$$\boxed{E^2 = p^2c^2 + m_0^2 c^4}$$

for light: $E = hf$

certainly finite

also

$$E = m_0 \gamma c^2$$

$$E = \frac{m_0}{\sqrt{1-\beta^2}} c^2$$

FLASH: light travels at the speed of...

light.

so $\beta = 1 \Rightarrow E = \frac{m_0}{0} c^2$

only finite if $m_0 = 0$

From $\boxed{\;\;}$: $E = pc$

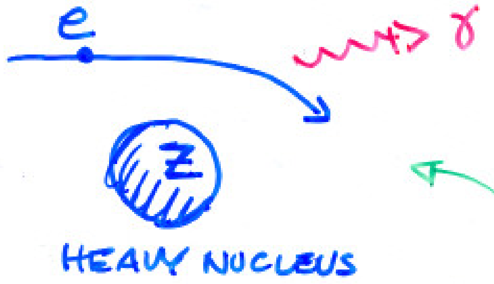
$p = E/c \;\left(= \frac{hf}{c}\right)$

like in Maxwell's theory (energy & momentum densities)

X-Rays

There are a couple of things going on @ your dentist's x-ray machine.

Important physical process:



(or any other charged projectile)

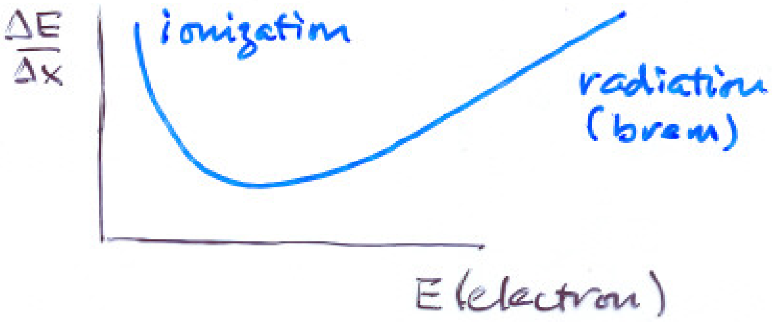
this radiation is called bremsstrahlung "braking radiation"

$$-\frac{\Delta E}{\Delta x} \propto \frac{K}{m^2}$$

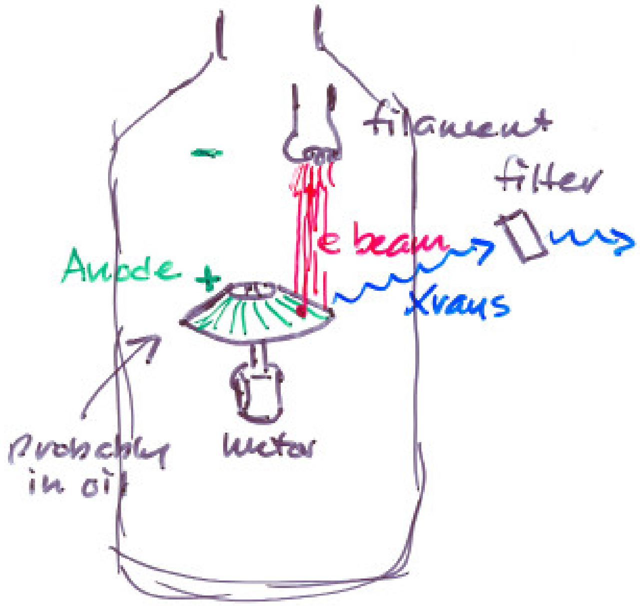
so electrons "brem" much more than, say, protons or "muons"

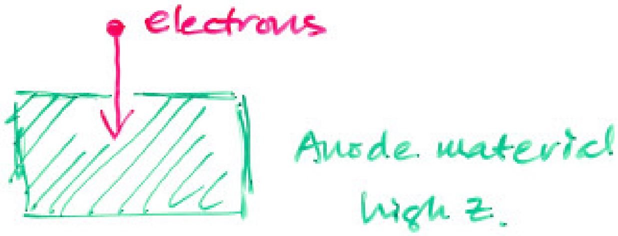
charged particles passing through matter also lose energy by ionizing the material's atoms.

