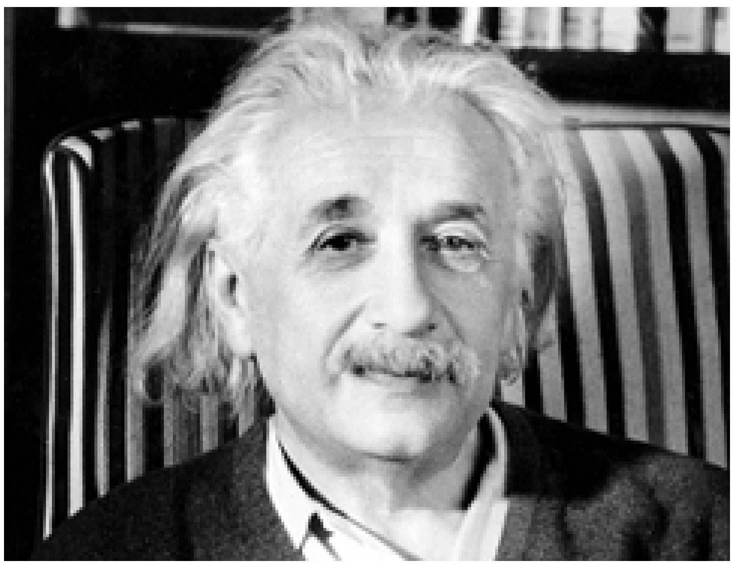
# Ch. 2. Particle Properties of Waves

*The King*



Albert Einstein (1879-1955)

World Year of PHYSICS 2005

www.physics2005.org

# Light

하나님이 이르시되 빛이 있으라 하니 빛이 있었고

빛이 하나님이 보시기에 좋았더라 하나님이 빛과 어둠을 나누사

(창세기 1:3-4)

**“Let there be light,” and there was light.**

**God saw that the light was good, and he separated the light from the darkness.**

**(Genesis 1:3-4)**

# Light

- We all *know* what light is; but it is not easy to *tell* what it is.

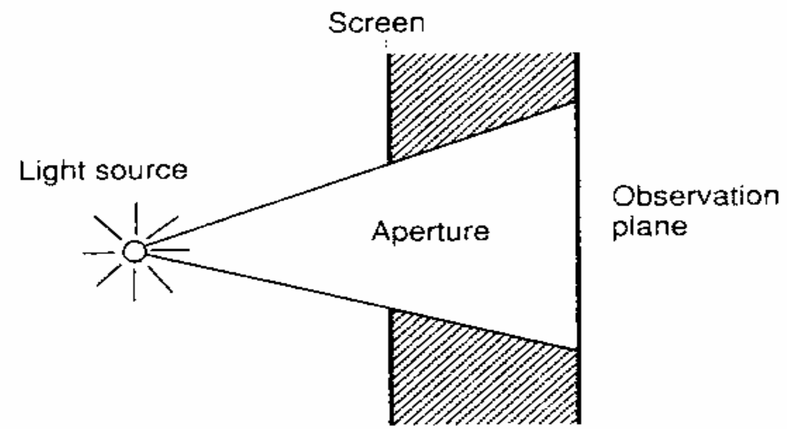
  - Samuel Johnson

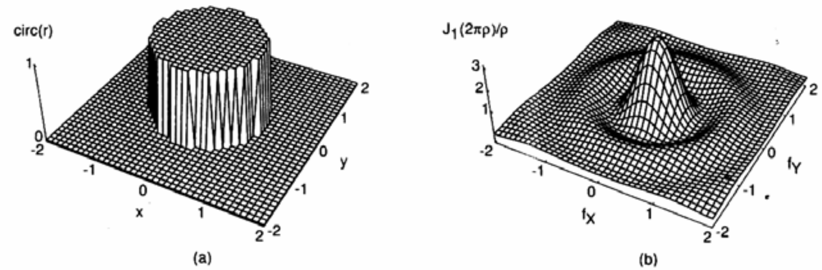
- 파동성(Wave : 전자파(Electromagnetic Wave)의 일종)

- 입자성(Particle : Photon; 光子)

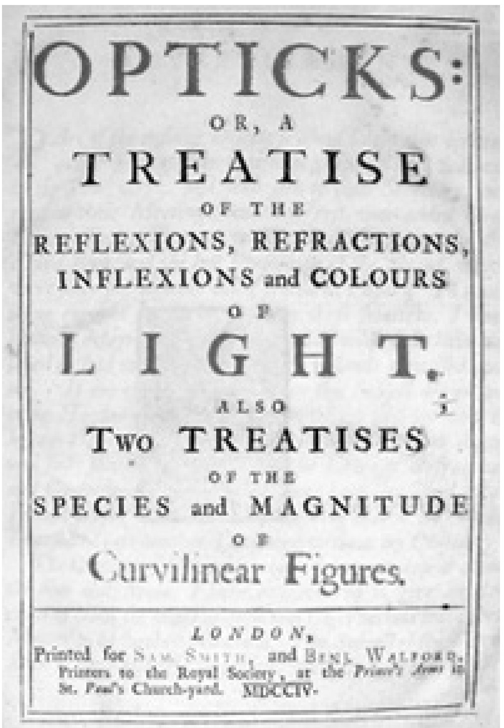
# History of the Study on Light

- 1665 Grimaldi
- 1678 Huygens
- 1704 Newton
- 1804 Young
- 1818 Fresnel
- 1860 Maxwell
- 1905 Einstein



# Newton

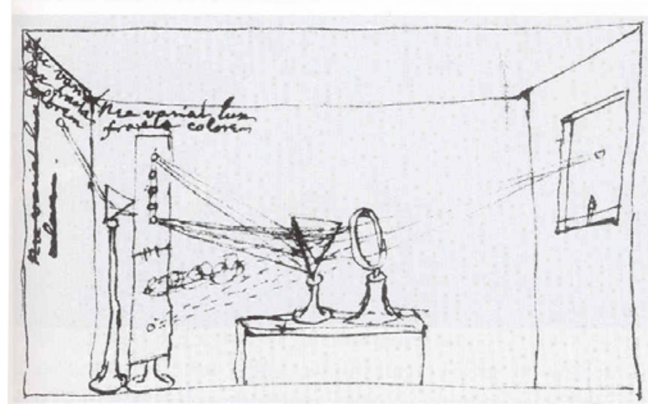


OPTICKS:
OR, A
TREATISE
OF THE
REFLEXIONS, REFRACTIONS,
INFLEXIONS and COLOURS
OF
LIGHT.
ALSO
Two TREATISES
OF THE
SPECIES and MAGNITUDE
OF
Curvilinear Figures.

LONDON,
Printed for SAM. SMITH, and BENJ. WALFORD,
Printers to the Royal Society, at the Prince's Arms in
St. Paul's Church-yard. MDCCIV.

Isaac Newton

(1642-1727)

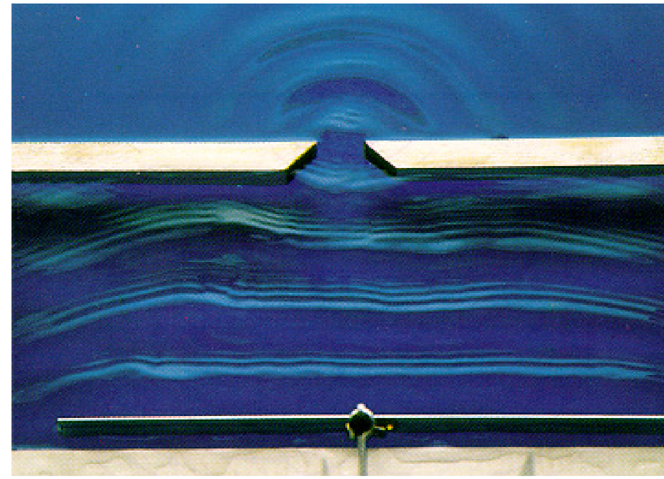


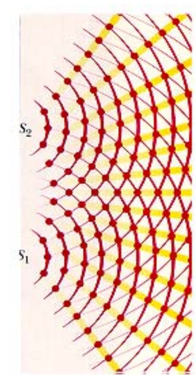
A sketch (left) from Newton's 1672 notebook shows sunlight entering through the window at right, passing through a triangular prism, and splitting into a spectrum of colors. One of the earliest known studies of optics (the science of light and vision) was done by Islamic mathematician Ibn al-Haytham (965–1040), also known as Alhazen. His sketch of lenses is below.

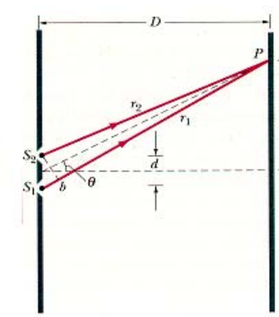
J. Hakim, The Story of Science – Newton at the Center, Smithsonian Books, Washington DC, USA, 2005

# Young

Thomas Young (1773-1829)





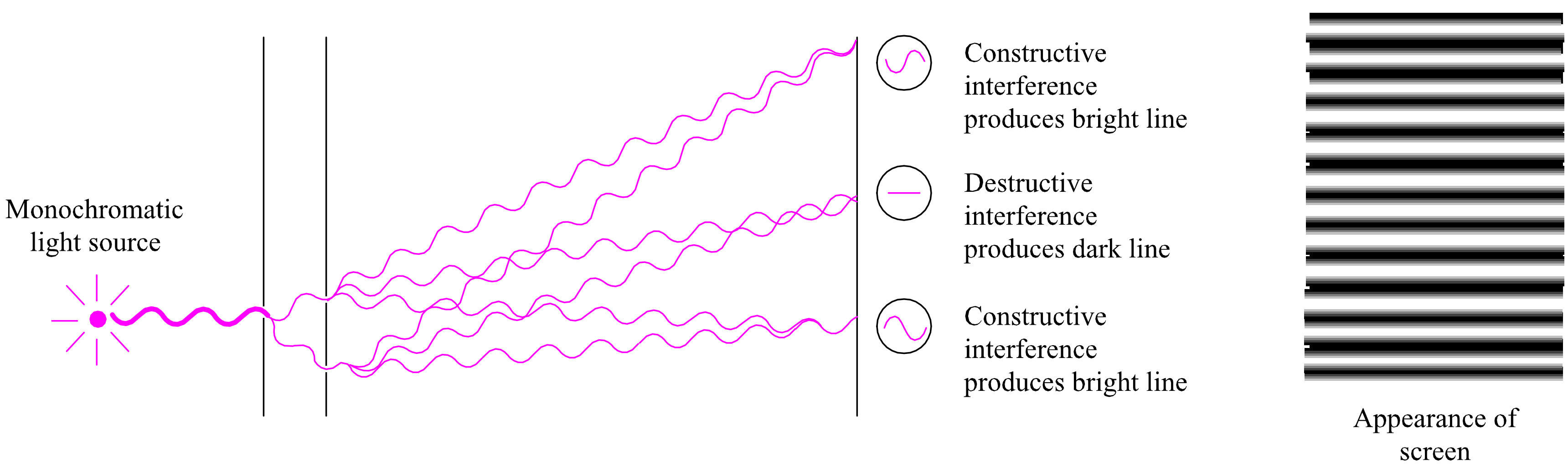



그림 2.4  Young의 실험에서 간섭의 기원.

