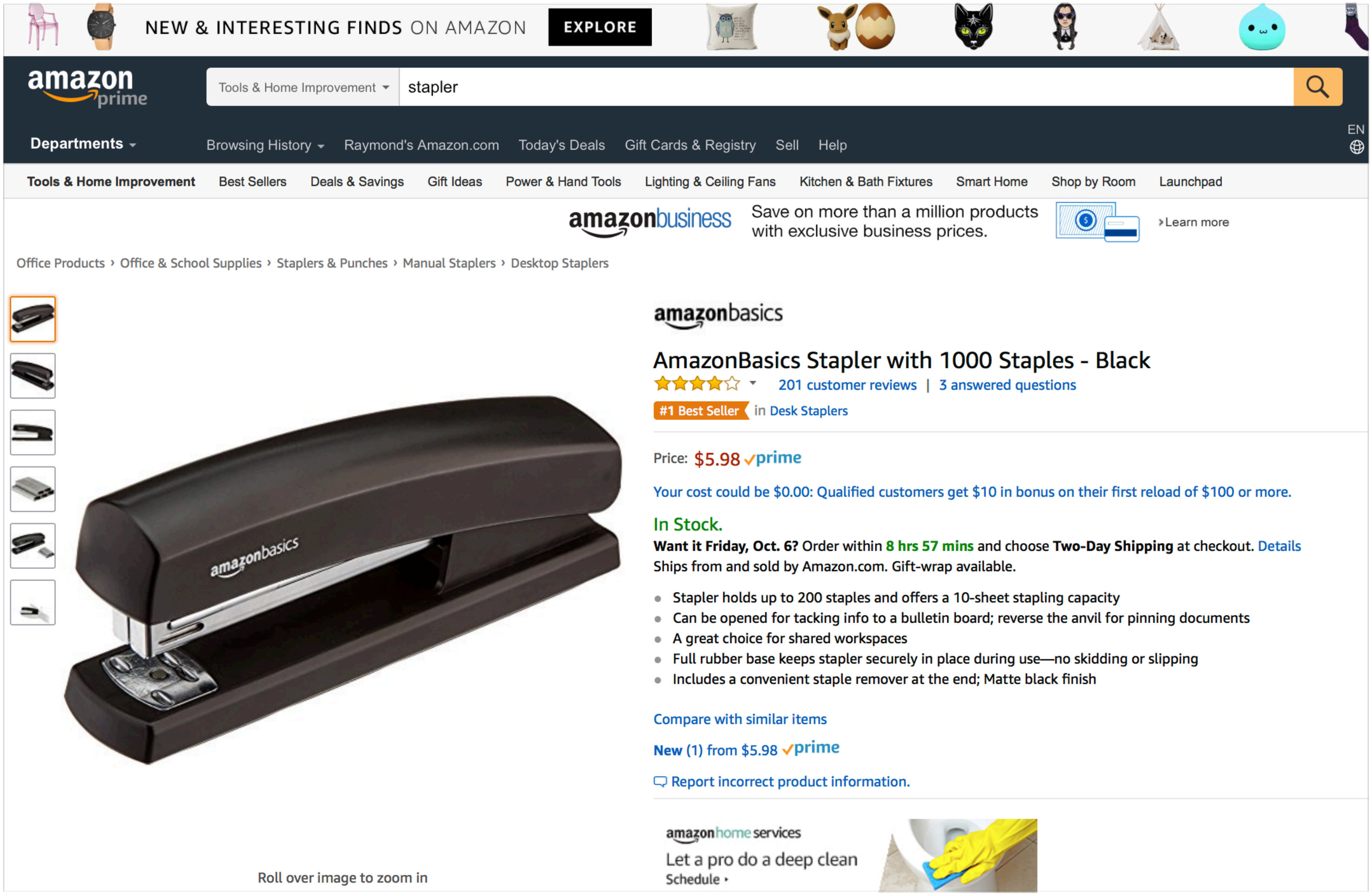
3. Experimental Basis of Quantum Physics, 3

lecture 15, October 4, 2017



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housekeeping

exam 1 was last friday ;)