$$-\frac{\Delta E}{\Delta x} \propto \frac{\ln E}{\beta^2}$$



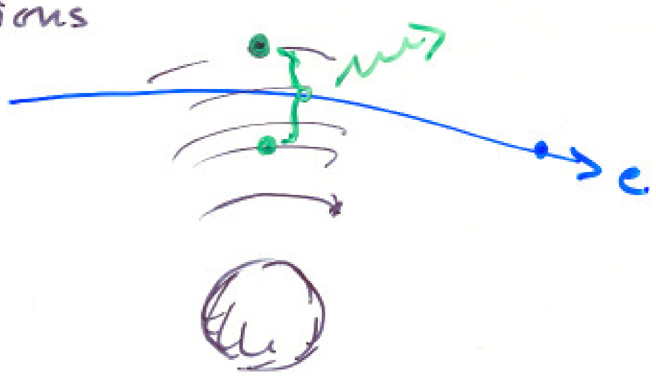
@ the Dentist...


filament
filter
-
e beam
Anode +
Xrays
probably in oil
motor

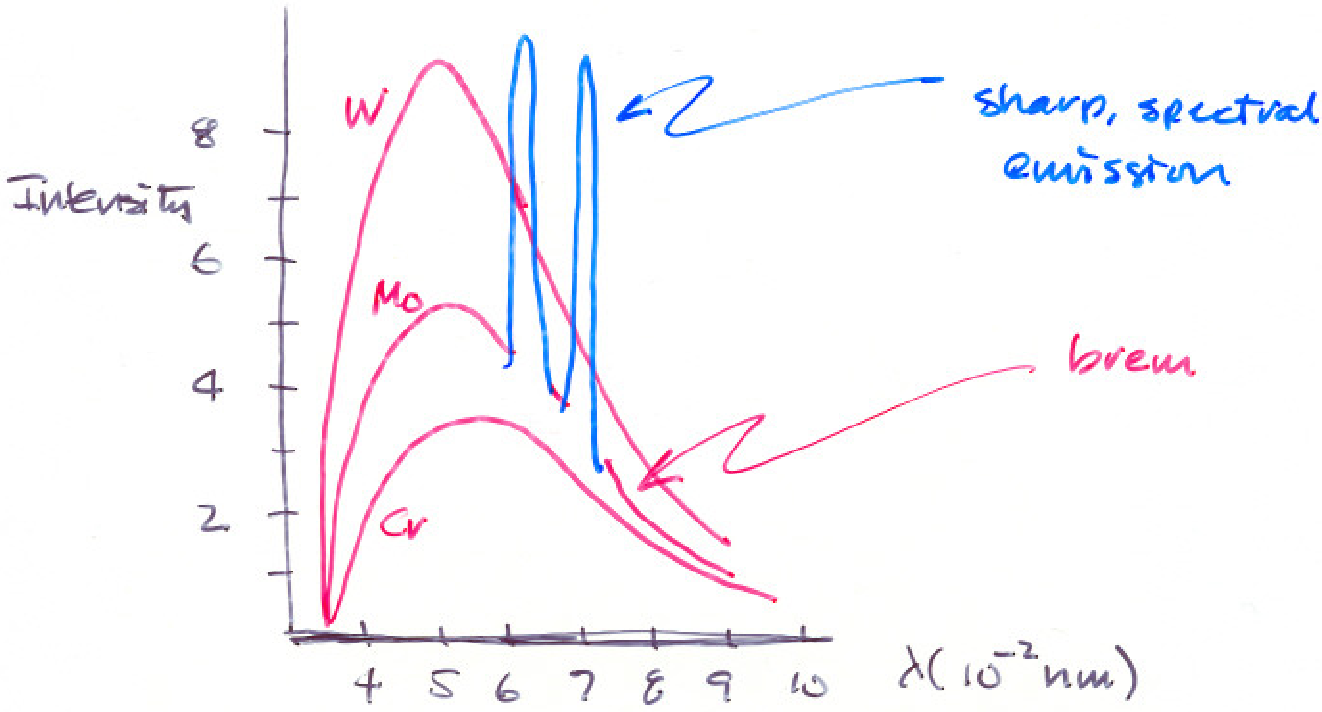

electrons
Anode material
high Z.

Bremsstrahlung is <u>continuous</u>.

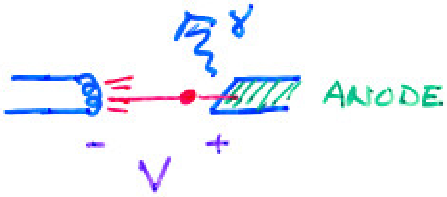
An electron can also stimulate atomic level transitions



This is DISCRETE...



