Boston QuarkNet Workshop
Photons:
Gamma Rays

August 4, 2021

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Discovery of Gamma Rays

- In 1900 French chemist Paul Villard (1860-1934) studied radiation from radium. He placed radium chloride in a thin glass ampoule inside a lead tube with one end closed. The tube rested on a photographic plate double-wrapped in black paper. He formed a beam of radiation with a 6 mm wide rectangular slot in a lead bar followed by a region with a magnetic (*B*) field. Villard found that part of the beam was deflected by the *B* field, as cathode rays would be, and part of the beam was not deflected and could penetrate 0.2 mm thickness of lead.
- In 1903 Ernest Rutherford named these undeviated rays “gamma rays,” since they were more penetrating than the rays from radioactive materials that he had named “alpha” and “beta” in 1899.

Identification of Gamma Rays

- In 1914 Ernest Rutherford and Edward Andrade used the diffraction of gamma rays from crystals to show that they were like x-rays but of shorter wavelength.
- X-rays were initially called "soft" or "hard" based on their penetration depth (short or long) in matter. Today x-rays and gamma rays are usually referred to by their photon energy rather than their wavelength (λ).

soft x-rays – 0.1 keV (λ about 10 nm) to 10 keV (λ about 0.1 nm)
(Typical atom diameter is about 0.1 – 0.2 nm.)

hard x-rays – 5 keV (λ about 200 pm) to 100 keV (λ about 10 pm)

gamma rays – Energy > a few 10s of keV (λ < a few 10s of pm)

Notice overlaps: soft → hard x-rays and hard x-rays → gamma rays.

X-rays or Gamma Rays?

- Radiation from a cathode ray tube is usually called x-ray,
  e. g. dental x-ray machine run at 60 keV or
  CT machine run at 20 – 150 keV.
- Radiation from a radioactive source is usually called gamma ray,
  e. g. Tc-99m 141 keV gamma ray for a bone scan.

Light Quanta to Photons: Compton Effect

- Arthur Compton (1892-1962) wrote his dissertation at Princeton on x-ray reflection (PhD 1916).
- After work developing aircraft instrumentation during WW I and a year at the Cavendish Lab at Cambridge, he became a professor at Washington U., St. Louis and continued his study of x-rays.

Initial Thoughts

- For hard x-rays and gamma rays, scattering was reduced below values expected from Thomson's scattering theory and concentrated in the forward direction.
- Compton suggested (May 1923) that "this reduced scattering of very short wave-length X-rays might be the result of interference between rays scattered from different parts of the electron, if the electron's diameter is comparable to the wave-length of the radiation."
- He investigated the scattering phenomenon in greater detail with an x-ray spectrometer.

Compton's X-ray Tube

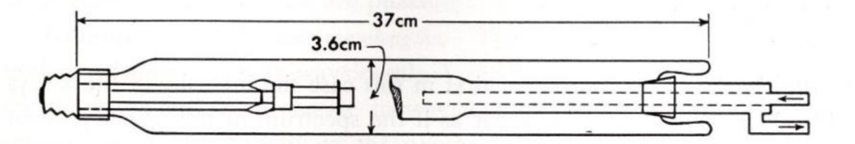


Fig. 2. X-ray tube.

- The molybdenum target of Compton's x-ray tube was water cooled (dashed line in diagram) to carry away the heat generated by the 1.5 kW cathode ray beam. Only about 1% of the beam energy was converted to x-rays.
- The narrow tube diameter (3.6 cm ensured a large proportion of x-rays hit the graphite scatterer.