# Maxwell


James Clerk Maxwell (1831–1879)

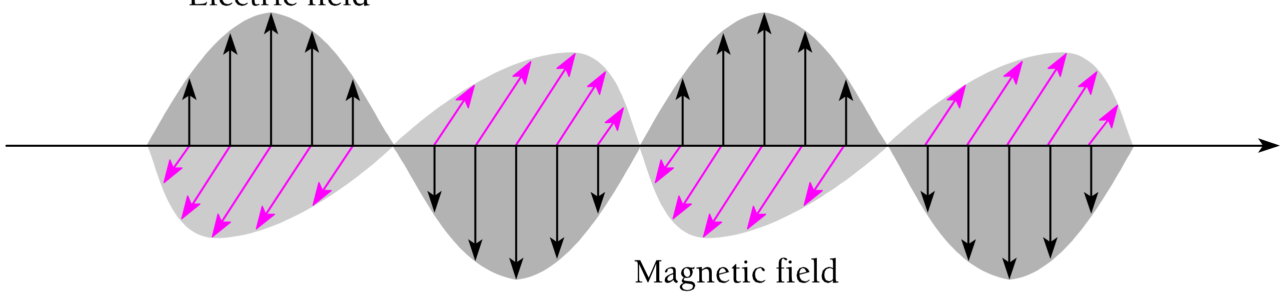



그림 2.1 전자기파의 전기장과 자기장은 같이 변하고, 서로 수직이며 파의 진행 방향에 대해서도 수직이다. (진공 중에서의 그림)

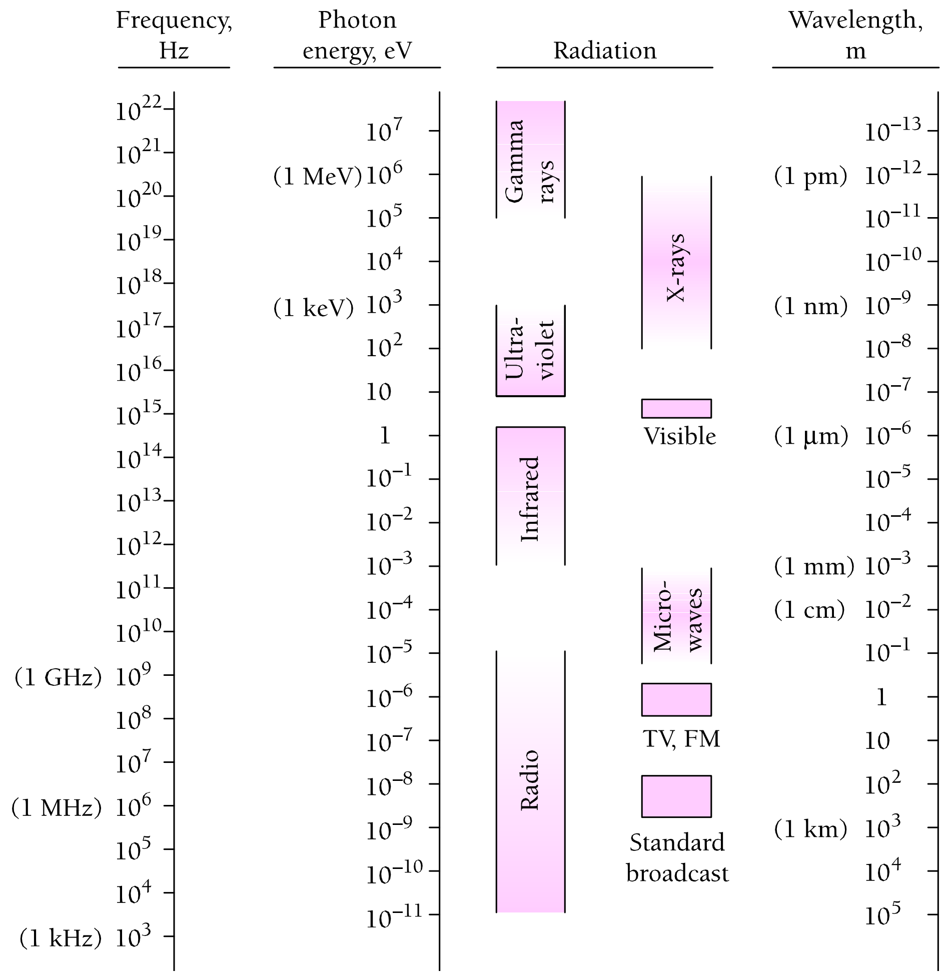
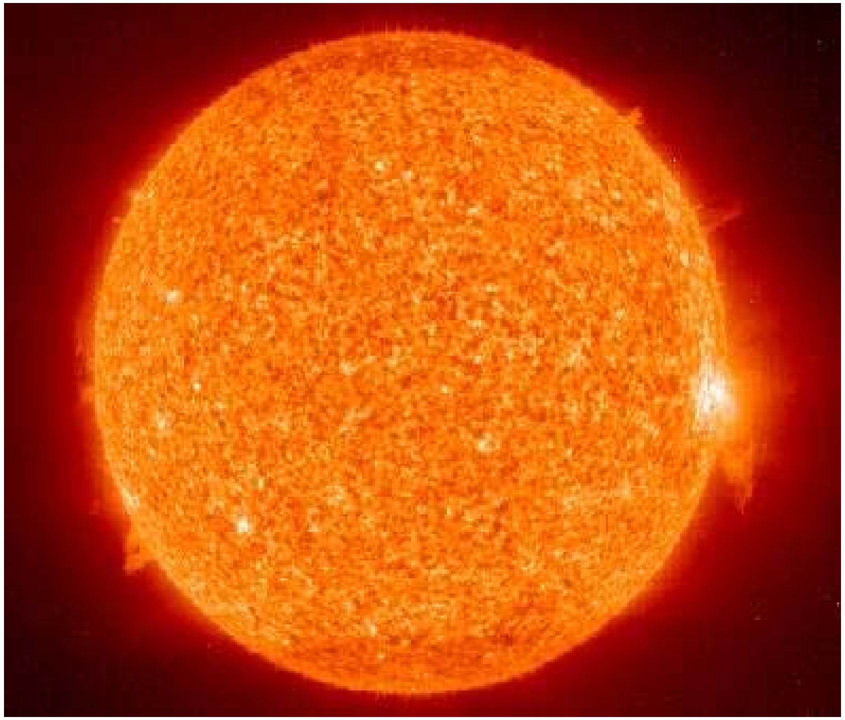
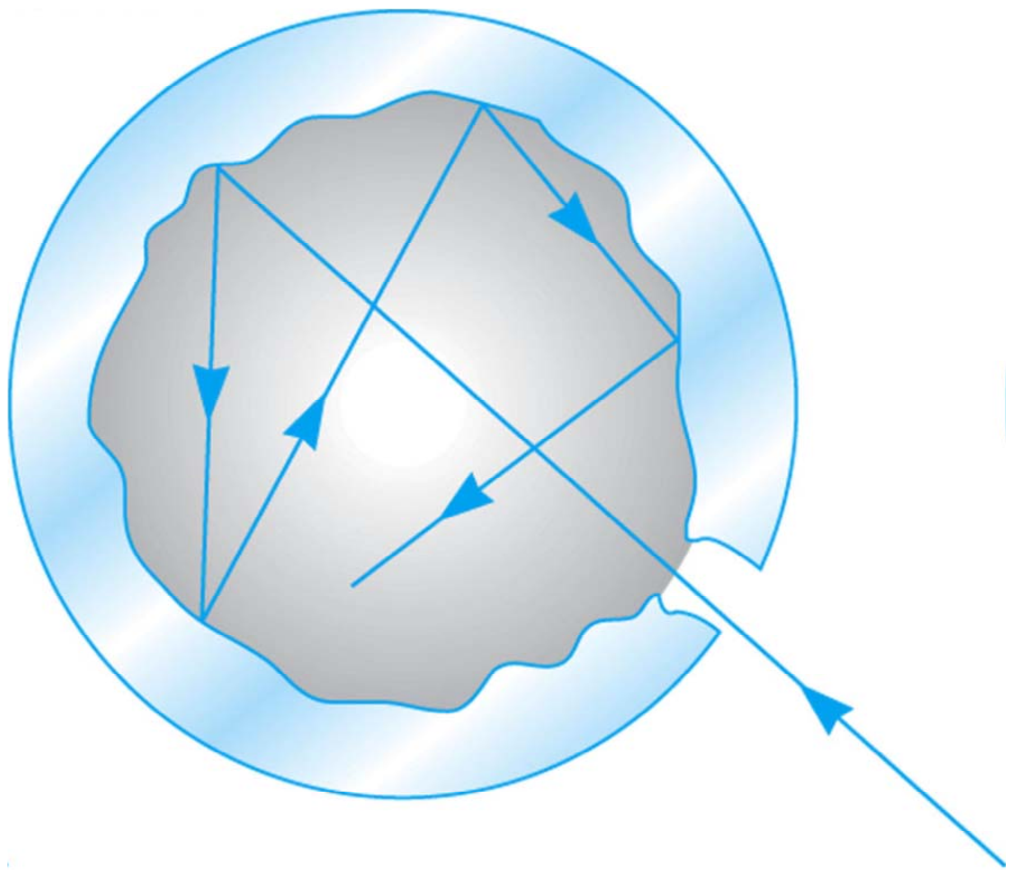



그림 2.2 전자기 복사의 스펙트럼.

# Thermal Radiation



# Blackbody



# Blackbody Radiation

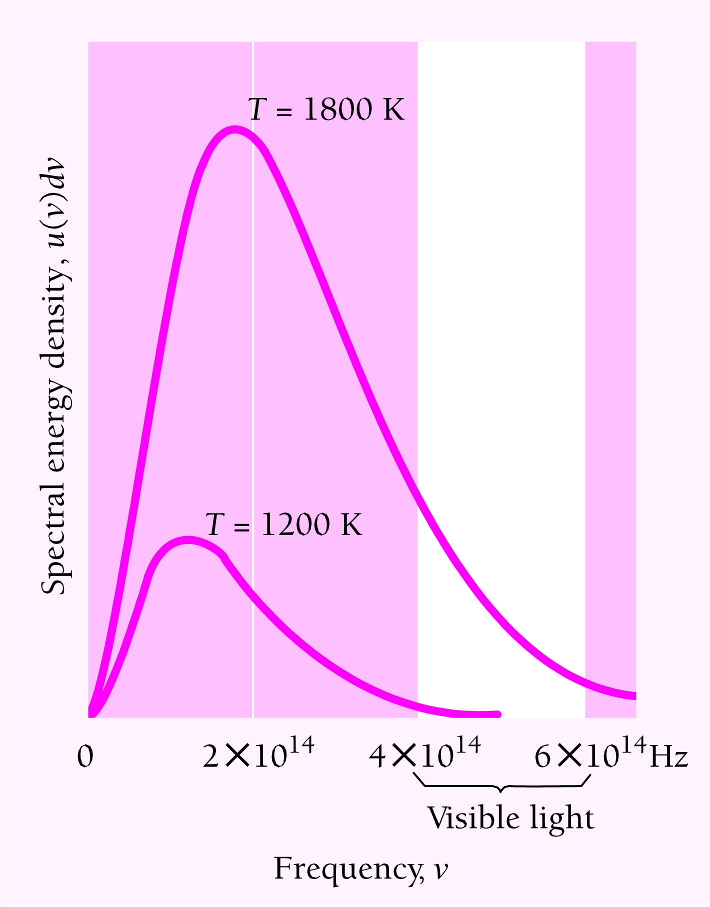



그림 2.6 흑체 스펙트럼. 복사의 에너지 스펙트럼 분포는 그 물체의 온도에만 의존한다. 온도가 높을수록 더 많은 양의 복사를 내고 또 최대 방출이 일어나는 진동수도 높아진다. 최대 방출이 일어나는 진동수의 온도 의존성은 제9.6절에서 다시 논의할 Wien의 변위법칙을 따른다.

