Boston QuarkNet Workshop
Photons:
X-ray Vision

August 3, 2021

Rick Dower

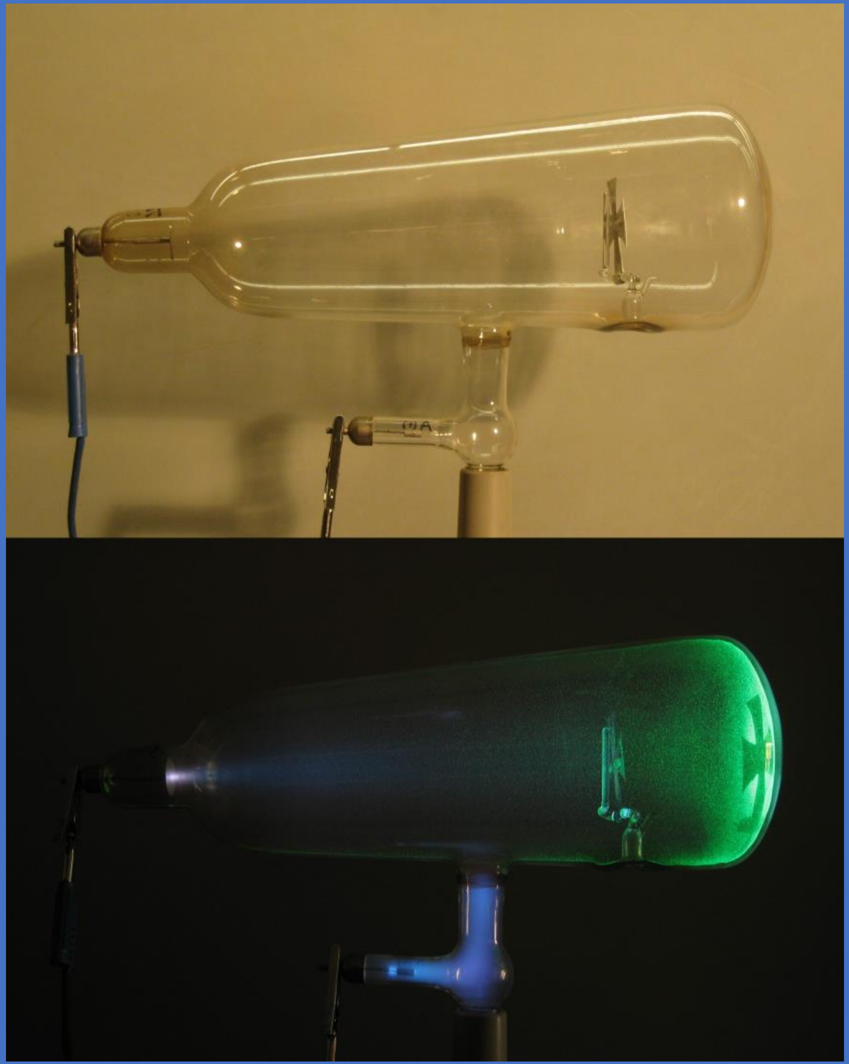
Wilhelm Röntgen (1845-1923)

Professor at University of Würzburg

Röntgen Memorial at Würzburg

Röntgen’s Lab at University of Würzburg

Fluorescence and X-rays from a Crookes Tube



X-ray Discovery

- November 8, 1895
- Röntgen set out to study the fluorescence produced on the glass walls of a Crookes tube when struck by high voltage cathode rays. The tube was surrounded by opaque black cardboard.
- Röntgen noticed that a paper screen coated with barium platinocyanide glowed in his darkened laboratory, even when 2 m away from tube, whenever cathode rays were produced.

Röntgen’s Results (1)

December 28, 1895

- “[A]ll bodies are transparent to this agent, though in very different degrees….pine boards two or three centimetres thick absorbingly slightly….Lead of a thickness of 1.5 millimetres is practically opaque.”
- “[P]hotographic dry plates are sensitive to X-rays.”
- “The retina of the eye is not sensitive to these rays.
- “No regular noticeable regular reflection of the rays takes place from any of the substances examined.”
- No detectable deviation occurs in prisms made of various substances.
- X-rays are not deviated by a magnet.
- “X-rays are not identical with cathode rays, but … are produced by the cathode rays at the glass wall of the discharge apparatus.”