X-ray Devices are characterized by their accelerating voltages



The maximum E_γ is when e gives up all of its kinetic energy to radiation.

$$K_{elec} = eV$$

exercise in units...

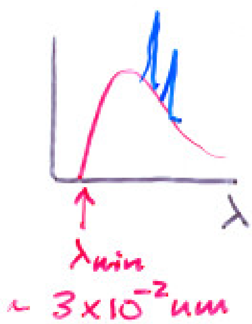
$$e = 1.6 \times 10^{-19}\,C$$

$$[V] = \text{volts} = J/C$$

$$[K] = J \text{ or } eV$$

$$E_\gamma^{max} = K_{elec} = eV$$

$$= h\nu_{max} = \frac{hc}{\lambda_{min}}$$



what's the voltage?

$$eV = \frac{hc}{\lambda_{min}}$$

$$V = \frac{hc}{e\lambda_{min}}$$

$$h = 6.6261 \times 10^{-34}\ J \cdot s$$

but very useful in different configurations...

$$h = 4.1357 \times 10^{-15}\ eV \cdot s$$

$$[h] = eV \cdot s \quad \rightarrow \quad [h]\ \cancel{J} \cdot s \left(\frac{eV}{1.6 \times 10^{-19}\ \cancel{J}} \right)$$

$$h = \frac{6.6261 \times 10^{-34}\ J \cdot s}{1.6 \times 10^{-19}\ J/eV} = 4.14 \times 10^{-15}\ eV \cdot s$$

also we'll find $h/2\pi$ useful... has a name:

$$\hbar \quad \text{"h-bar"} \equiv \frac{h}{2\pi} = 1.054 \times 10^{-34}\ J \cdot s = 6.5821 \times 10^{-16}\ eV \cdot s$$

also find hc useful:

$$(hc) = (4.1357 \times 10^{-15}\ eV \cdot s)(3 \times 10^{8}\ m/s)\left(10^{+9}\ \frac{nm}{m}\right)$$

$$\cancel{= 1.241 \times 10^{-15}\ eV \cdot nm}$$

$$= 1241\ eV \cdot nm$$

$$(hc) = (6.6261 \times 10^{-34}\ J \cdot s)(3 \times 10^{8}\ m/s)$$

$$hc = 1.99 \times 10^{-25}\ J \cdot m$$

so, back to problem

$$V = \frac{hc}{e\lambda_{min}}$$

"hard" way

$hc = 1.99 \times 10^{-25}\ J \cdot m)$

$$V = \frac{(1.99 \times 10^{-25}\ J \cdot m)}{(1.6 \times 10^{-19}\ C)(3 \times 10^{-2} \times 10^{-9}\ m)}$$

$V = 41{,}460\ J/C = 41{,}460\ V$

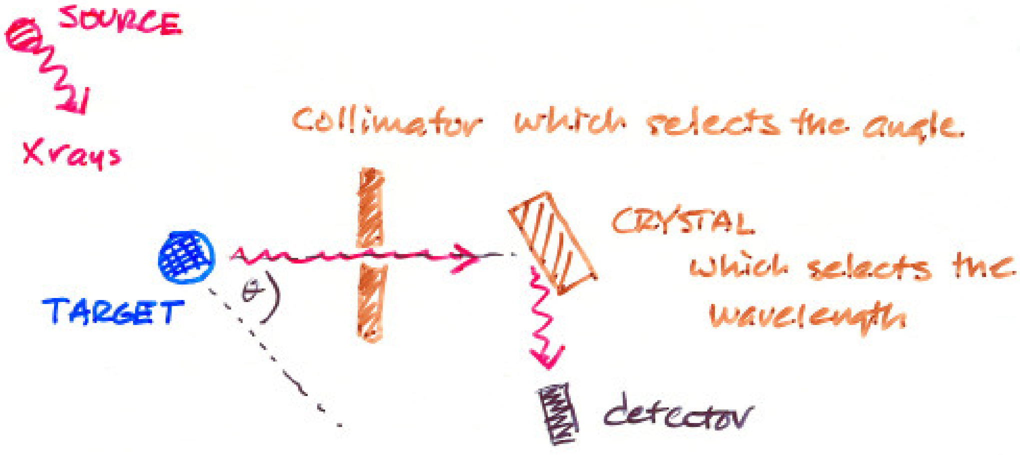
"easy way"

$hc = 1241\ eV \cdot nm$

$$V = \frac{1241\ \cancel{e}V\ nm}{\cancel{e}\ (3 \times 10^{-2}\ nm)}$$

$V = 41{,}400\ V$

takes some getting used to...!