- actually, next one is scheduled for Friday, 3 Nov
- I may make it a week early

Honors option

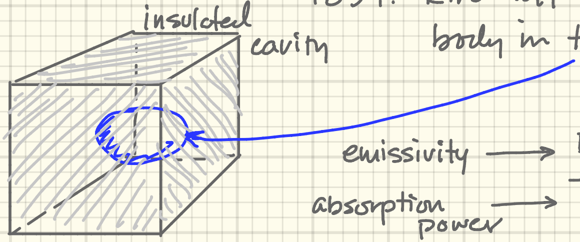
- Go to: https://qstbb.pa.msu.edu/storage/PHY215/honors/
- read the MinervaInstructions1_2017_215 document

more detail of some of the goings-on

in the 19th and early 20th Centuries

black body radiation
photoelectricity
x-rays
Compton scattering

Blackbody Radiation



1859: Kirchhoff showed for any body in termal equilibrium with radiation

power radiated per unit area per unit frequency of the object

emissivity → E_f

absorption power → A_f

$$\frac{E_f}{A_f} = \underbrace{J(f,T)}_{\text{only}}$$

perfect absorber & emitter

A Blackbody has $A_f = 1$

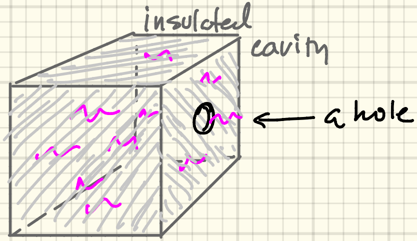
1879: Stefan measured

$$R_B = \int_0^\infty E_f \, df = \sigma T^4$$

R_B — power radiated by BB / unit area
"radiant emittance"

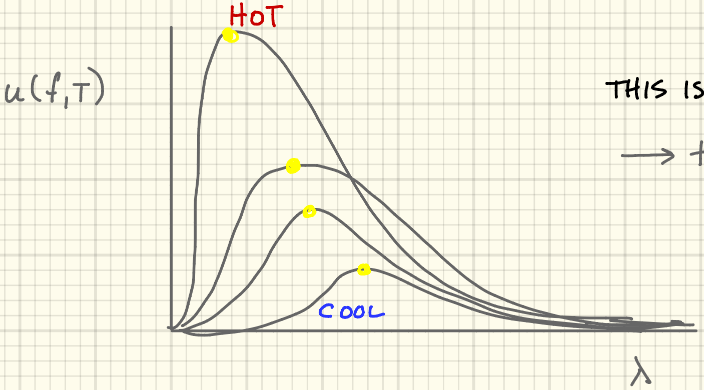
σ — Stefan's Constant
$0.56686 \times 10^{-7}\ \mathrm{W/m^2K^4}$

1884: Boltzmann derived it from Maxwell E&M + Thermodynamics more useful is the radiation rather than the BB itself.



$$J(f,T) = u(f,T)\frac{c}{4}$$

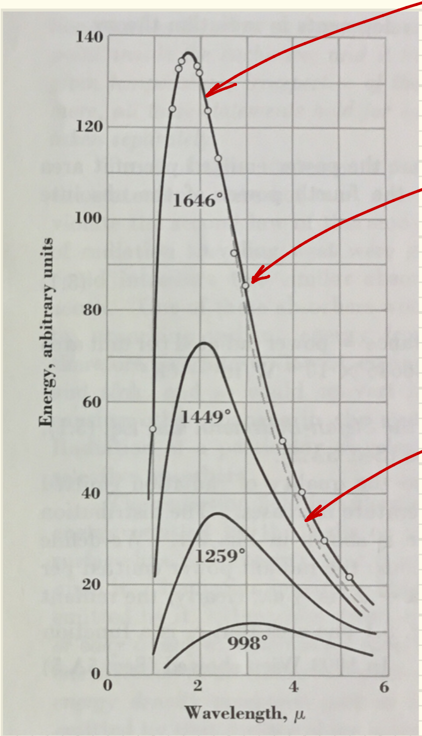
energy per unit volume per unit frequency of radiation