Röntgen's Results (2)

December 28, 1895

- The unknown agents are called "rays" because of "the entirely regular formation of shadows, which are sees when…bodies are brought between the apparatus and the fluorescent screen (or the photographic plate)."
- "I have tried in many ways to detect interference phenomena of the X-rays; but, unfortunately, without success."
- "Ought not…the new rays be ascribed to longitudinal vibrations in the ether?"

March 9, 1896

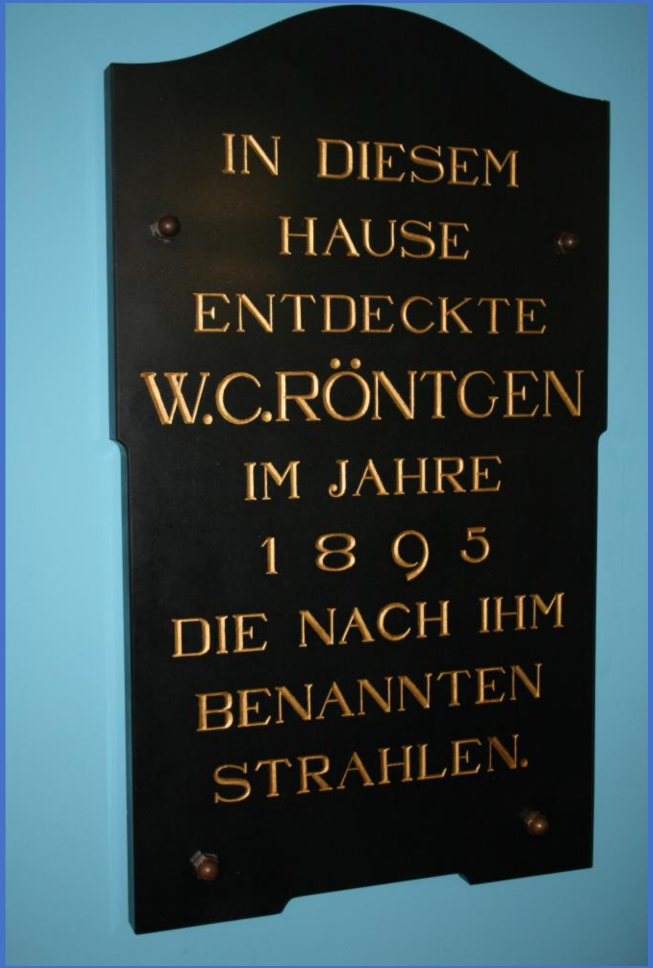
- "Electrified bodies in air, charged either positively or negatively, are discharged if X-rays fall upon them."
- "I have not found any solid body which cannot, under the action of cathode rays, produce X-rays."

First X-ray Photo - December 22, 1895

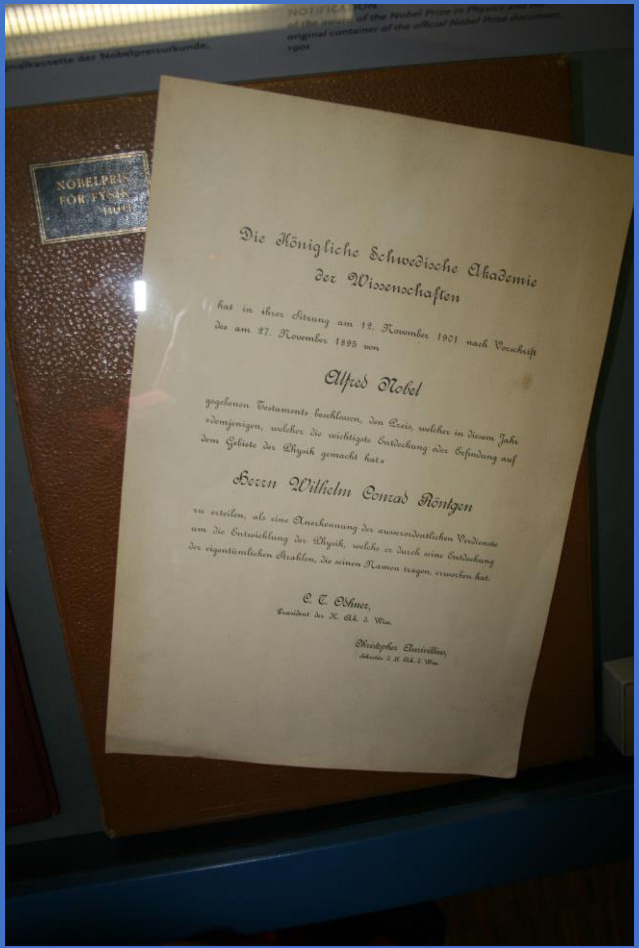
- X-ray photo of Anna Bertha Röntgen’s hand (with ring) is the first medical x-ray.
- She exclaimed “I have seen my death.”
- After Röntgen’s presentation at the Physico-Medical Society of Würzburg on 12/28/1895 and an Austrian newspaper story on 1/5/1896, medical x-rays became a sensation throughout the world.