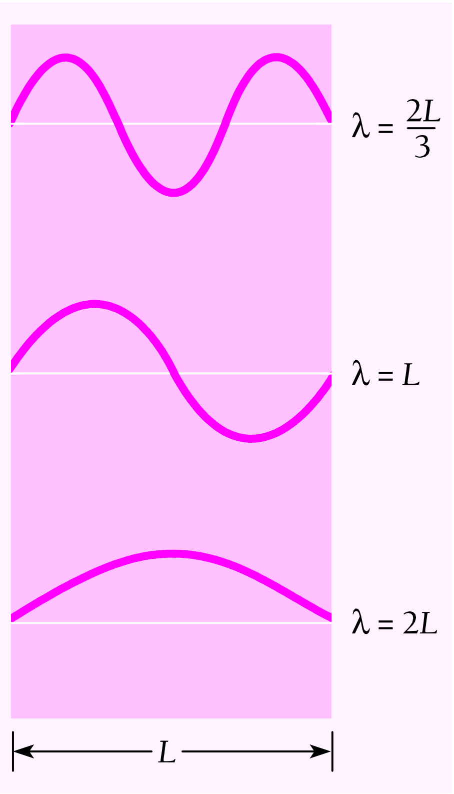


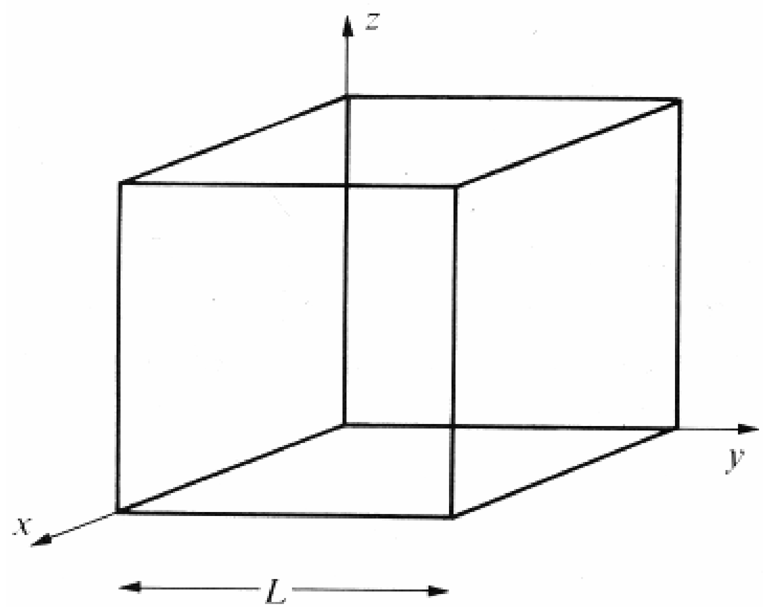

그림 2.7 완전 반사체로 되어 있는 벽을 가진 공동에서의 전자기파는 정상파들로 구성된다. 이 때 벽에서 정상파의 마디를 이루며, 존재 가능한 파장에 제한을 받게 된다. 벽간의 간격이 L일 때의 세 가능한 파장을 보여주고 있다.

# Cavity Modes I

$$\nabla^2 \mathbf{E}(\mathbf{r},t) = \frac{1}{c^2}\frac{\partial^2 \mathbf{E}(\mathbf{r},t)}{\partial t^2}$$

$$k = \frac{2\pi}{\lambda} = \frac{2\pi\nu}{c} = \frac{\omega}{c}$$

$$\nabla \cdot \mathbf{E}(\mathbf{r},t) = 0$$




$$E_x(\mathbf{r},t) = E_x(t)\cos(k_x x)\sin(k_y y)\sin(k_z z)$$

$$E_y(\mathbf{r},t) = E_y(t)\sin(k_x x)\cos(k_y y)\sin(k_z z)$$

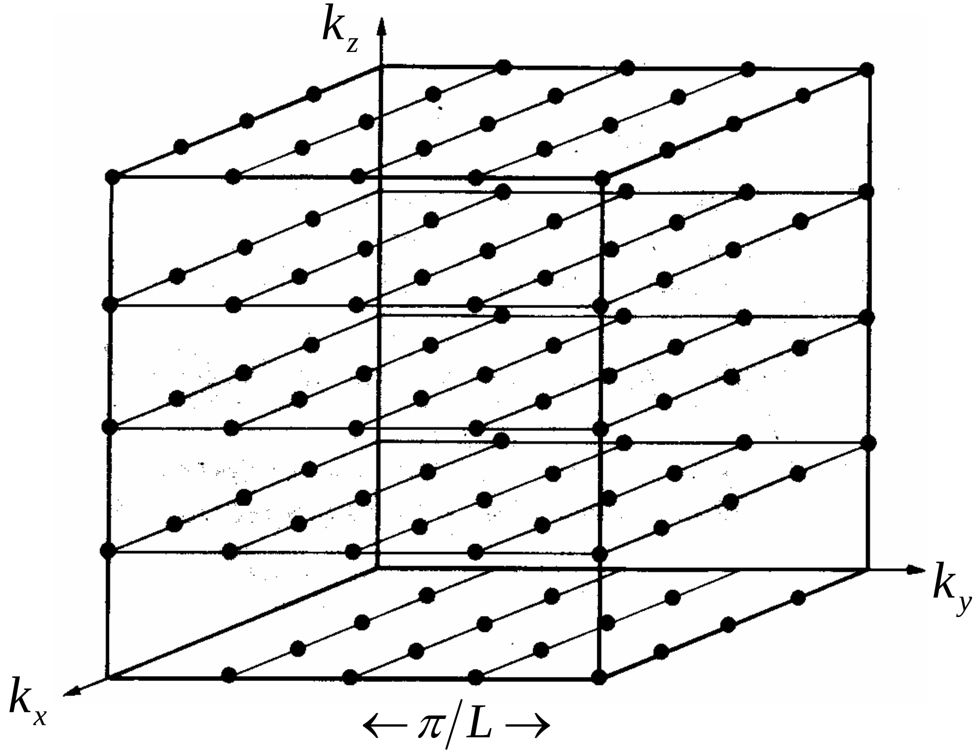
$$E_z(\mathbf{r},t) = E_z(t)\sin(k_x x)\sin(k_y y)\cos(k_z z)$$

# Cavity Modes II

$$k_x = \pi n_x / L, \quad k_y = \pi n_y / L, \quad k_z = \pi n_z / L$$

$$n_x, n_y, n_z = 0, 1, 2, 3, \ldots$$

$$\mathbf{k} \cdot \mathbf{E}(t) = 0$$



# Mode Density I

$$\frac{\frac{1}{8}\left(4\pi k^2 dk\right)}{\left(\pi / L\right)^3} \times 2$$

Mode density G($k$)

Number of modes between $k$ and $k + dk$ (per unit volune) $= G(k)dk$

$$G\left(k\right)dk = \frac{k^2}{\pi^2}dk \qquad G(k) = \frac{k^2}{\pi^2}$$

Many books use the notation of $\rho(k)$ rather than G($k$).

# Mode Density II

Mode density $G(\nu)$

Number of modes between $\nu$ and $\nu + d\nu$ (per unit volune) $= G(\nu)d\nu$

$$\nu = \frac{ck}{2\pi}$$

$$G(\nu)d\nu = G(\nu)d\nu$$

$$G(\nu) = G(\nu)\frac{dk}{d\nu} = \frac{k^2}{\pi^2}\frac{2\pi}{c} = \frac{8\pi\nu^2}{c^3}$$

# Spectral Energy Density

Spectral energy density $u(\nu)$

Energy of radiation fields between $\nu$ and $\nu + d\nu$ (per unit volune) $= u(\nu)d\nu$

$$u(\nu)d\nu = \bar{E}G(\nu)d\nu$$

# Rayleigh-Jeans Law

$$\bar{E} = \frac{\int_0^\infty E e^{-E/(k_B T)} dE}{\int_0^\infty e^{-E/(k_B T)} dE} = k_B T$$

(By Boltzmann Distribution
or by the equipartition principle)

