PARTICLELIKE PROPERTIES OF LIGHT

(or, of electromagnetic radiation, in general)

Continued:

Let's summarize what we have said so far:

I. Arguments ~~Effects~~ supporting the wave-like nature of light:

(a) Young's double-slit experiment;

(b) Diffraction phenomena (Newton tried to explain them using his theory, but the explanation worked only for very simple situations – but not for pronounced ~~[illegible]~~ effects, such as, e.g. diffraction grating

(c) Maxwell's Equations and the experiments verifying them

II. Arguments supporting the particle-like nature of light:

(d) Photoelectric effect

So far, on the list there is only one argument in favor of particle-like nature

But the list is not finished yet! More argument can be add to I. as well as to II.

Let's continue the story.

Pronounced wave-like properties (interference, diffraction) can be observed for "soft forms" of electromagnetic radiation ("radiofrequency" radiation used in (wireless) communication – radio, TV, cell phones – and radar frequencies, a.k.a. microwaves).

On the other hand, "soft" radiation does not cause photoelectric effect – it's occur only for "harder" radiation, for visible light, or even "harder", like ultraviolet

~~So, perhaps~~

So, perhaps "softer" EM radiation has a wave-like nature, and with "hardening" it changes to particlelike nature?

This is only partially true – indeed, when the frequency increases (the wavelength becomes shorter), the particlelike properties are more strongly manifested – but the wave-like properties don't go away, oh, no!

Example – scattering of X-rays by crystal. It is evidently diffraction!

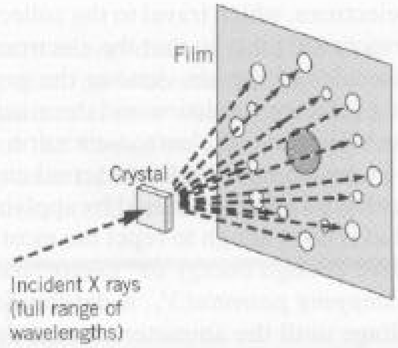
In 1895, Wilhelm Konrad Roentgen, a German physicist, discovered an entirely new form of radiation – X-rays – which had many amazing properties.

Question:	can you give me some examples of the properties of X-rays that for people living 100 years ago were clearly amazing?

For more than 10 years, the nature of X-rays was really mysterious.

Until Max von Laue (a German) and the Braggs (father and son) started shining X-rays on crystals. It turned out that crystals act as 3-dimensional diffraction gratings for X-rays!

The diffraction effects for X-rays are strongly



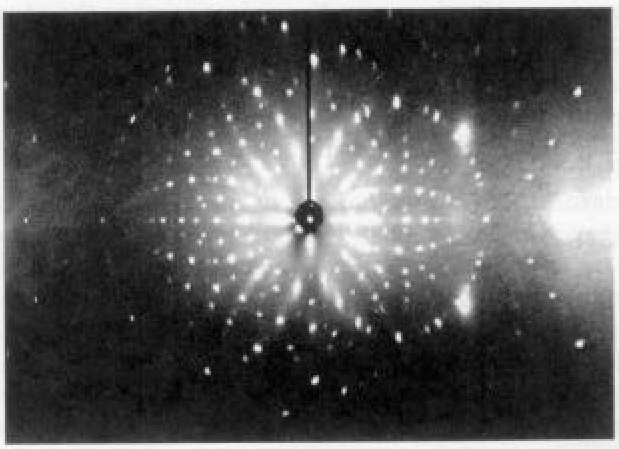


FIGURE 3.7 (Top) Apparatus for observing X-ray scattering by a crystal. An interference maximum (dot) appears on the film whenever a set of crystal planes happens to satisfy the Bragg condition for a particular wavelength. (Bottom) Laue pattern of NaCl crystal.