1901 – Röntgen received the first Nobel Prize in Physics

Plaque in Röntgen Memorial



Nobel Prize Certificate



When you hear “Charles Barkla,” who comes to mind?

No. This is Charles Barkley (1963 -   )

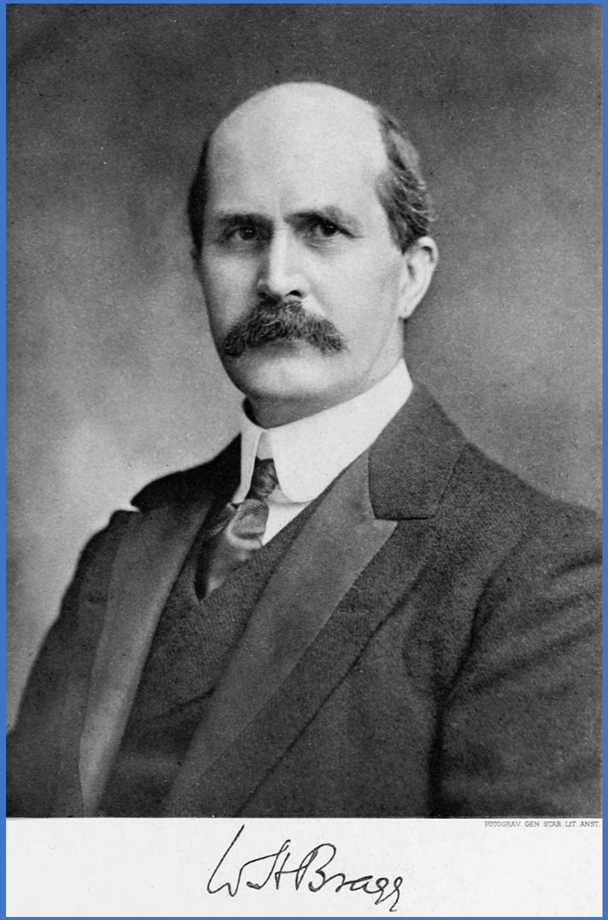
Charles Barkla (1877 – 1944)

- After studying math and physics at Liverpool, Barkla was admitted to Trinity College, Cambridge in 1899. He began to study the secondary radiation from gases subject to x-rays. (After 18 months, he transferred to King’s College to join their Chapel Choir.)
- Barkla’s principal apparatus, in addition to an x-ray tube, was a gold leaf electroscope to measure ionization and thin aluminum sheets to examine the attenuation of x-rays.

Barkla’s Results

- 1906 – Barkla examined the absorption of secondary x-rays in different directions emitted from carbon that was illuminated by a beam of primary x-rays. He concluded that the x-ray beam was polarized.
- Barkla also noticed that primary x-rays impinging on targets of different low-atomic-mass elements produced, in addition to scattered primary x-rays, more easily absorbed secondary x-rays. The absorption of these secondary x-rays was characteristic of the scattering element.
- 1908 - The “hardness” or penetrating power of these characteristic K (harder) and L (softer) x-rays increases with increasing atomic weight.
- Barkla advocated the idea that x-rays were pulses in the aether.
- 1917 – Barkla received the Nobel Prize in Physics “for his discovery of characteristic Röntgen radiation of the elements.”