1923 Compton Expt.

Millikan hated Einstein's idea... worked for a decade at UC to disprove it.

and beautifully confirmed it by 1913.

Definitive test also at UC by Arthur Holly Compton.
DISCOVERY OF PHOTON

Imagine $\gamma + e \rightarrow \gamma + e$ elastic scattering

at rest

① $\vec{q} + \vec{P} = \vec{q}\,' + \vec{P}\,'$ ② $E_\gamma + E_e = E_{\gamma'} + E_{e'}$

*

① since $|\vec{q}| = \frac{hf}{c}$ and $|\vec{q}\,'| = \frac{hf'}{c}$

will have different frequencies → measure the photon, not electron

SAY WHAT?

mixing scattering kinematics for particles with optics...

$$\vec{p}\,' = \vec{q} + \underset{\phi}{\underset{\uparrow}{\vec{p}}} - \vec{q}\,'$$

$$\vec{p}\,' = \vec{q} - \vec{q}\,'$$

$$p'^2 = (\vec{q} - \vec{q}\,')^2 = q'^2 + q^2 - 2\vec{q}\cdot\vec{q}\,'$$

$$p'^2 = \left(\frac{hf'}{c}\right)^2 + \left(\frac{hf}{c}\right)^2 - 2\left(\frac{hf}{c}\right)\left(\frac{hf'}{c}\right)\cos\theta \qquad \star$$

from ②

$$E_\gamma + E_e = E_{\gamma'} + E_{e'}$$

$$hf + mc^2 = hf' + \sqrt{p'^2c^2 + m^2c^4}$$

$$p'^2c^2 + m^2c^4 = (hf + mc^2 - hf')^2$$

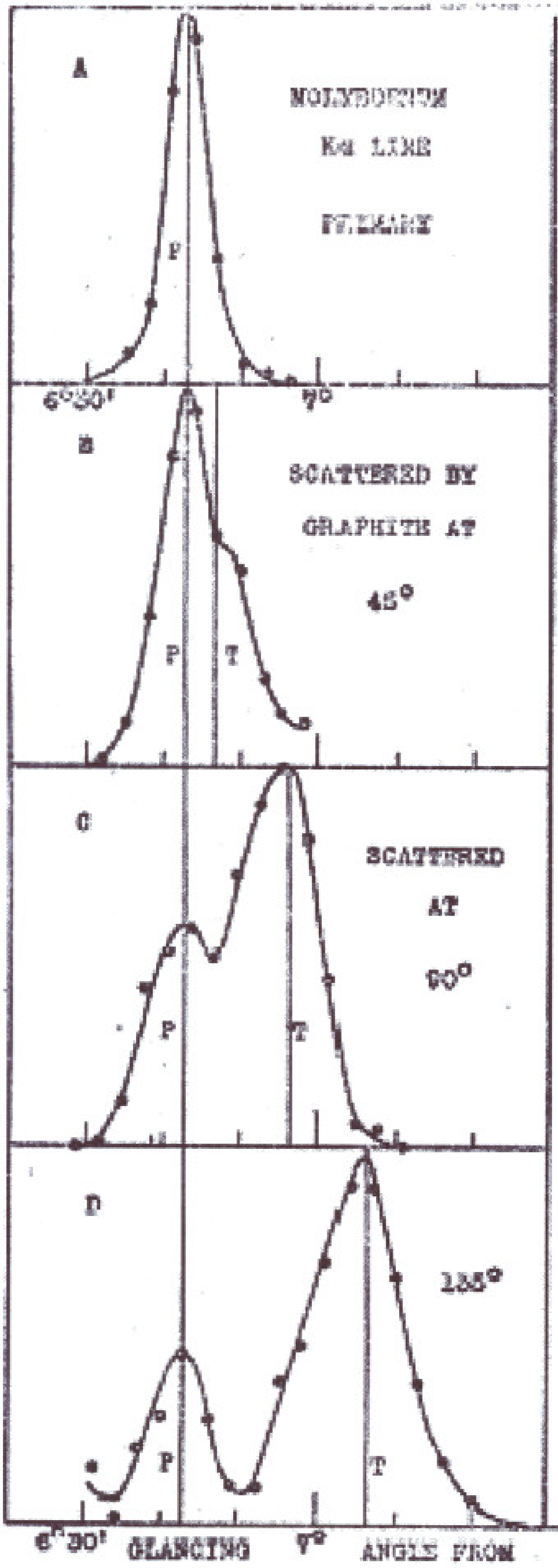
$$p'^2 + m^2c^2 = \left(\frac{hf}{c}\right)^2 + \left(\frac{hf'}{c}\right)^2 - 2\left(\frac{hf}{c}\right)\left(\frac{hf'}{c}\right) + 2mh(f - f') + m^2c^2$$