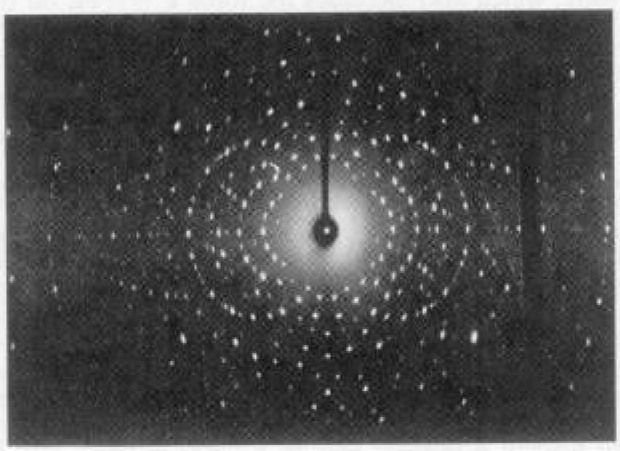
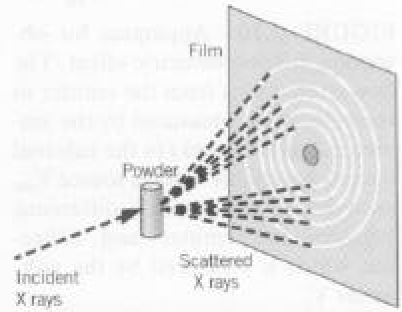


FIGURE 3.8 Laue pattern of a quartz crystal. The difference in crystal structure and spacing between quartz and NaCl makes this pattern look different from Figure 3.7.



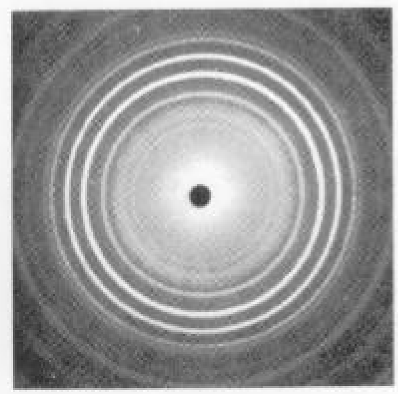
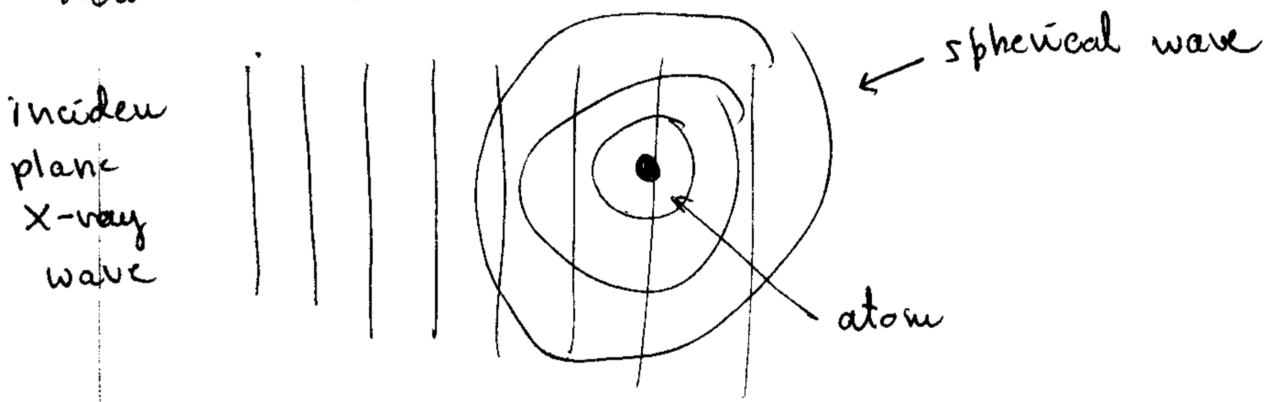


FIGURE 3.9 (Top) Apparatus for observing X-ray scattering from a powdered sample. Because the many crystals in a powder have all possible different orientations, each scattered ray of Figure 3.7 becomes a cone which forms a circle on the film. (Bottom) Diffraction pattern (known as *Debye-Scherrer* pattern) of a powder sample.

