned to investigating the relationship to material characteristics.

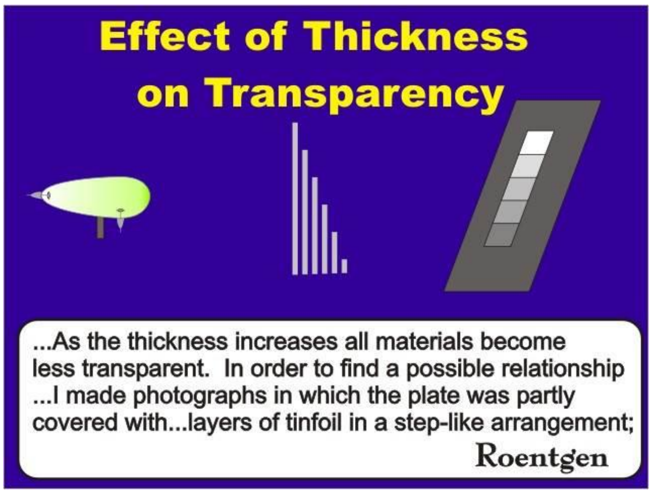

Fig.10. The use of a step wedge to investigate the effect of thickness on transparency.

In other experiments the effect of material density on transparency was studied. It was observed that the product of density and thickness was not the only factor affecting penetration. Various substances had different attenuations even when the product of density and thickness was the same. This third characteristic, in addition to thickness and density, was not specifically identified at that time. Today we know that characteristic is the atomic number (Z) of the material.

It was the ability to penetrate materials that made the x-radiation completely different from any other known radiations. Therefore it was the property studied in many experiments to determine the characteristics of both materials and the radiation that determined penetration.

Characteristics of the radiation that affect penetration.

To investigate what we would recognize as the spectral characteristics of the radiation, Roentgen constructed and used a device that was the first of what would become known as a penetrameter.

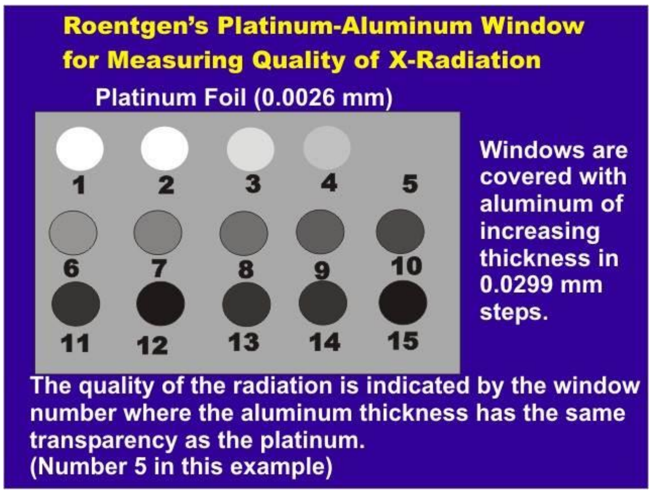

Fig.11. The general design of a device developed to investigate the spectral characteristics or quality of the radiation.

This is based on the principle that would be used years later for measuring the KV of x-ray spectra. It was built into a cassette and was a common test instrument used by physicists until the development of digital electronic KV meters. Similar devices are used in industrial radiography.

Filtration. It was observed by Roentgen that filtration increased penetration and he used his device to measure the effect as illustrated here.

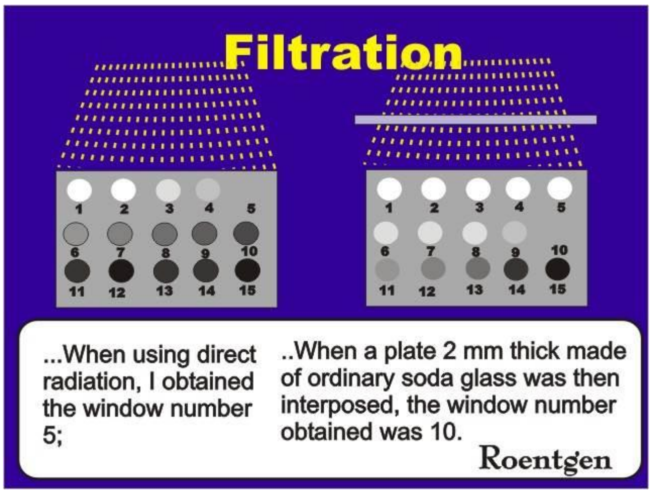

Fig.12. Measuring the effects of filtration on an x-ray beam spectrum.