THIS IS WHAT PEOPLE MEASURED

→ the tasks

1. find the function $u(f,T)$
2. explain it



Planck's prediction

o data

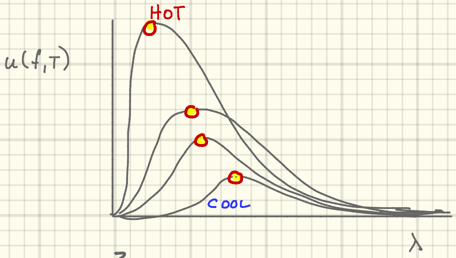
Wien's prediction

Data from the turn of the century.

1 phenomenological try
- Wilhelm Wien

2 theories
- "Raleigh-Jeans"
  strict Maxwell E&M
- Planck
  strict...well...surprise

Two Wien ideas, actually



"Wien's Displacement Law"

about the peaks ●

$$\lambda_{max} \cdot T = \text{constant} = 2.89\times10^{-3}\,\mathrm{m\cdot K}$$

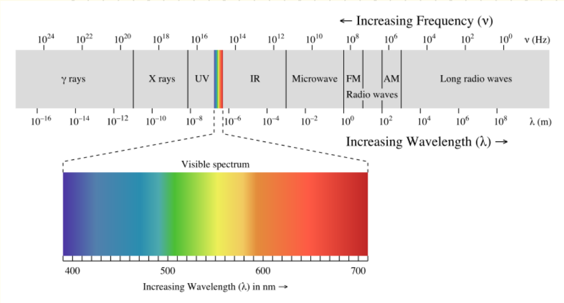
Two examples: 1)

peak sensitivity of our eyes? ~ 500nm

what T?

$$T = \frac{2.89\times10^{-3}\,\mathrm{m\cdot K}}{500\times10^{-9}\,\mathrm{m}} = 5800\,\mathrm{K}$$

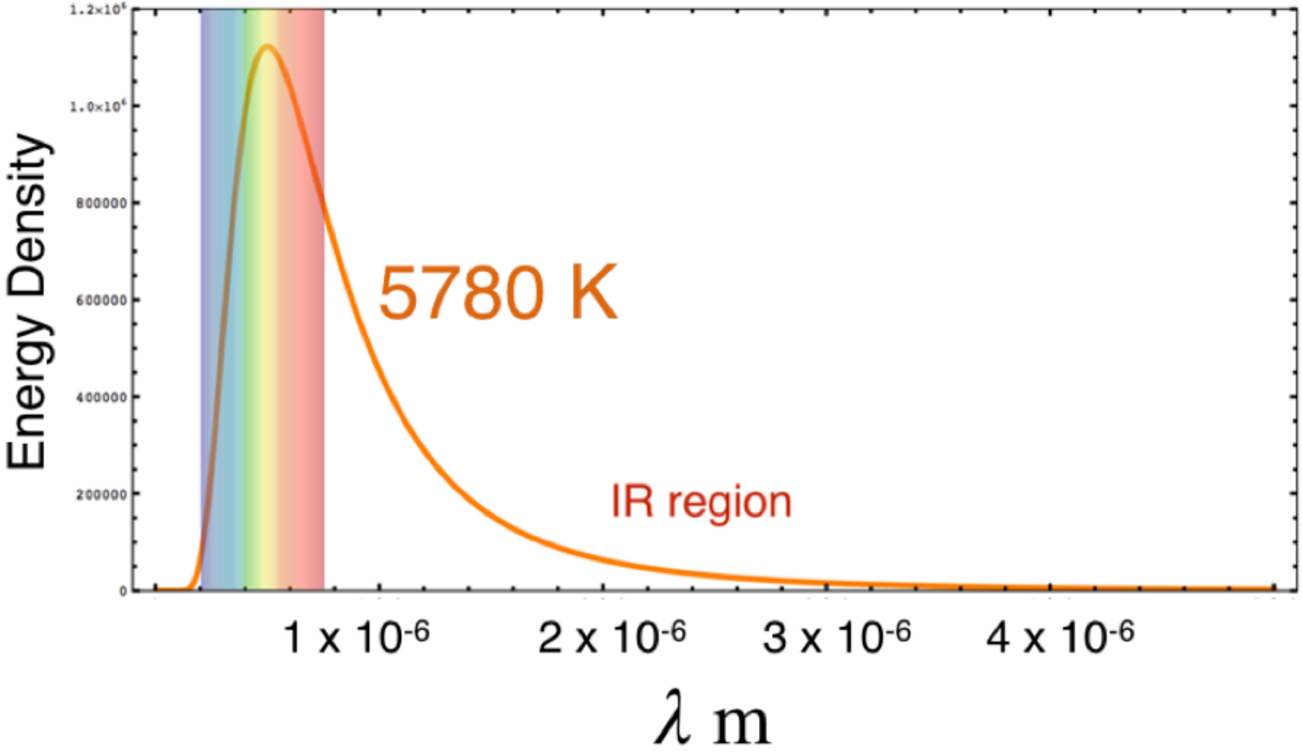
surface temp of sun.