$$u(\nu)d\nu = \bar{E}G(\nu)d\nu = \frac{8\pi^2\nu^2}{c^3} k_B T d\nu$$

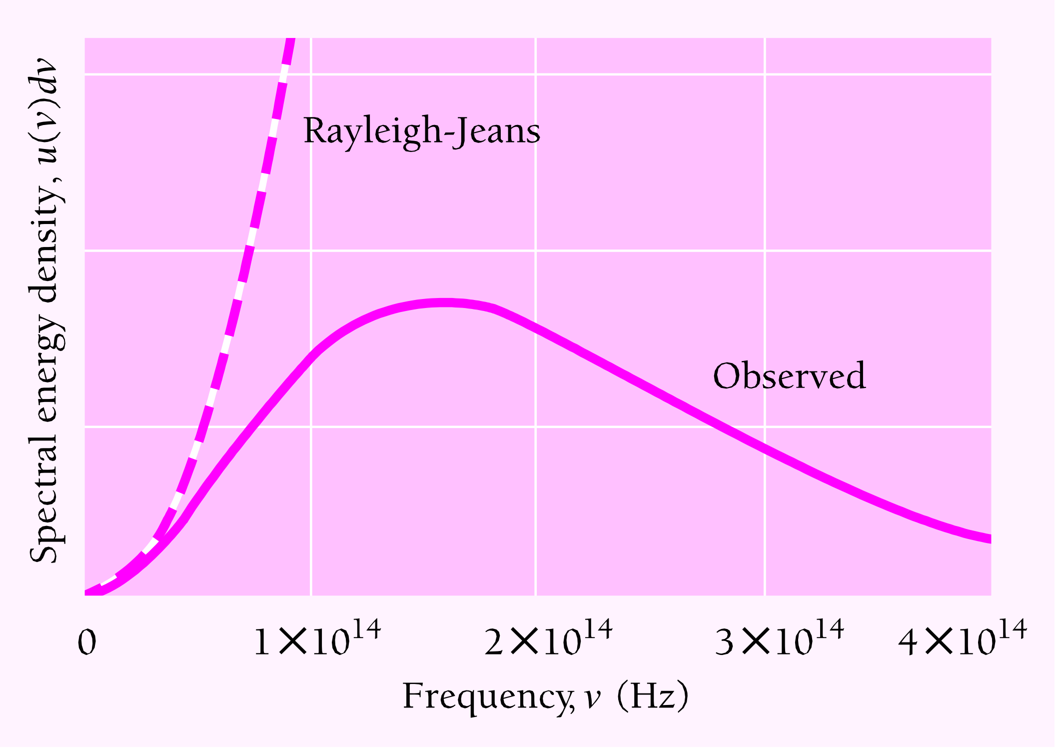
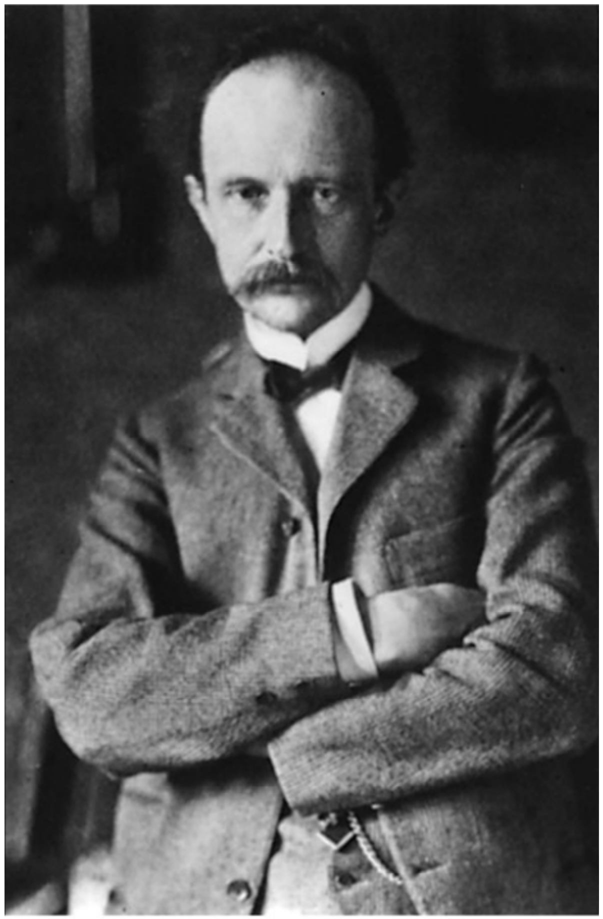



그림 2.8  1500K 흑체에서 나오는 실제 복사 스펙트럼과 Raylegh-Jeans 공식의 비교.

# Planck




In 1900

"After some weeks of the most intense work of my life, light began to appear to me and unexpected views revealed themselves in the distance."

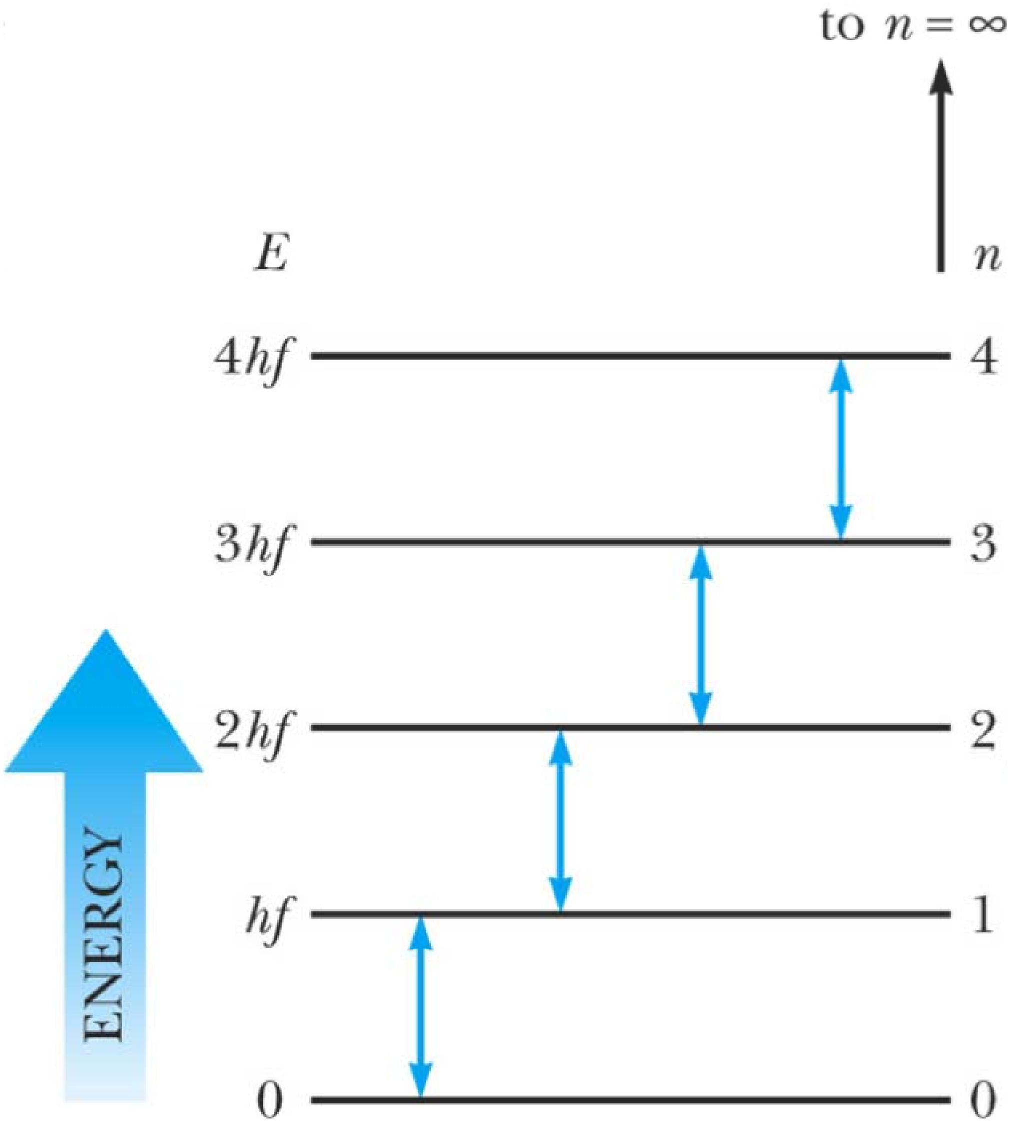
Max Planck (1858-1947)

# Planck's Blackbody Radiation Law

$$u(\nu) = \frac{8\pi h \nu^3}{c^3} \cdot \frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$$

$$h = 6.626 \times 10^{-34}\,\mathrm{J \cdot s}$$ Planck's constant

$$\hbar = \frac{h}{2\pi}$$






주의

$$E_n = nh\nu$$

$$n = 0, 1, 2, \cdots$$

Fig. 3-9, p. 74

# Planck's Law I
(for advanced students only)

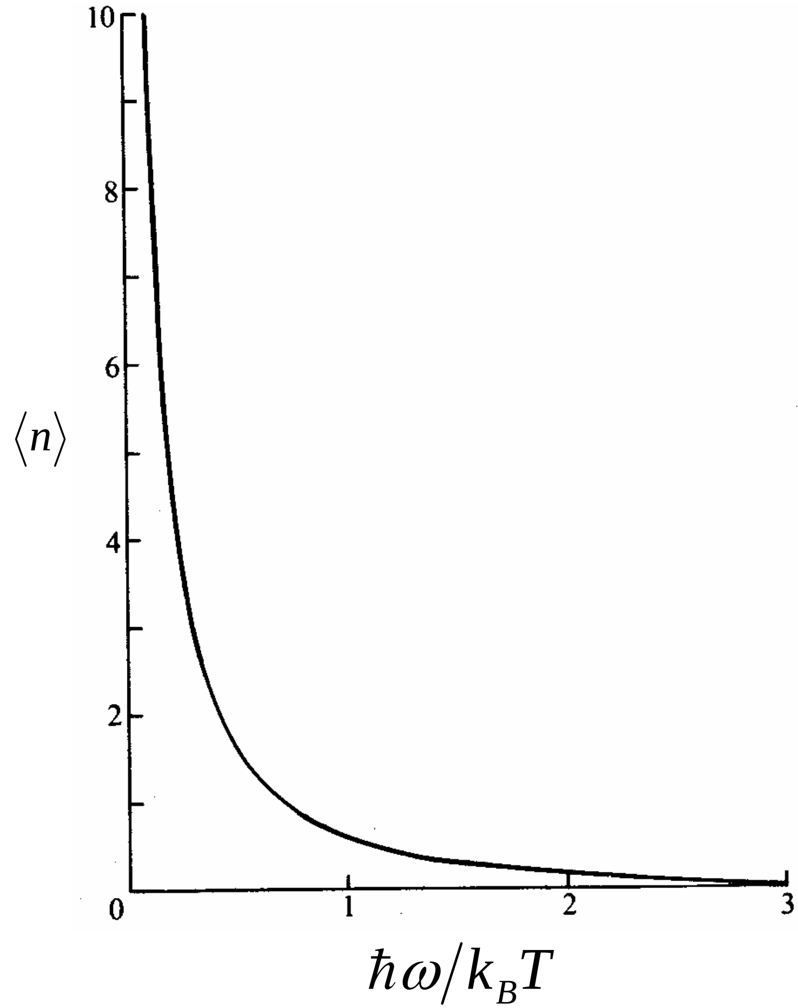
$$P(n) = \frac{\exp(-E_n/k_B T)}{\sum_n \exp(-E_n/k_B T)}$$

$$A = \exp\left(-\hbar\omega/k_B T\right)$$

$$\langle n \rangle = \sum_n nP(n) = (1-A)\sum_n nA^n$$

$$= (1-A)A\frac{\partial}{\partial A}\sum_n A^n = \frac{A}{1-A}$$

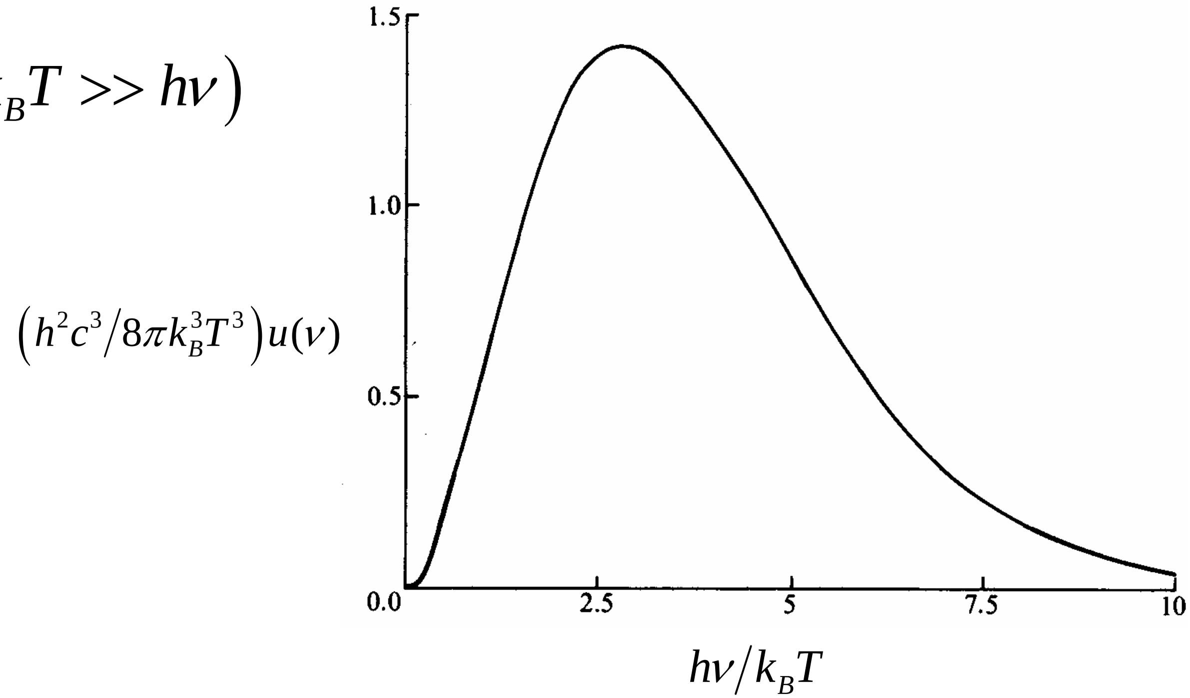
$$\langle n \rangle = \frac{1}{\exp\left(h\nu/k_B T\right) - 1}$$