***X-ray tube pressure or "hardness*"**. The pressure, or quality of the vacuum, in these early tubes was highly unstable and varied considerably. The pressure within a tube also was a factor in determining the voltage that developed across the tube. The terms "soft" and "hard" were used to describe the range of pressures and how the tube was operating. The glowing region within a tube varied with the pressure and could sometimes be used to judge its degree of "hardness".

The major significance was that as a tube became "harder" with reduced pressure the radiation became more penetrating. Roentgen observed this effect on the human hand as illustrated below.

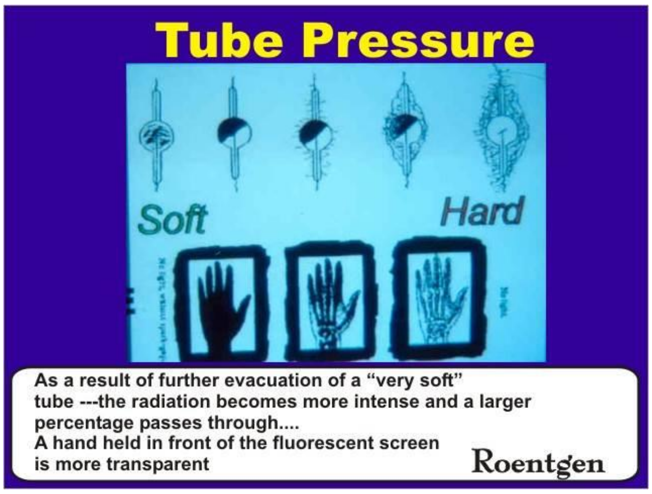

Fig. 13. Roentgen's observation of the effect of tube "hardness" on penetration through a human hand. Also illustrated is the change in the glowing region within a tube with pressure. This particular drawing is thought to be from a source other than Roentgen.

This variation in tube pressure was a considerable problem with the early x-ray tubes. Holding the hand in front of a fluoroscopic screen was a common practice to judge the degree of "hardness" and when the beam was appropriate for an imaging procedure.

This problem, along with some other limitations, was eliminated by the development of the hot-cathode tube.

Effect of anode material on x-ray production. Roentgen used a dual anode tube to demonstrate the effect of anode material on the efficiency of x-ray production. He experimented with several electrode configurations within tubes. His earlier tubes, such as used at the time of the discovery, were obviously not designed as x-ray tubes with anodes arranged for that purpose. As he learned more about how the radiation was being produced he obtained and used tubes that were designed for that purpose.

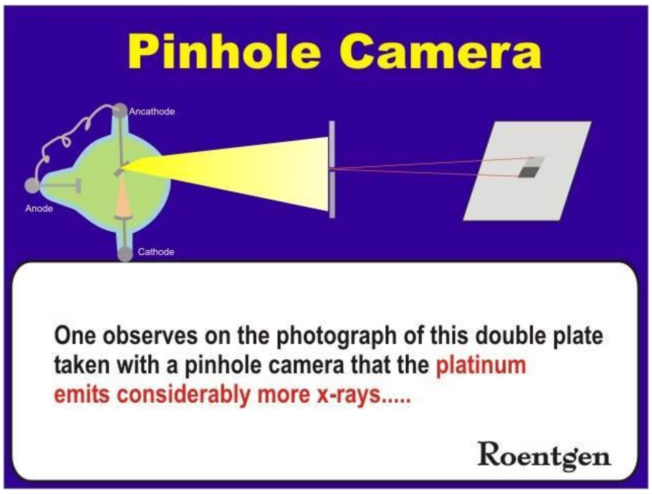

Fig. 14. An experiment to demonstrate the effect of anode materials.

Ionization of air.

Early in his investigations Roentgen had observed that x-rays were able to discharge electrified bodies. Before publishing on this he wanted to verify that the ionization of the air was being produced directly by the x-rays and not the high-voltage fields and discharges around the tubes and electrical apparatus. To isolate his experiments from the electrical fields he conducted them inside a large metal box into which only the x-rays could enter through a small hole.

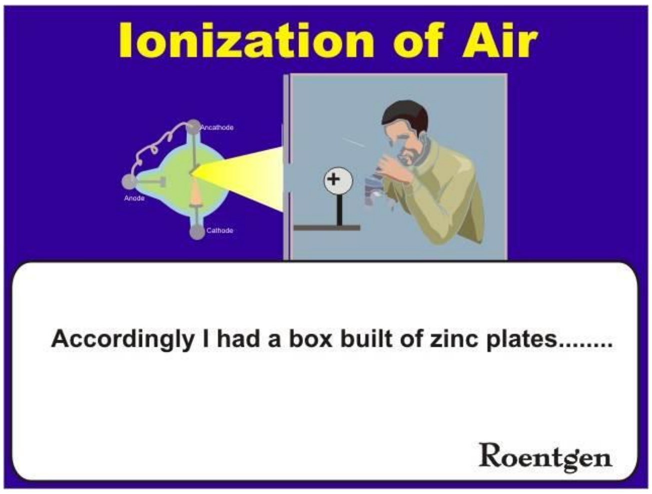

Fig.15. A shielded enclosure to investigate the ionization of air.