2) body temperature 37°C

$$\lambda = \frac{2.89\times10^{-3}\,\mathrm{m\cdot K}}{(273+37)\,\mathrm{K}} = 9.3\times10^{-6}\,\mathrm{m}$$

$= 9\,\mu\mathrm{m}$


Energy Density
1.2×10^6
1.0×10^6
800000
600000
400000
200000
0
5780 K
IR region
1 x 10^-6
2 x 10^-6
3 x 10^-6
4 x 10^-6
λ m

Wien's Radiation Law

almost a guess: $u(f,T) = Af^3 e^{-\beta f/T} = A\lambda^{-5} e^{-\alpha/\lambda T}$

$A, \beta, \alpha \rightarrow$ fit

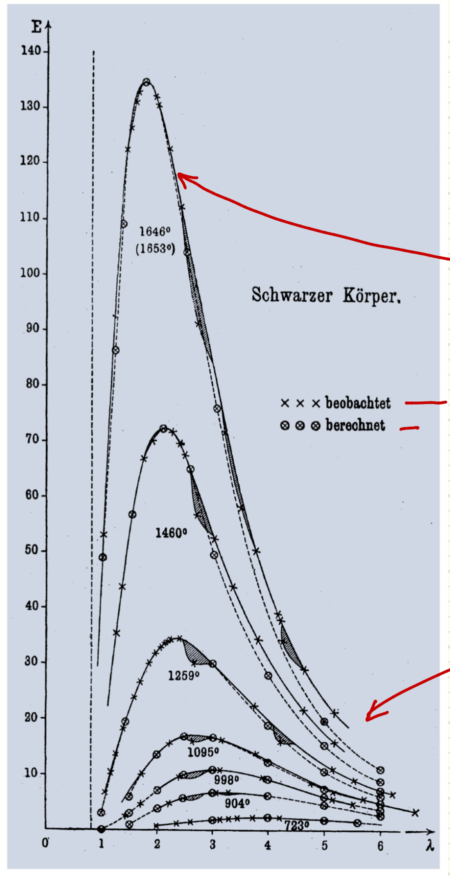
Wien worked pretty well

- remember where peak λ was for body temperature?

  9μm

- how about room temperature? 20°C?