Compton's X-ray Spectrometer

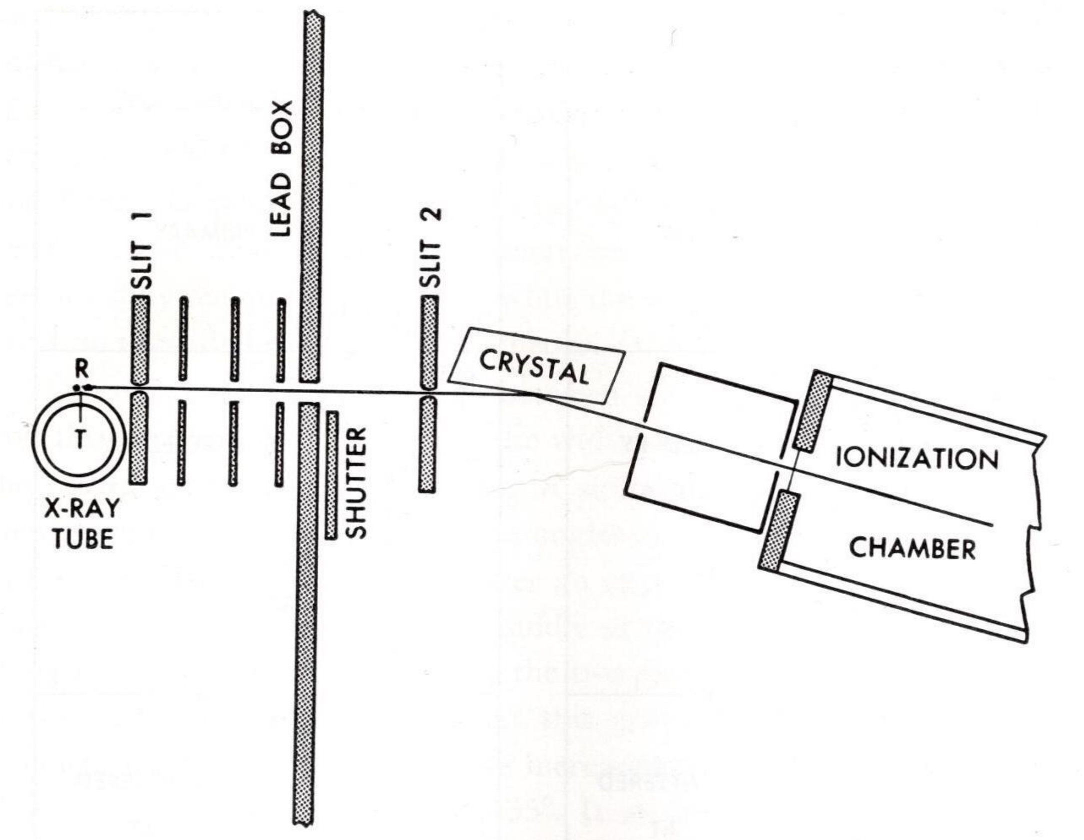


Fig. 1. Measuring the wavelength of scattered x-rays.

- T marks the molybdenum anode location in the center of the x-ray tube seen end-on here.
- R marks the location of the graphite scatterer.
- In this diagram, the angle between incident x-rays and x-rays scattered from the graphite is 90 degrees.

Compton's Results

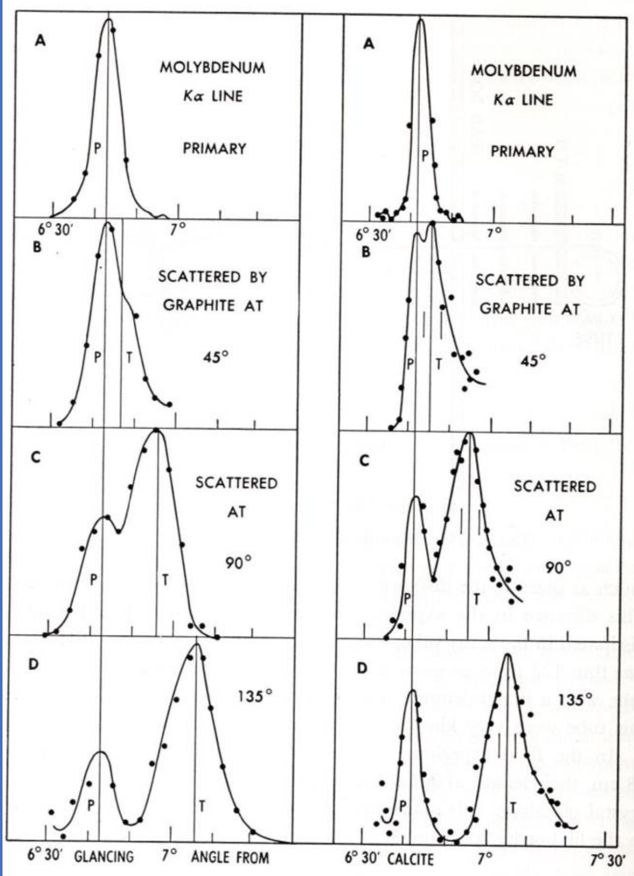


FIG. 3 FIG. 4

- The width of the slits in Compton's apparatus was about 0.1 mm, with the narrower slits used for the data in Figure 4.
- In addition to the undeviated peak at all angles, there is a peak shifted to larger angles in the spectrometer (longer λ) at larger scattering angles.
- Compton found this peak at exactly the place predicted by applying Einstein's theory of radiation quanta interacting with stationary electrons.

Photons - 1

- “When I presented my results at a meeting of the American Physical Society in 1923,” Compton recalled, “it initiated the most hotly contested scientific controversy that I have ever known.”
- Compton and others later devised ways of examining the recoil electrons at the same time as the scattered x-ray quanta and confirmed the application of the Einstein theory to the scattering.
- The term “photon” was originally coined by physiologists to denote the smallest quantity of perceived light. In that context, it disappeared.
- Gilbert Lewis resurrected the term in 1926 for his concept of a light quantum travelling from atom to atom.