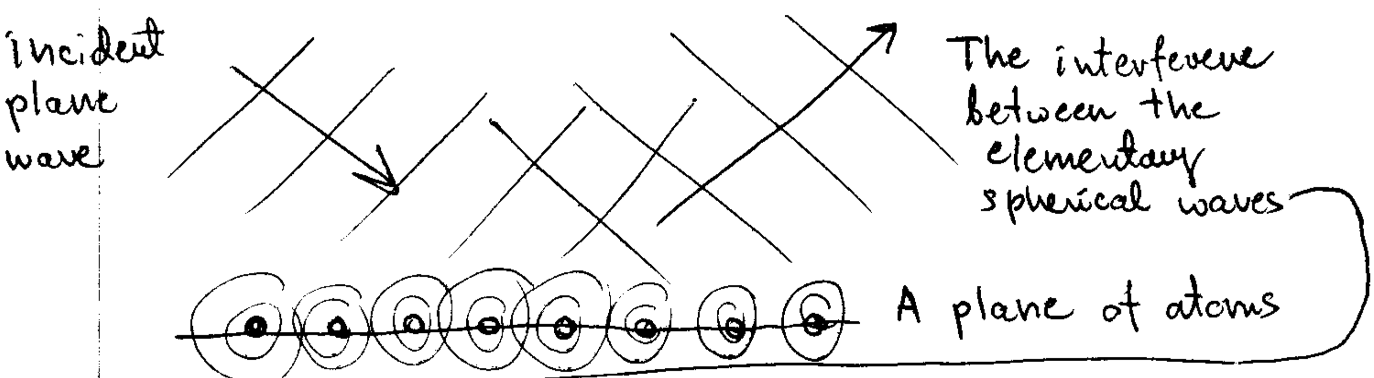
manifested in crystals, because the typical wavelengths (~1 – 0.1 nm) are comparable to interatomic spacing in crystals.

Question: Why we don't observe diffraction of visible light in crystals?

How does diffraction work in crystals?

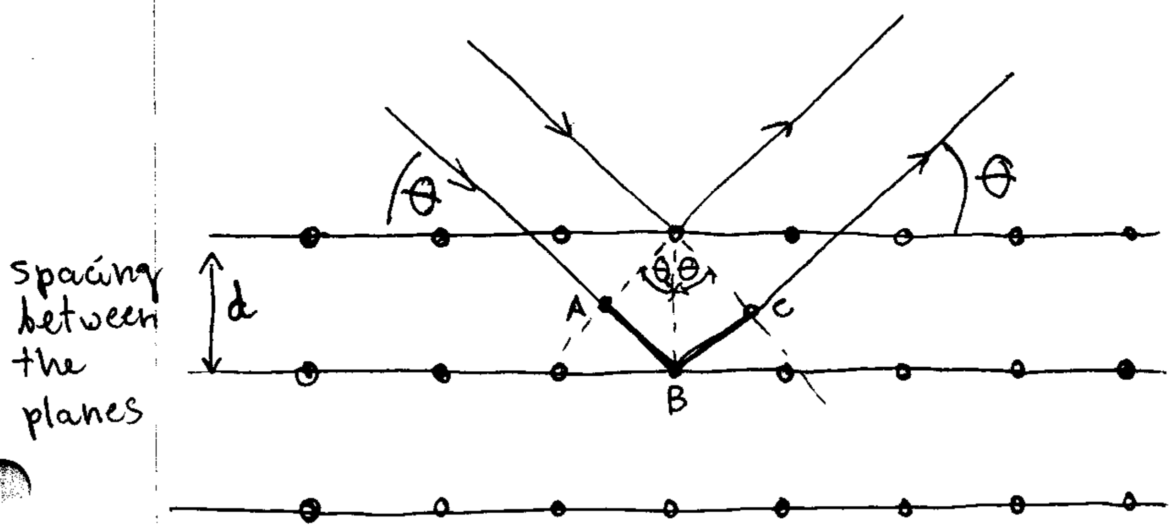


When a plane X-ray wave is incident on a single atom, a scattered wave is produced in the form of a spherical wave.