William Henry Bragg (1862– 1942)



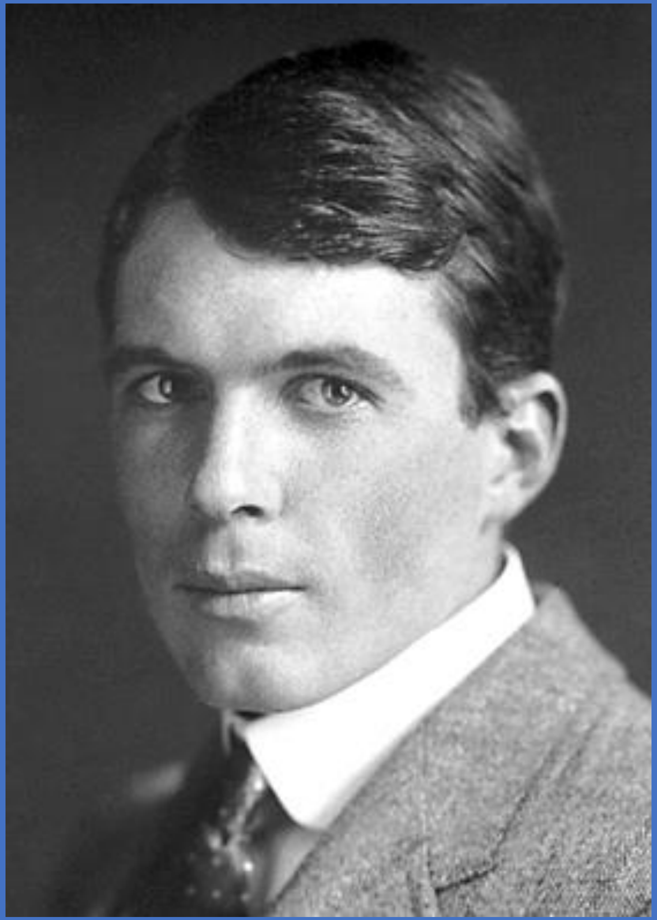
- While a professor at University of Leeds (after 1908), W. H. Bragg developed the view that x-rays were neutral pairs of charged particles since the entire energy of a cathode ray could be converted to an x-ray and transferred to a secondary electron ejected by that x-ray.
- Acorn-dropped-in-pond analogy

Max von Laue (1879 – 1960)

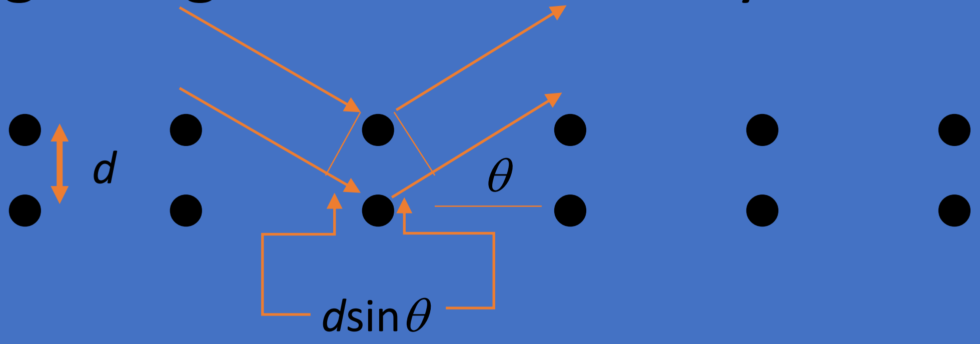
- 1912 - At the University of Munich, Laue realized that x-rays may have wavelengths similar to the atomic spacing in crystal lattices. He directed Friedrich and Knipping to place a photographic plate behind a large copper sulfate crystal illuminated by x-rays. They saw spots characteristic of wave diffraction. Laue developed a mathematical theory of crystal diffraction.
- 1914 – von Laue received the Nobel Prize in Physics "for his discovery of the diffraction of X-rays by crystals."

Can you name a parent-child pair of Nobel Prize winners?

William Lawrence Bragg (1890 – 1971)



- In 1912, Lawrence developed the Bragg equation for the coherent diffraction of x-rays at grazing incidence to a crystal:



$$n\lambda = 2d\sin\theta$$

W. H. Bragg and W. L. Bragg studied x-rays reflected from crystals.

X-ray spectrometer developed by W. H. Bragg (Science Museum London)

X-rays reflected from rock salt (NaCl) *PRS* A 88 (1913), 431.