  ~ 10μm

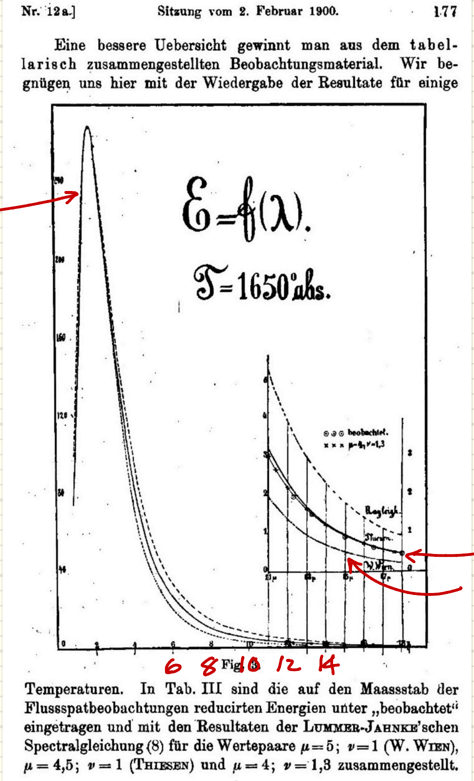


dashed curve

Wien

experiment

wien



Nr. 12a.] Sitzung vom 2. Februar 1900. 177

Eine bessere Uebersicht gewinnt man aus dem tabellarisch zusammengestellten Beobachtungsmaterial. Wir begnügen uns hier mit der Wiedergabe der Resultate für einige

Fig. 3.

Temperaturen. In Tab. III sind die auf den Maassstab der Flussspatbeobachtungen reducirten Energien unter „beobachtet" eingetragen und mit den Resultaten der Lummer-Jahnke'schen Spectralgleichung (8) für die Wertepaare $\mu=5$; $\nu=1$ (W. Wien), $\mu=4,5$; $\nu=1$ (Thiesen) und $\mu=4$; $\nu=1,3$ zusammengestellt.

Figure from Otto Lummer und Ernst Pringsheim, "Über die Strahlung des schwarzen Körpers für lange Wellen," *Verhandlungen der Deutschen Physikalischen Gesellschaft.* **2**, (1900) 163-180.

6 8 10 12 14

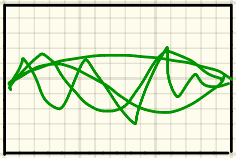
data

Wien

deviations at high λ... infrared VERY HARD EXPERIMENTS!

Another approach: purely E & M

Lord Ralieigh & James Jeans 1900–1905 (after Planck)



← all normal modes

$$u(f,T)\,df = \underset{\substack{\uparrow \\ \text{“Jeans number”}}}{N(f)}\langle E\rangle\,df$$

$$N(f)\,df = \frac{8\pi f^2}{c^3}\,df$$

$$\langle E\rangle = \frac{R}{\underset{\substack{\uparrow \\ \text{Planck named } k_B}}{N_A}}\,T$$

$$\left.\begin{matrix} \\ \\ \end{matrix}\right\} \quad u(f,T)\,df = \frac{8\pi f^2}{c^3}\,kT\,df$$

$$\langle E\rangle = \frac{1}{2}kT \times \underset{\substack{\uparrow \\ \text{2 polarizations}}}{\#\text{dof}} = kT$$

$u(f,T)\,df = \frac{8\pi f^2}{c^3} kT\,df$ or $u(\lambda,T)\,d\lambda = \frac{8\pi}{\lambda^4} kT\,d\lambda$

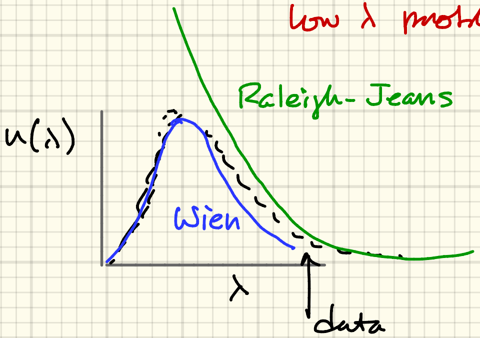
not good any way you look at it!