get p'^2 from $\star$

$$2\left(\frac{hf}{c}\right)\left(\frac{hf'}{c}\right)(1 - \cos\theta) = 2mhc\left(\frac{f}{c} - \frac{f'}{c}\right)$$

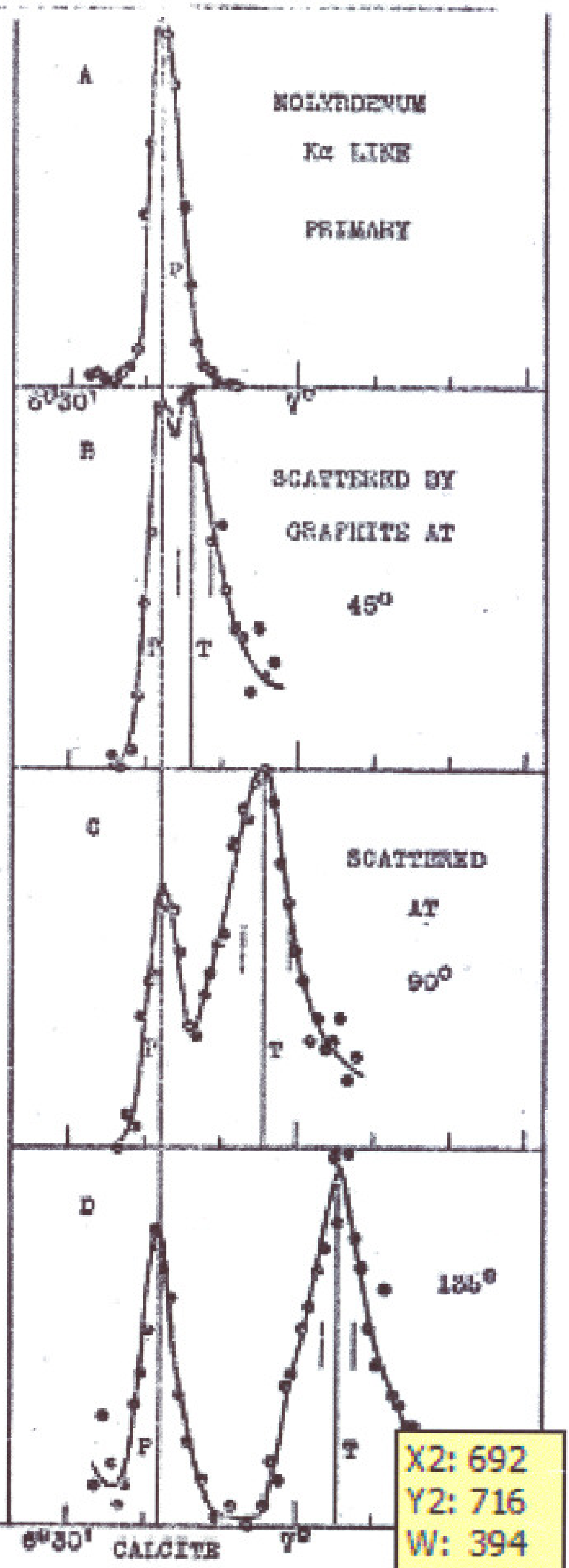
remember… measure λ…

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$



A
MOLYBDENUM
Kα LINE
PRIMARY
P
6°30'
7°
B
SCATTERED BY
GRAPHITE AT
45°
P
T
C
SCATTERED
AT
90°
P
T
D
135°
P
T
6°30'
GLANCING
7°
ANGLE FROM

Fig. 3



A
MOLYBDENUM
Kα LINE
PRIMARY
P
6°30'
7°
B
SCATTERED BY
GRAPHITE AT
45°
T
T
C
SCATTERED
AT
90°
P
T
D
135°
P
T
6°30'
CALCITE
7°