# Planck's Law II

$$u(\nu) = G(\nu)\langle n \rangle h\nu = \frac{8\pi\nu^2}{c^3} \cdot \frac{h\nu}{\exp(h\nu/k_B T) - 1}$$

$$u(\nu) \approx 8\pi\nu^2 k_B T / c^3 \quad (k_B T >> h\nu)$$




$$u(\nu) \approx \left(8\pi h\nu^3/c^3\right) \exp(-h\nu/k_B T) \quad (k_B T << h\nu)$$

# After All... Due to Einstein

$$u(\nu) = G(\nu)\langle n \rangle h\nu = \frac{8\pi\nu^2}{c^3} \cdot \frac{1}{\exp\left(h\nu / k_B T\right) - 1} \cdot h\nu$$

# Einstein



Nobel Prize in Physics 1921

"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"

Fig. 3-13, p. 81

# Photoelectric Effect

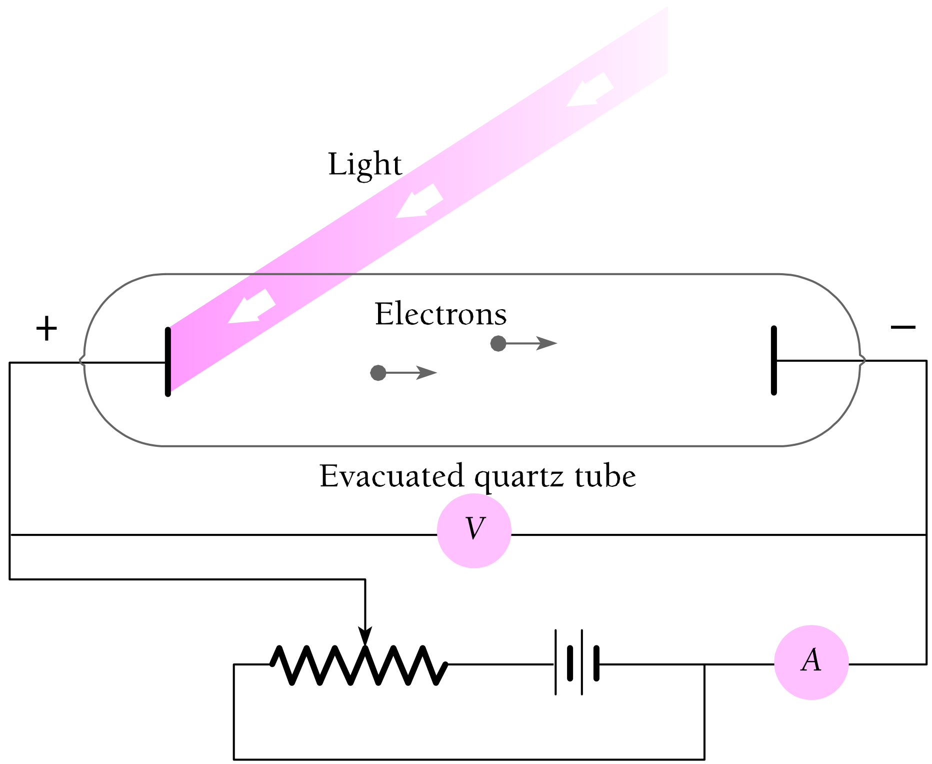



그림 2.9 광전효과의 실험적 관측.

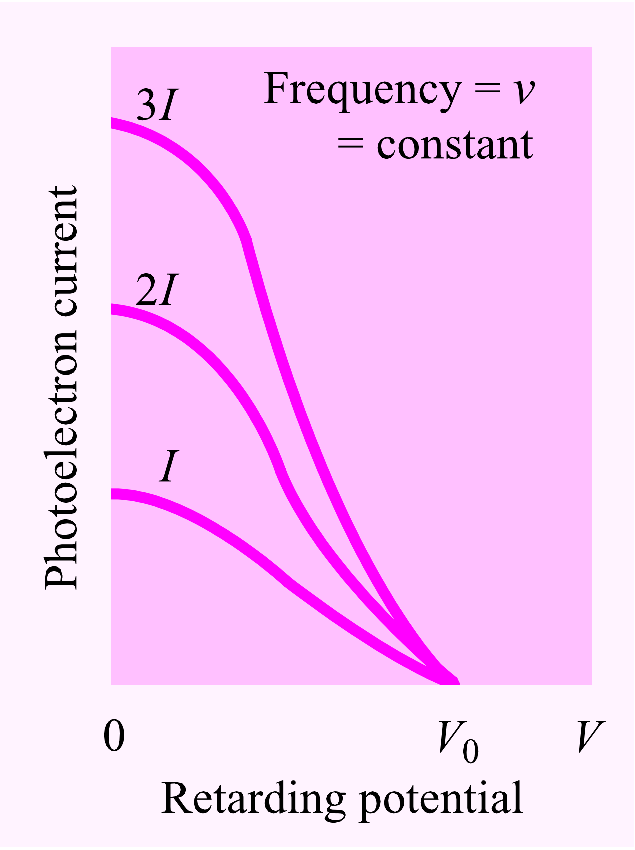



그림 2.10 모든 저지 전압에서, 광전자 전류는 빛의 강도 I에 비례한다. 같은 진동수의 모든 빛의 세기에 대하여 최대 광전자 에너지에 해당하는 소멸전압 $V_0$는 동일하다.

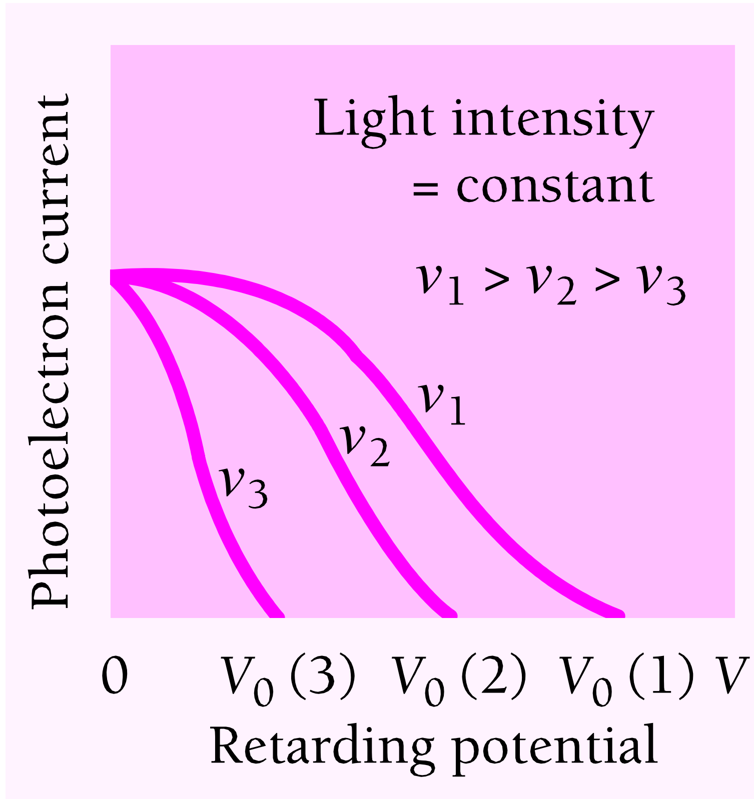



그림 2.11 저지전압 $V_0$가 빛의 진동수에 의존하므로 최대 광전자 에너지도 빛의 진동수에 의존한다. V= 0일 때의 광전자 전류는 주어진 빛의 세기에서 진동수에 관계없이 항상 일정하다.

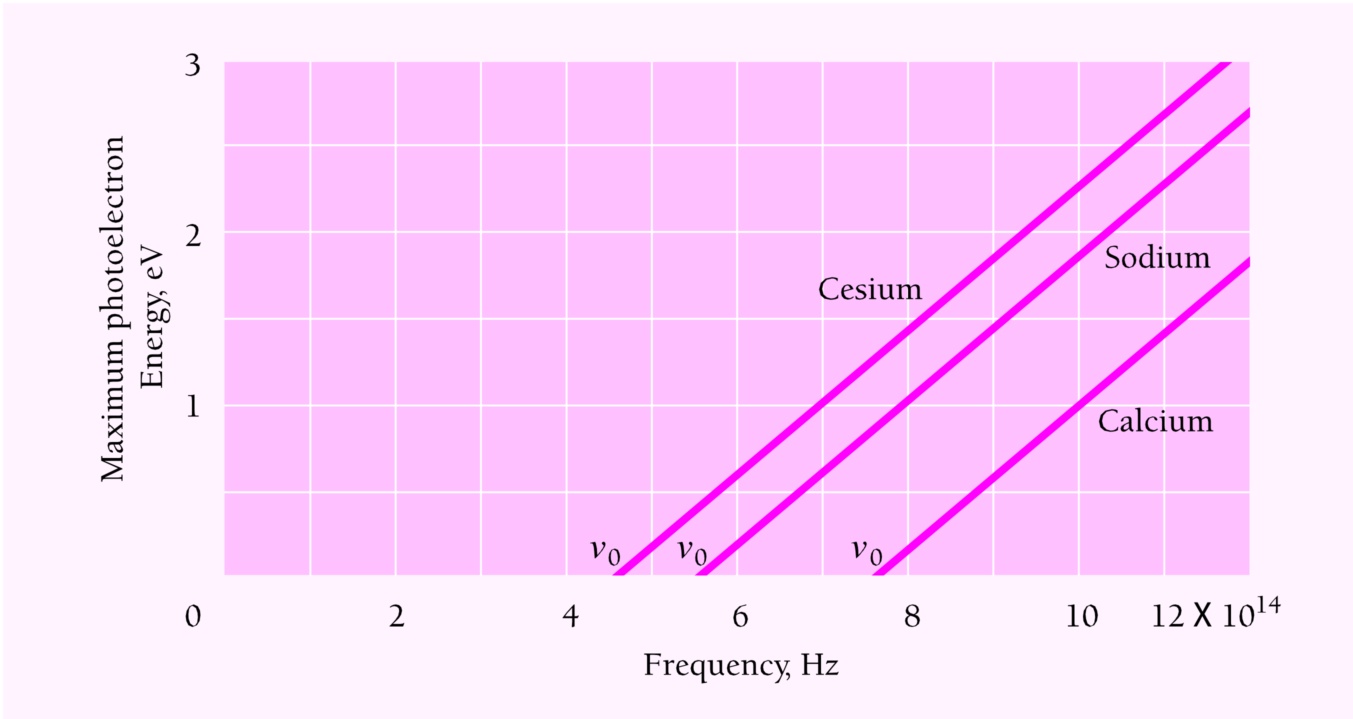
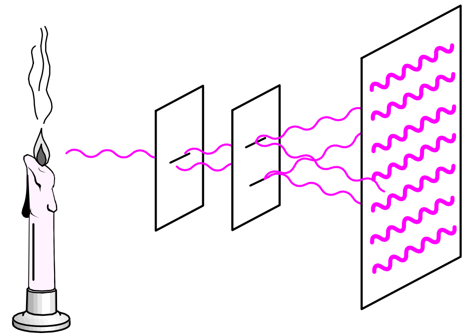



그림 2.12 세 금속 표면에서, 최대 광전자 운동 에너지 $KE_{max}$와 입사파 진동수와의 관계.