One experiment to demonstrate that the ionization was in the air and also remained in the air for some time is illustrated below.

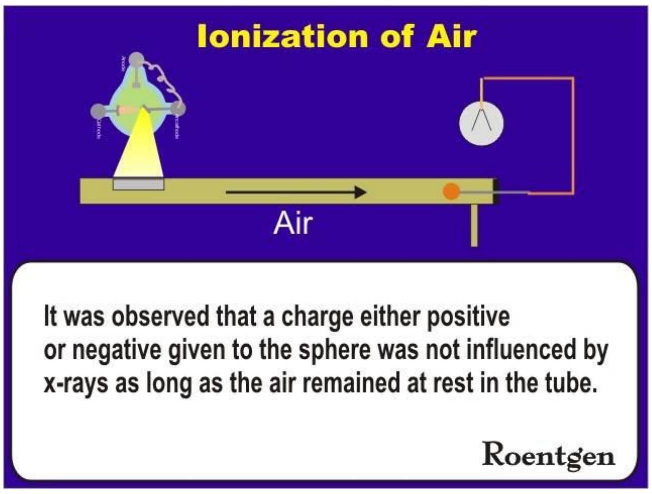

Fig.16. Verifying that the ionization was within the air.

IV. RESULTS AND CONCLUSIONS

During a period of less than three months of very intense experimentation Roentgen discovered, evaluated, and documented essentially every property and characteristic of the new kind of radiation as illustrated below.

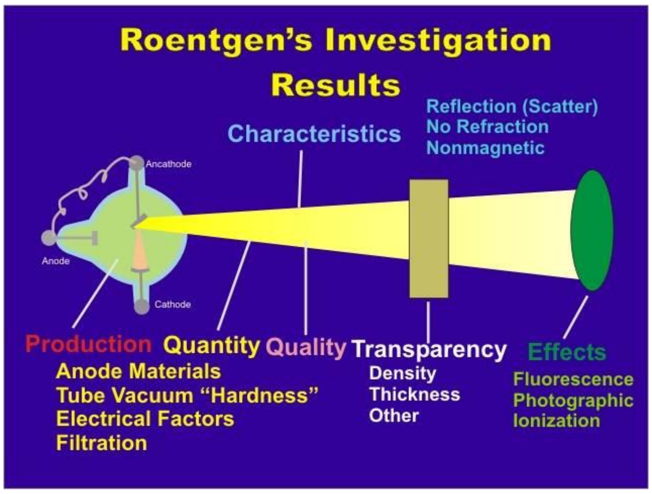

Fig.17. The properties of x-radiation that were investigated by Roentgen along with a summary of the results.

V. THE PRESENTATION

He submitted his first paper (Ref.1) for publication on December 28, 1895, less than two months after the discovery. In addition to submitting it for publication he sent reprints to several colleagues and distinguished scientists at other institutions. It was through this distribution of reprints to persons who understood the significance of his discovery and preliminary investigations that it was introduced to the world.

Following his first paper and announcement Roentgen received invitations from various groups, including the German parliament, the Reichstag, to lecture and describe his work and discovery, which he refused. The invitation that he did accept was from his Wurzburg colleagues and the Wurzburg Physical-Medical Society. This was delivered as shown below to a large audience of professors, high-ranking government officials and military officers, and students.

Fig. 18. Roentgen's public lecture and demonstration of the new kind of radiation.

He began by stating that because of the interest that had developed he believed it was his duty to discuss his work but that the experiments were still in a preliminary stage. He then referred to the work of several others, including Hertz and Lenard, and that this had encouraged him to conduct experiments along the same lines. He then described his observation of fluorescence of the small screen and that the tube was the source. He focused on the penetrating characteristics of the radiation, which he said he discovered by accident, and the use of photography to demonstrate this characteristic. He then demonstrated with several materials and objects.

Perhaps the highlight of the presentation was when he asked His Excellency Albert von Koliker, the famous anatomy professor, for permission to produce an x-ray image of his hand. When the image was developed and shown to the audience it generated tremendous applause. Von Koliker stated that in his many years (almost half a century) of attending medical and scientific meetings, this was the most significant presentation he had experienced. After leading the audience in three cheers for Roentgen he proposed that the new kind of radiation be called "Roentgen's Rays" which was approved by the audience.

REFERENCES

The references for this paper are the reports published by Roentgen (Ref. 1-3) and the English translations with additional information in the book by Glasser (Ref. 4)

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