Fig. 4

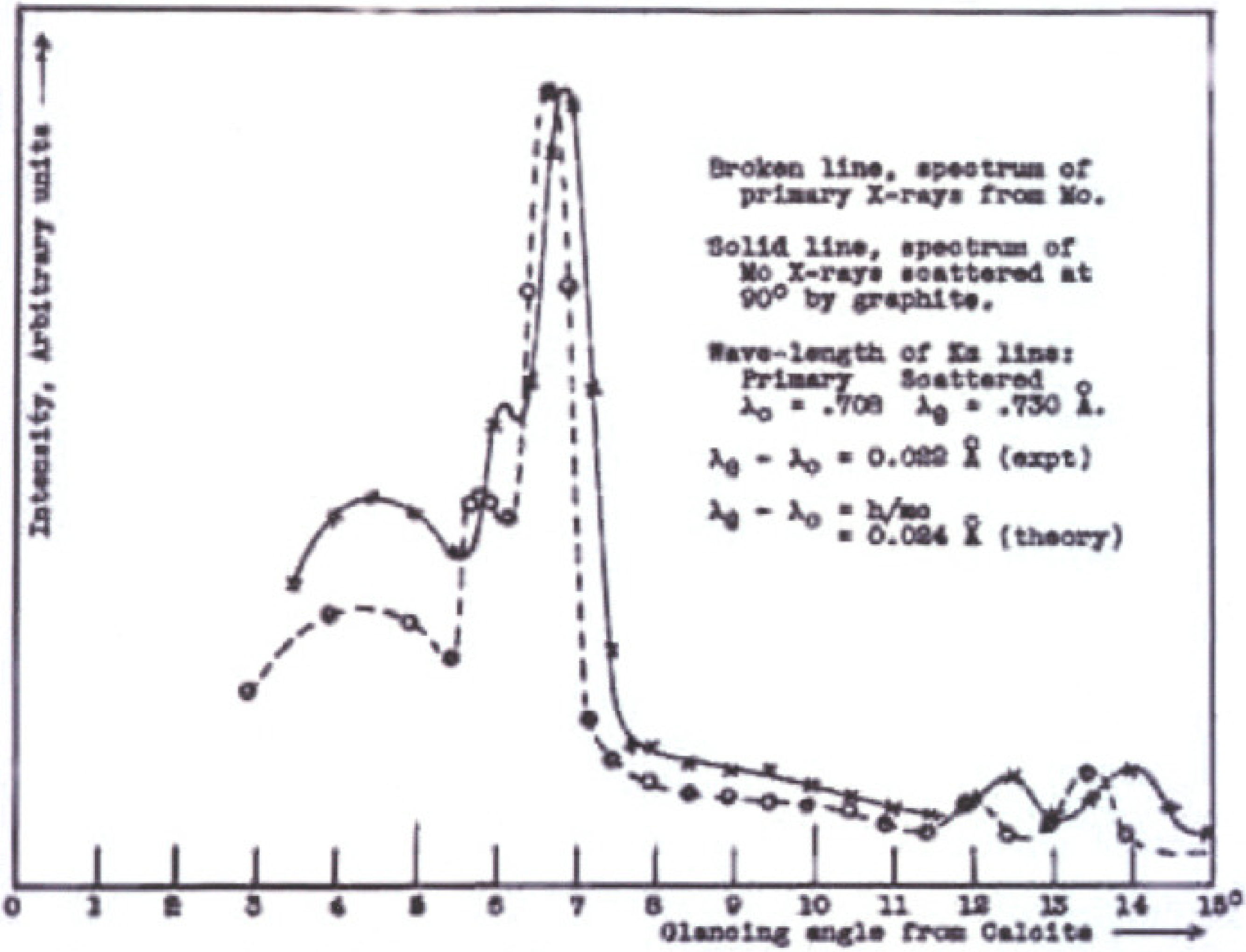
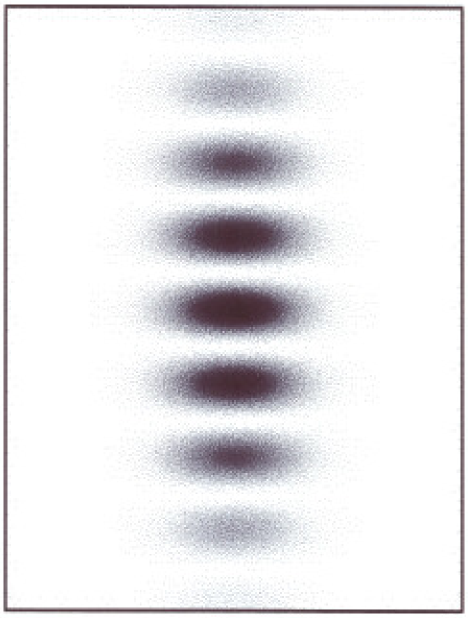