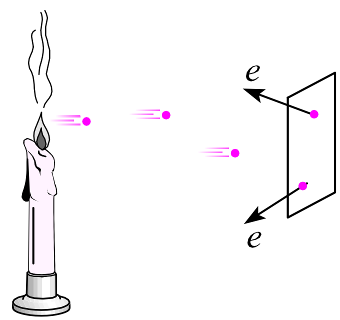
# 光子(Photon)

에너지 $$E = h\nu = \frac{h}{T} = \frac{hc}{\lambda}$$

운동량 $$p = \frac{h}{\lambda}$$



(*a*)




(*b*)

그림 2.14  (a) 파동설은 양자론으로는 설명할 수 없는 빛의 간섭과 회절을 설명한다. (b) 양자론은 파동설로는 설명할 수 없는 광전효과를 설명한다.

# X-Ray

Wilhelm Conrad Röntgen
(1845-1923)

Picture of Mrs. Röntgen's hand, taken on Dec. 22, 1885.

He probably could have made tons of money by patenting his X-ray machine – but he didn't. A friend wrote of him, "His outstanding characteristic was his integrity…. [He] was in every sense the embodiment of the ideals of the nineteenth century: strong, honest and powerful, devoted to his science and never doubting its value." – From J. Hakim, The Story of Science – Newton at the Center, Smithsonian Books, Washington DC, USA, 2005.

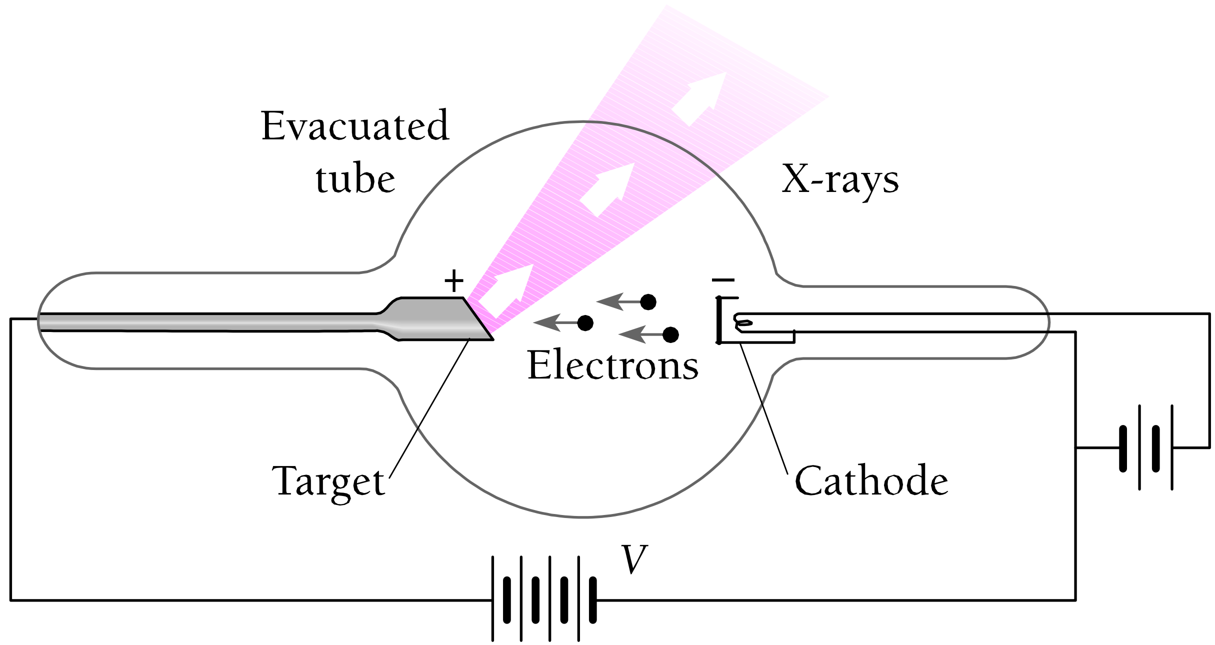
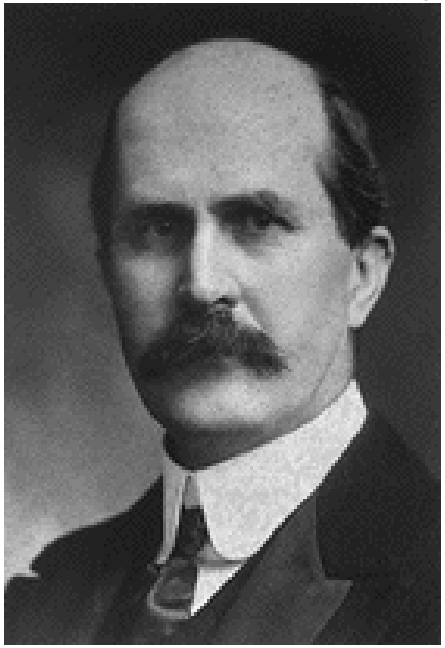


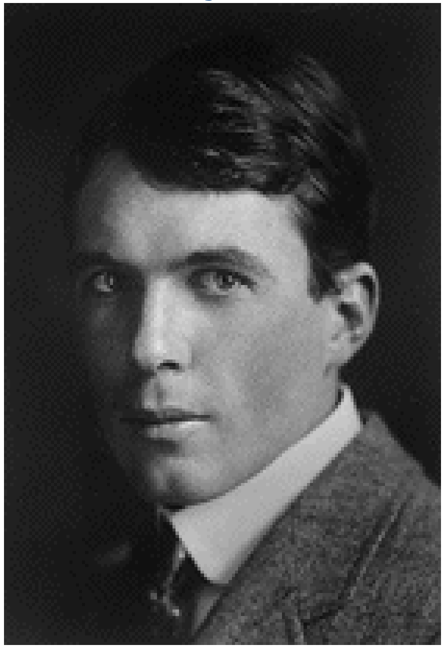

그림 2.15  x-선 튜브. 가속 전압 V가 클수록 전자가 빨라지고 x-선 파장은 짧아진다.

# The Braggs

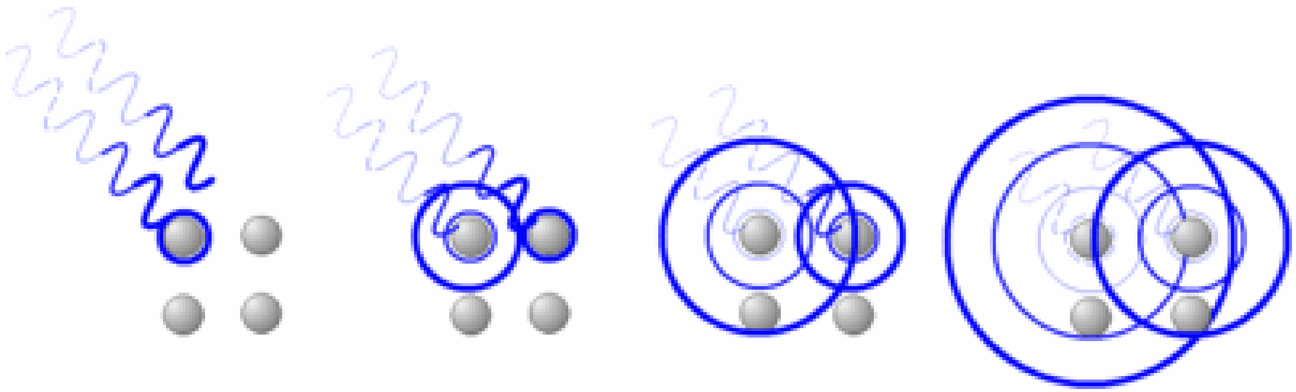
The Nobel Prize in Physics 1915
"for their services in the analysis of crystal structure by means of X-rays"

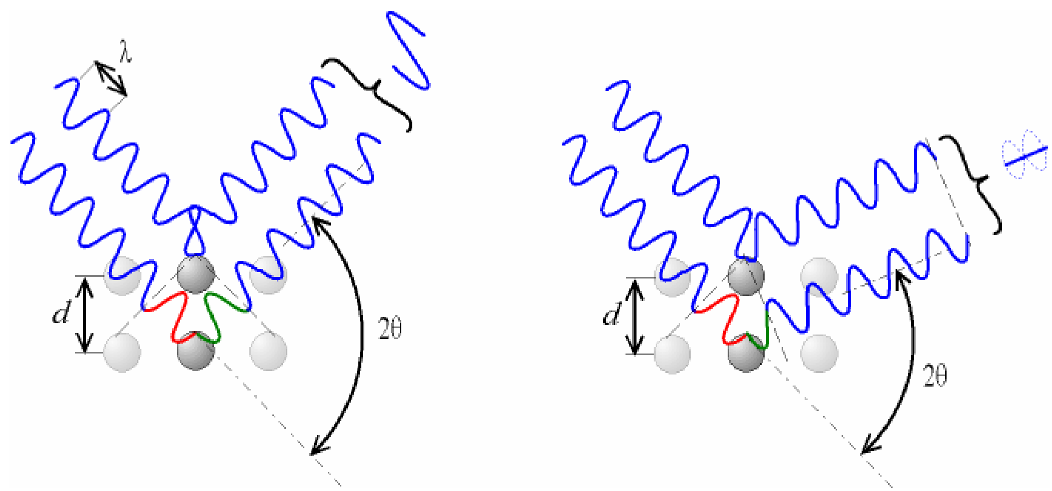


Sir William Henry Bragg
(1862-1942)