Photons - 2

- 1927 - Arthur Compton received the Nobel Prize in Physics
  "for his discovery of the effect named after him."
- In his Nobel address, Compton described his experiments and noted that "Here we do not think of the X-rays as waves but as light corpuscles, quanta, or, as we may call them, photons. Moreover, there is nothing here of the forced oscillation pictured on the classical view, but a sort of elastic collision, in which the energy and momentum are conserved." Compton used the term "photon" at least 12 times in his Nobel address.
- Compton again used "photon" in a February 1929 *Scientific American* article, where he noted, "The light which makes the plants grow and which gives us warmth has double characteristics of waves and particles, and is found to [consist] ultimately of photons."
- The use of "photon" in physics literature grew slowly during the 1930s, then rapidly after WW II.

Gamma Rays From Radioactive Sources

- $^{137}_{55}\mathrm{Cs} \rightarrow {}^{137m}_{56}\mathrm{Ba} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ $T_{1/2}$ = 30.2 yr

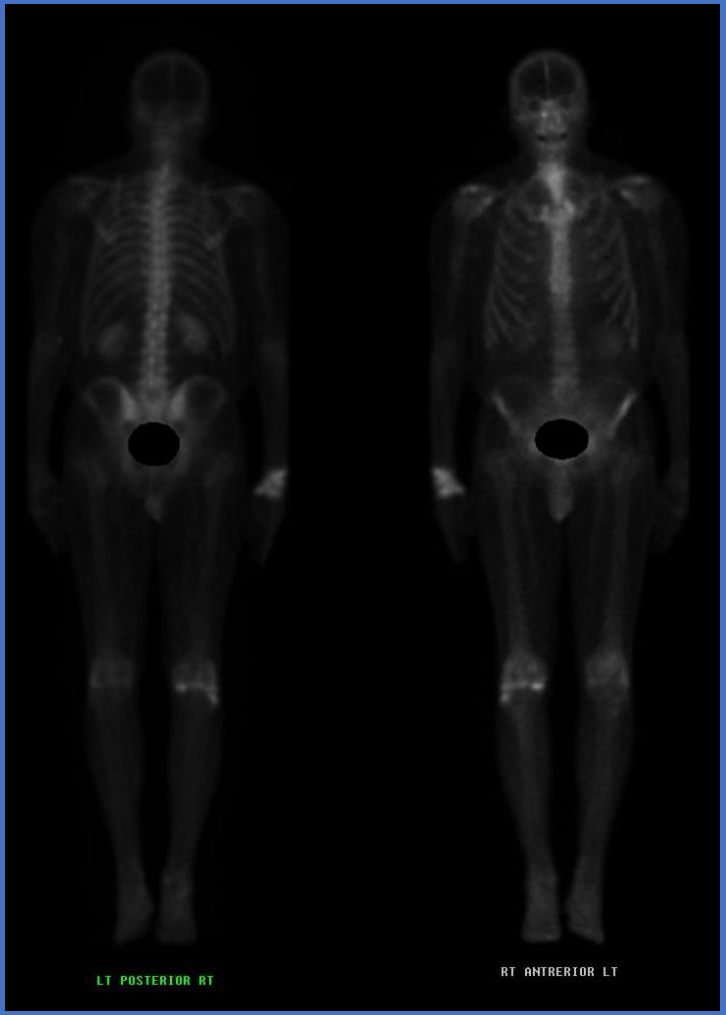
  $^{137m}_{56}\mathrm{Ba} \rightarrow {}^{137}_{56}\mathrm{Ba} + \gamma$ E_γ = 662 keV $T_{1/2}$ = 2.55 min

- $^{99}_{42}\mathrm{Mo} \rightarrow {}^{99m}_{43}\mathrm{Tc} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ $T_{1/2}$ = 2.75 day

  $^{99m}_{43}\mathrm{Tc} \rightarrow {}^{99}_{43}\mathrm{Tc} + \gamma$ E_γ = 141 keV $T_{1/2}$ = 6.01 hr

  $^{99}_{43}\mathrm{Tc} \rightarrow {}^{99}_{44}\mathrm{Ru} + \mathrm{e}^- + \bar{\nu}_\mathrm{e}$ $T_{1/2}$ = 211,000 yr

Bone Scan with Tc-99m



Gamma Rays in Astronomy

- Gamma ray bursts (GRB) lasting from milliseconds to minutes are immensely energetic. Short GRBs (<2 s) are thought to be the result of neutron star mergers. Long GRBs are thought to originate in supernova explosions. GRBs were first seen by the VELA satellites designed to detect nuclear blasts on Earth. They occur all over the sky and puzzled astronomer for many years.
- Recently the Large High Altitude Air Shower Observatory in China has reported detection of 12 sources, including the Crab Nebula, of high energy gamma rays along the plane of the Milky Way. Gamma rays of very high energy, including one with 1.4 PeV, are produced by inverse Compton scattering by high energy electrons.
(CERN Courier July/ August 2021, p. 11)