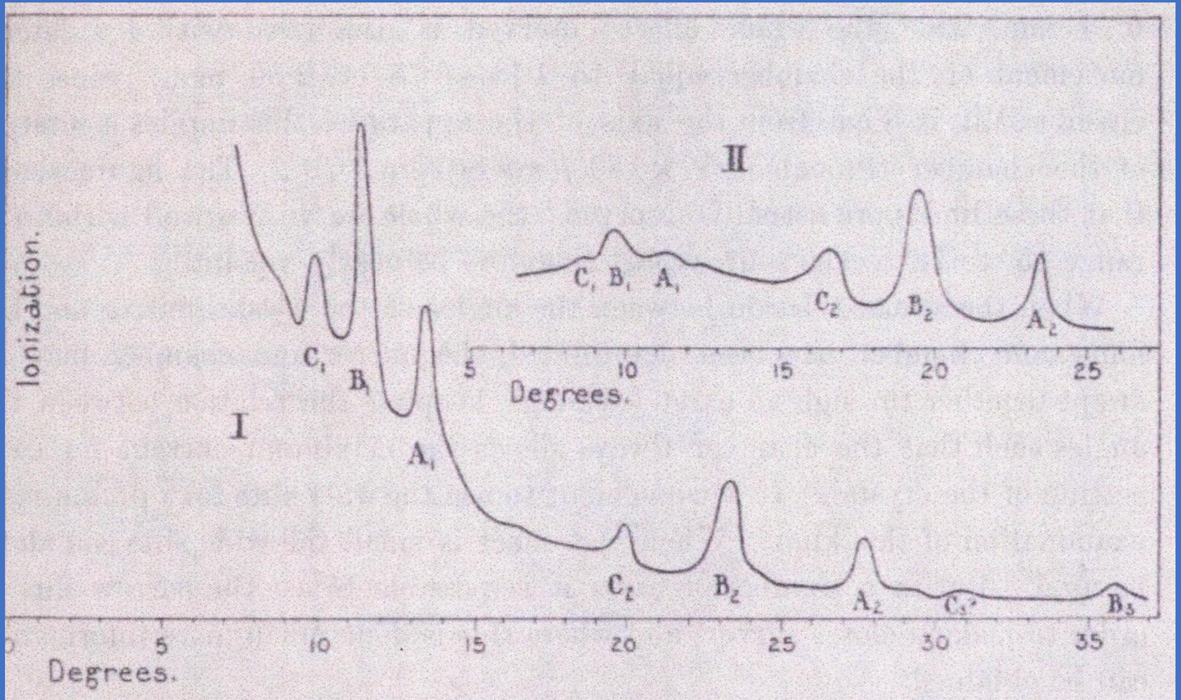


FIG. 3.—Reflection (I) from face (100) and (II) from face (111) of rock-salt. The curves show the variation of strength of reflected beam with angle of incidence.

Braggs' Spectrometer Measurements Results (*PRS* A 88 (1913))

- "The three peaks marked A, B, and C are common to the curves of all crystals so far investigated." (p. 430)

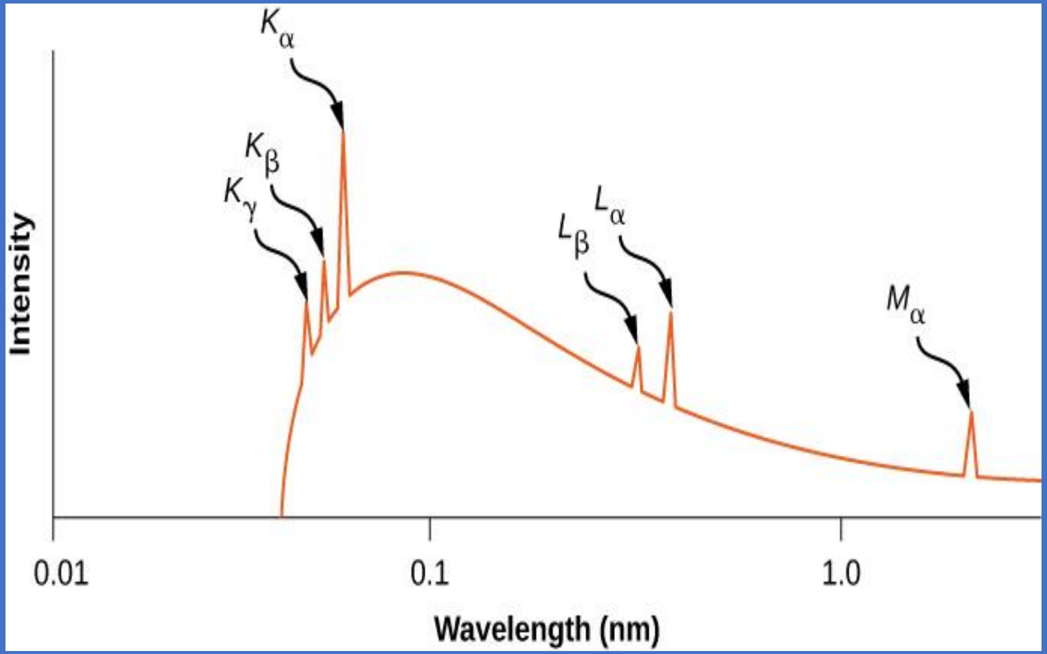
- "[T]he three peaks… may well [change] with the nature of the anticathode." (p. 434)

- Electromagnetic wave theory accounts for x-ray diffraction from crystals.