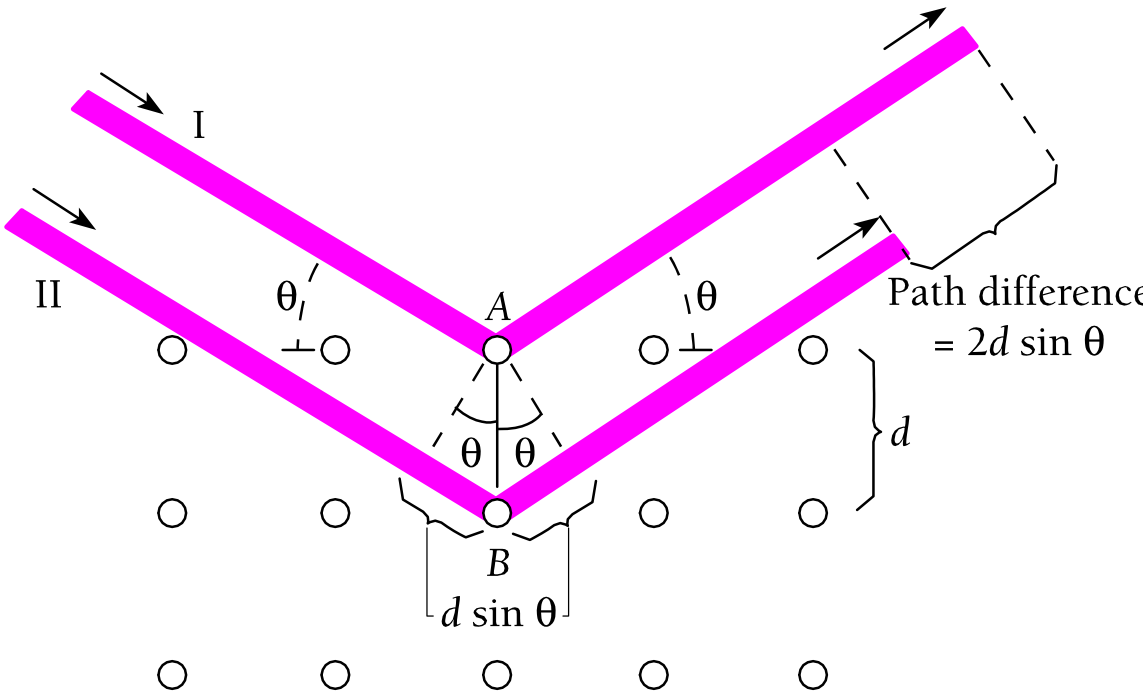
William Lawrence Bragg
(1890-1971)