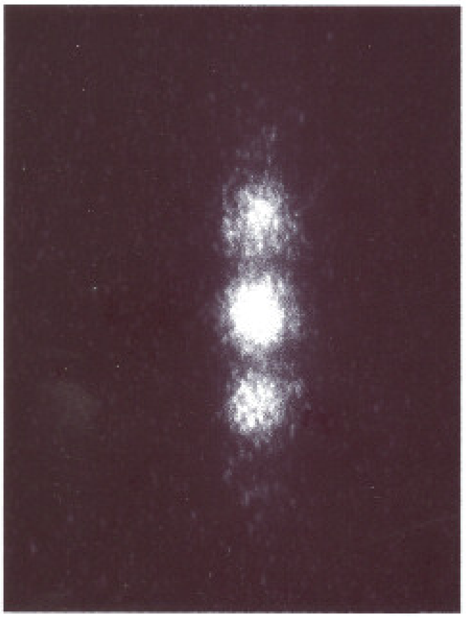
Fig. 4. Spectrum of molybdenum X-rays scattered by graphite, compared with the spectrum of the primary X-rays, showing an increase in wave-length on scattering.

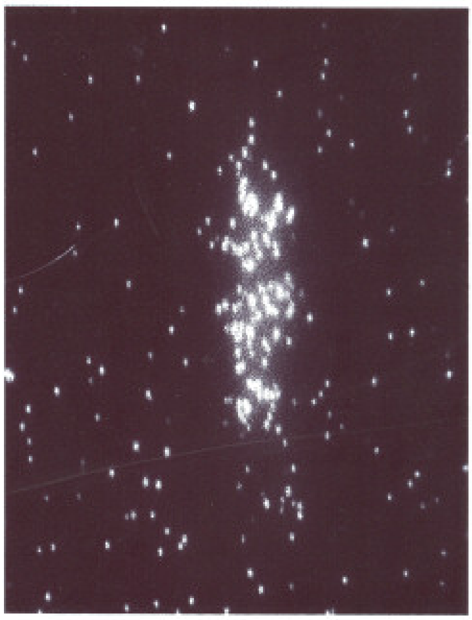
Einstein, 1909 anticipating the Complementarity Principle of Bohr

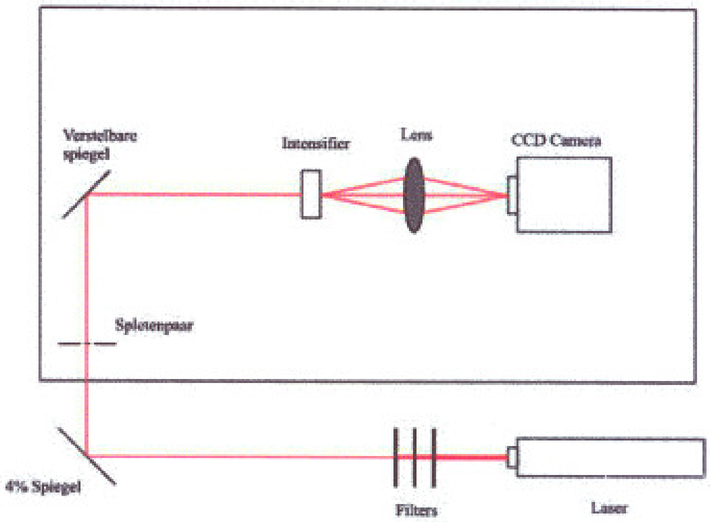
"

I have already attempted earlier to show that our current foundations of the radiation theory have to be abandoned…It is my opinion that the next phase in the development of theoretical physics will bring us a theory of light that can be interpreted as a kind of fusion of the wave and the emission theory…









http://www.optica.tn.tudelft.nl/education/photons.asp