  The particle theory of x-rays "represents the facts of energy transfer from electron to X-ray and vice versa." (p. 436)

  "The problem remains to discover how two hypotheses so different in appearance can be so closely linked together." (p. 436)

Spectrum of an X-ray Tube



- Minimum wavelength (λ_{min}) is given by x-ray tube voltage (V):
  $$eV = hc/\lambda_{min} .$$
- Bremsstrahlung (braking radiation) forms a continuum.
- X-ray intensity peaks in K, L, and M series are characteristic of the anode element.

Can you name another pair of parent-child Nobel Prize winners?

Two More Parent – Child Pairs of Nobel Prize Winners

- 1903 – Marie Curie “in recognition of the extraordinary services they rendered by their joint researches on the radiation phenomena discovered by Professor Henri Becquerel: (with Pierre Curie and Henri Becquerel) – Physics [1911 – Marie Curie for radium and polonium - Chemistry]

  1935 – Irène Joliot-Curie “in recognition of their synthesis of new radioactive elements (with Frédéric Joliot) – Chemistry

- 1906 – Joseph John Thomson “in recognition of the great merits of his theoretical and experimental investigations on the conduction of electricity in gases” – Physics

  1937 – George Paget Thomson “for the experimental discovery of the diffraction of electrons by crystals” (with Clinton Davisson) - Physics

Subsequent Developments in X-ray Studies

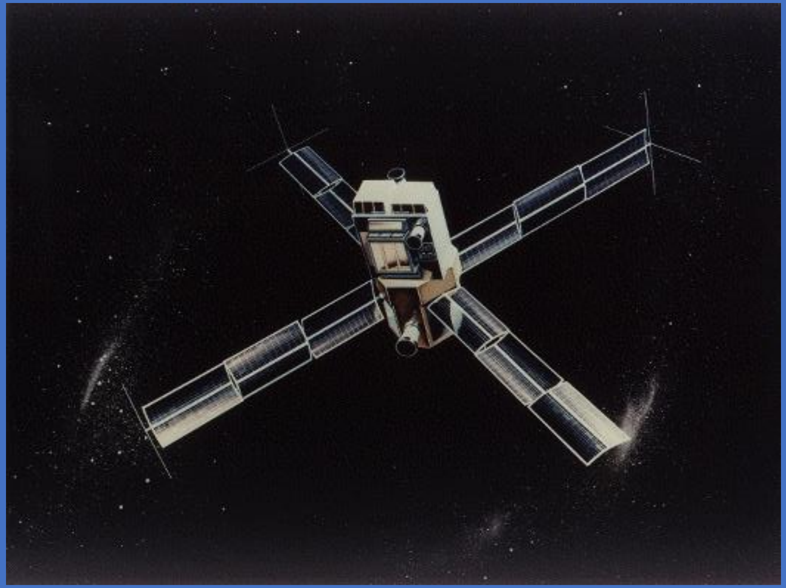
- The Braggs used x-rays to investigate the structure of a variety of crystals.
- W. H Bragg and W. L. Bragg received the Nobel Prize for Physics in 1915 “for their services in the analysis of crystal structure by means of X-rays.”
- Henry Moseley used a variety of anode materials in an x-ray tube to investigate the characteristic x-rays of a variety of elements.
- ONE MORE PARENT-CHILD PAIR OF NOBEL PRIZE WINNERS:

Manne Siegbahn (1886 – 1978) received the Nobel Prize in Physics “for his discoveries and research [including precision measurements] in the field of X-ray spectroscopy.”

Kai Siegbahn (1918 – 2007) received the Nobel Prize in Physics in 1981 “for his contribution to the development of high-resolution electron spectroscopy [of photoelectrons ejected by x-rays from surfaces].”

Astrophysical X-rays

SAS-3



Chandra