http://en.wikipedia.org/wiki/Bragg%27s_law

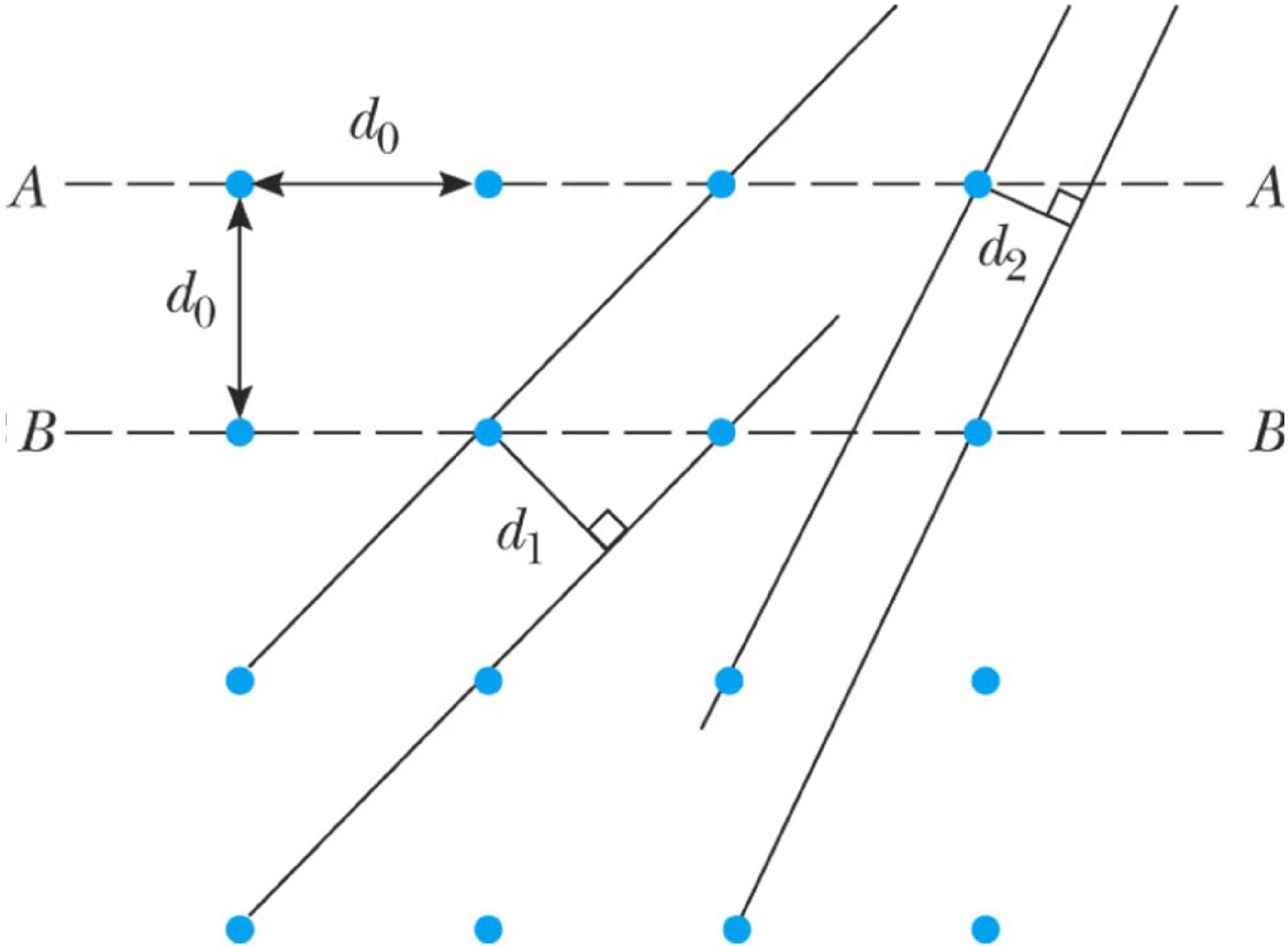
# Bragg's Law

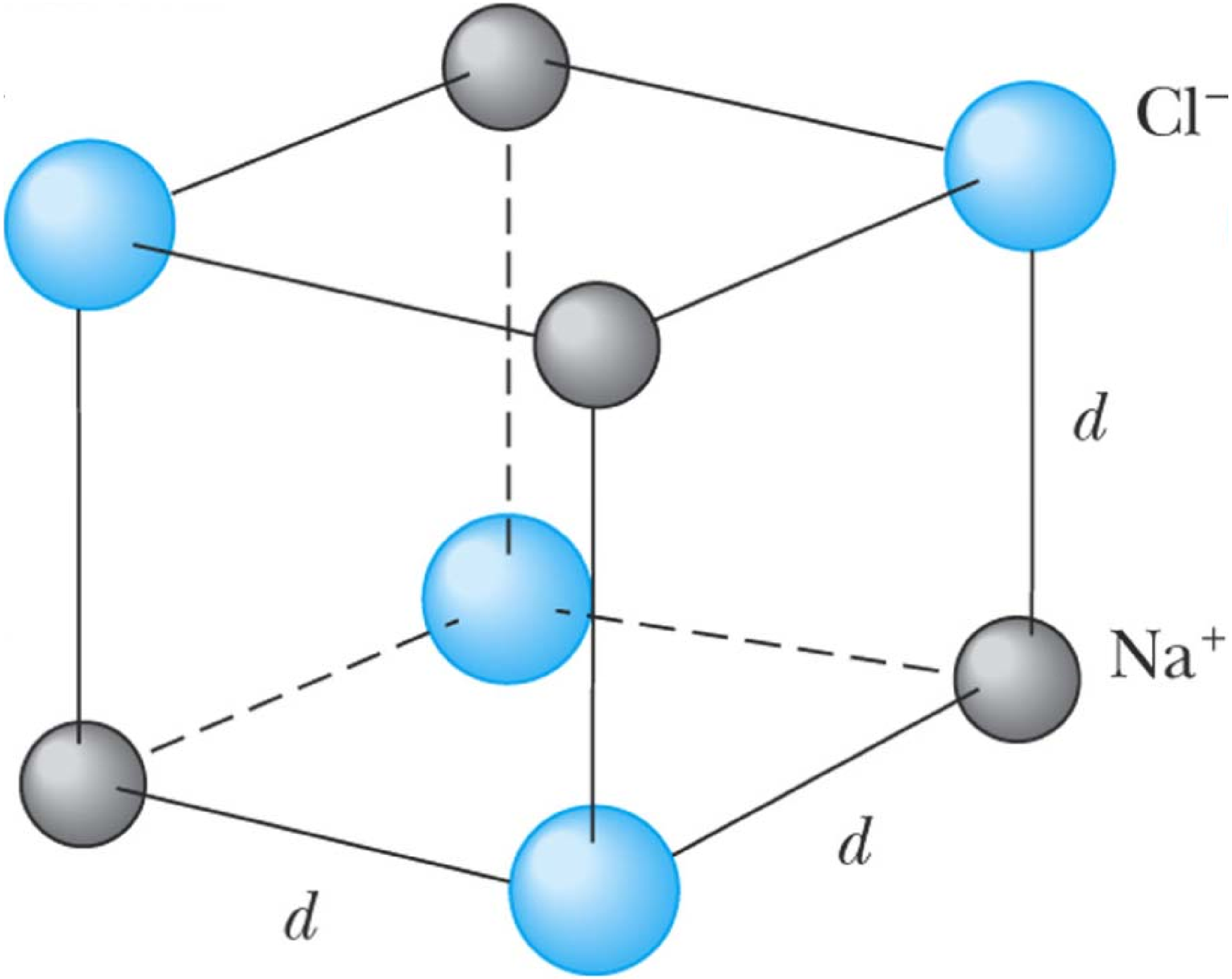



$$2d\sin\theta = n\lambda$$

$$(n = 1, 2, 3, \cdots)$$

그림 2.20 입방체 결정에서의 x-선 산란


$d_0$
A
A
$d_0$
$d_2$
B
B
$d_1$


Cl⁻
d
Na⁺
d
d

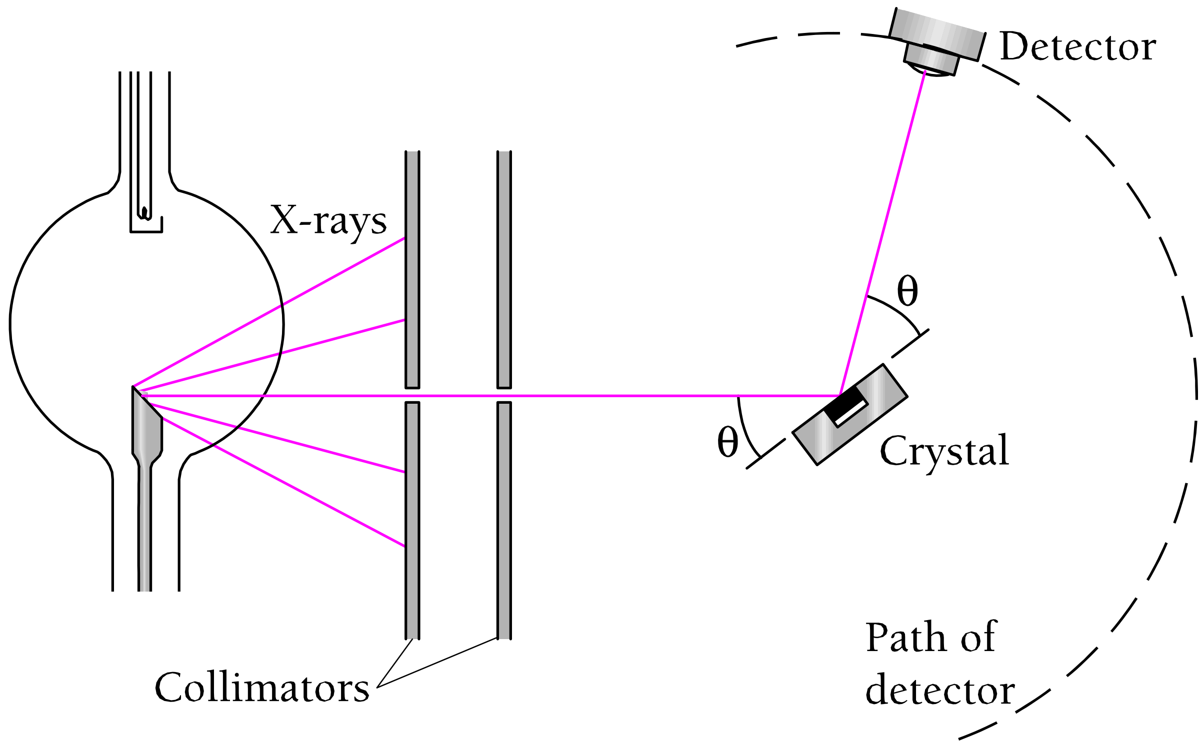



그림 2.21 x-선 분광기

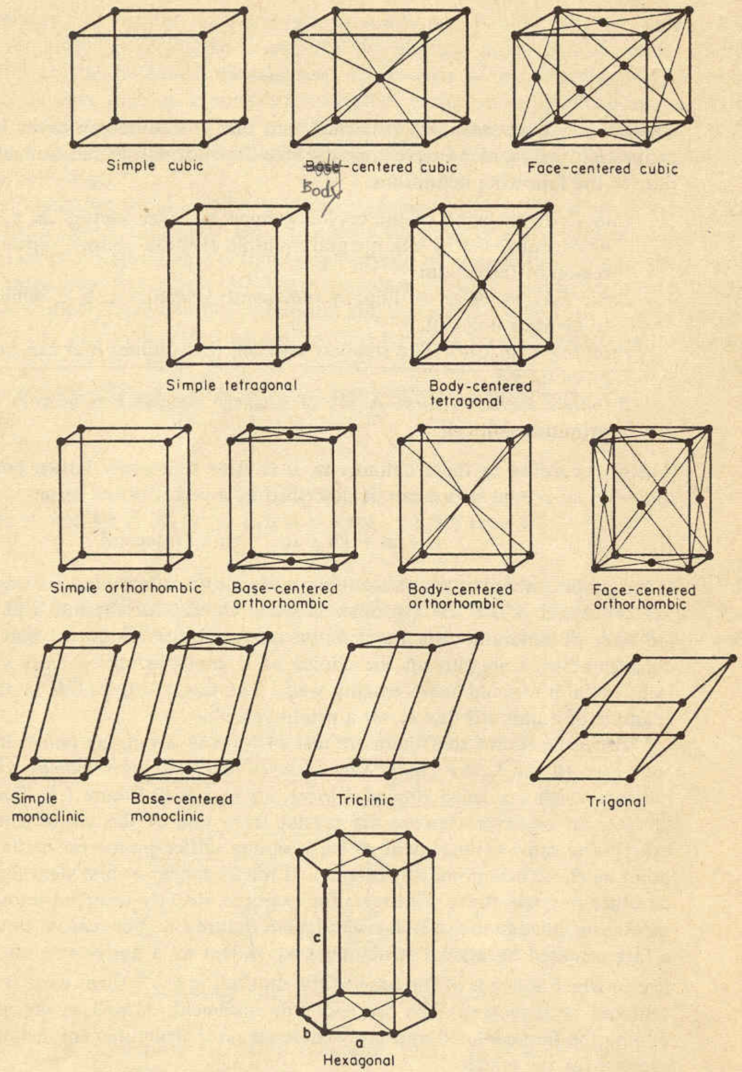
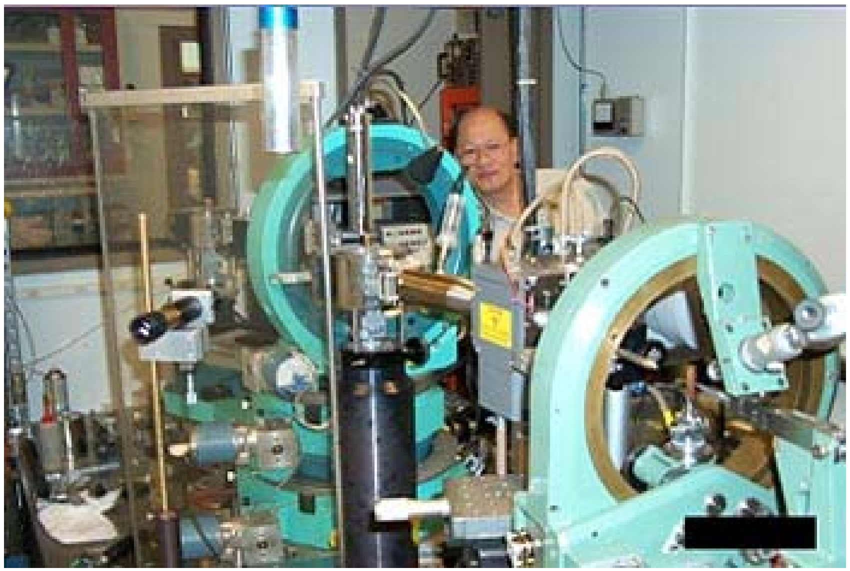
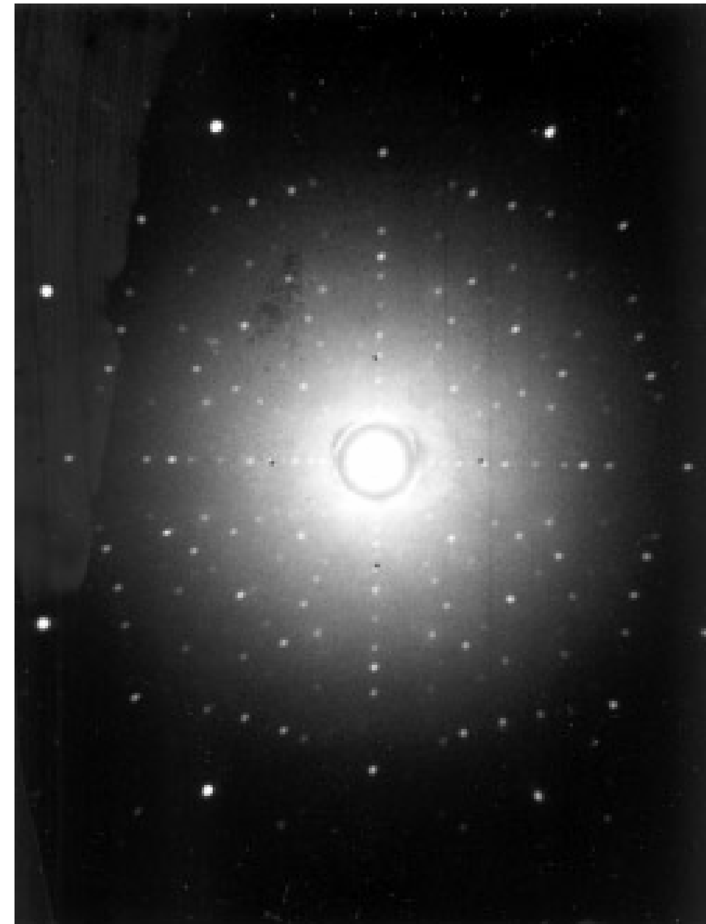


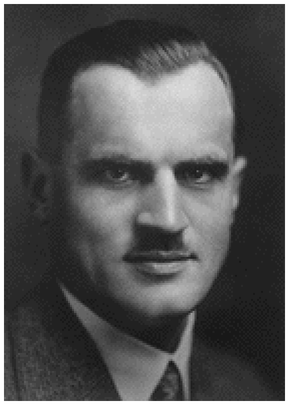

FIGURE 1.3. The fourteen Bravais lattices.





Lawrence Livermore National Laboratory, USA

# Compton Effect



Arthur Holly Compton
(1892-1962)

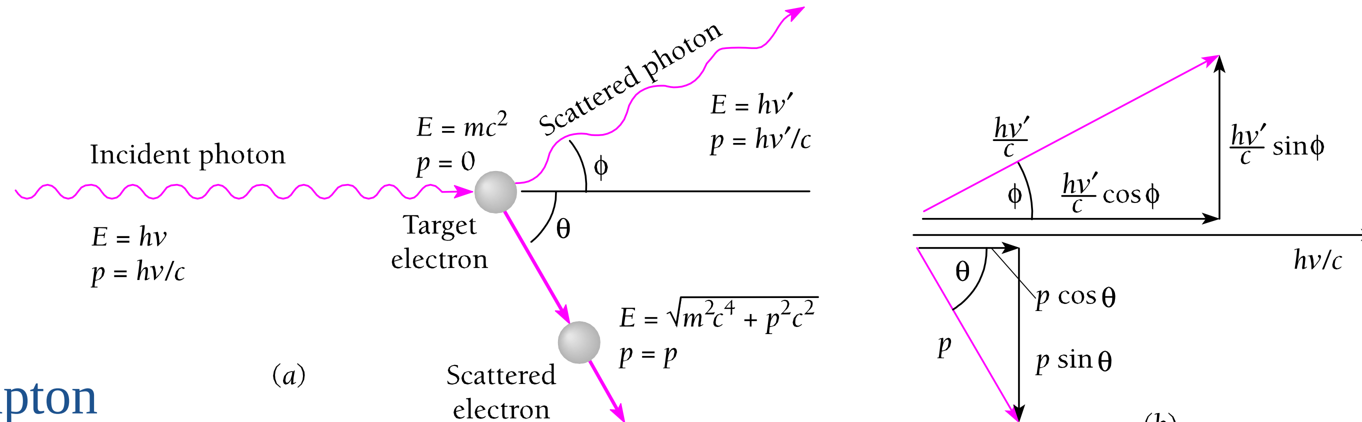



그림 2.22 (a) 전자에 의한 광자의 산란을 Compton 효과라 불린다. 이런 과정에서는 에너지와 운동량이 보존되므로, 산란된 광자는 입사한 광자보다 낮은 에너지(긴 파장)를 가진다. (b) 입사한 광자, 산란된 광자 그리고 전자의 운동량의 벡터 그림과 그 성분들.