→ produces a reflected plane wave (acts like a mirror)

Scattering from a <u>single</u> plane of atoms is <u>weak</u>. But if there are many planes, the scattering may be greatly <u>enhanced</u> due to constructive interference:



The difference in the "optical path" between the waves reflected by two adjacent atomic planes in the figure is represented by the ABC line. From simple trigonometry, we obtain: $ABC = 2d\sin\theta$

The condition for constructive interference is that ABC is equal to $n\cdot\lambda$, where λ is the wavelength, and n is an integer number.

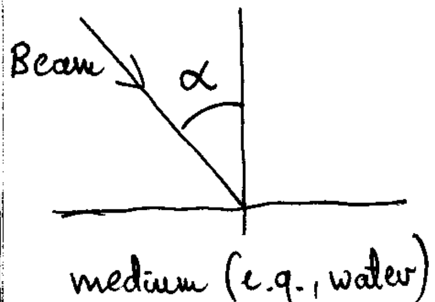
So:

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

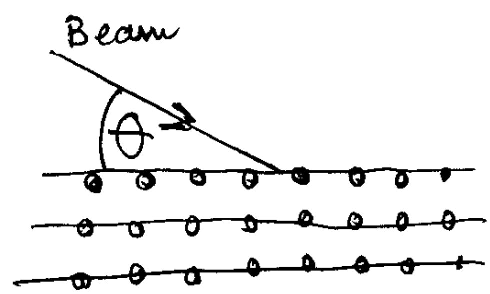
This is the <u>famous Bragg Law</u>.

Note that the angle θ is measured between the beam propagation direction, and the atomic plane.

Recall: in visible light optics, we measure the angle of incidence between the beam direction and a line perpendicular to the surface:



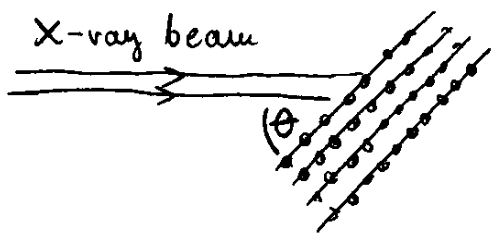
How we define the "angle of incidence" for <u>light</u>



How we define the "angle of incidence" for X-rays.

When the Bragg Law (or the "Bragg condition") $n\lambda = 2d\sin\theta$ is satisfied, we observe sharp reflections

Example: the spacing between atomic planes in NaCl is 0.565 nm (5.65 Å). Commonly used X-ray tubes with Cu anode produse X-rays with $\lambda = 0.154$ nm



We slowly rotate the crystal – for what θ values Bragg reflection will occur?

$$\sin\theta = \frac{n\lambda}{2d}:$$

$n=1$, $\sin\theta = 0.1363 \Rightarrow \theta = 7.83°$

$n=2$, $\sin\theta = 0.2726 \Rightarrow 15.81$

⋮

$n=7$, $\sin\theta = 0.9540 \Rightarrow \theta = 72.55°$

$n=8$, $\sin\theta > 1 \Rightarrow$ no reflection!

X-ray diffraction is a powerful tool for determining the <u>atomic structure of crystals</u>. For example, the structure of <u>proteins</u>, the basic building blocks of live organisms. Or DNA (you all know what DNA is, of course!).

<u>Bragg diffraction</u> is a strong argument supporting the <u>wave nature</u> of EM radiation!!!

<u>Next example:</u>

BLACKBODY RADIATION