$\int_0^\infty u(f,T)\,df \to \infty$

$\int_0^\infty u(\lambda,T)\,d\lambda \to \infty$

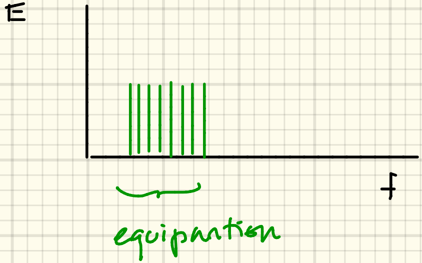
↑ high f problem

↑ low λ problem



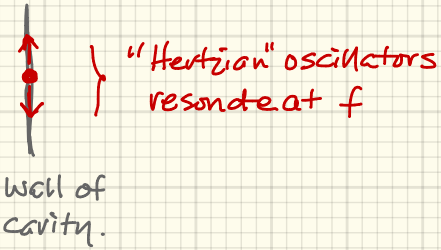
Max Planck 1895 attacked.

and retreated, and attacked, and retreated...



Complicated argument...

His model:



Planck found continuous f difficult

so he approximated

$$E = N\varepsilon$$

energy of oscillator

integer.

needed

$\varepsilon = hf$ to agree with Wien

planned to let h → 0 at the end

... but couldn't.

He too:

counted # states $N(f)\,df = \frac{8\pi f^2}{c^2}\,df$

and $u(T,f) = N(f)\langle E\rangle\,df$

But with $\varepsilon = hf$, $\langle E\rangle$ different.

$$\langle E\rangle = \frac{hf}{e^{hf/kT}-1}$$

So:

$$u(f,T)\,df = \frac{8\pi f^2}{c^3}\,\frac{hf}{e^{hf/kT}-1}\,df$$

"Planck Distribution"

from fitting: $h \doteq 6.626\times10^{-34}$ J·s

Planck's Constant

$$u(f,T)\,df = \frac{8\pi f^2}{c^3} \frac{hf}{e^{hf/kT}-1}\,df$$ "Planck Distribution"

from fitting: $h \cong 6.626 \times 10^{-34}\ \mathrm{J \cdot s}$

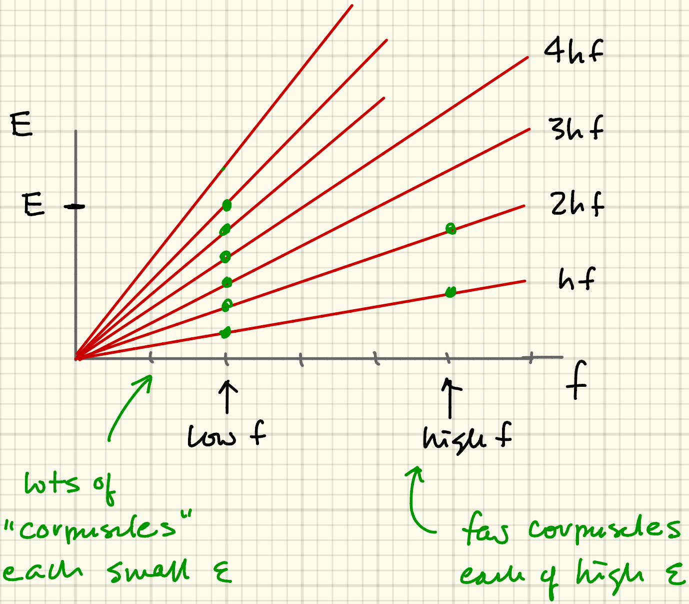
let: $\frac{hf}{kT} \ll 1$ $\left\{ \begin{array}{l} f \text{ small} \Rightarrow \lambda \text{ large} \\ T \text{ large} \\ h \to 0 \end{array} \right.$

$$u(f,T)\,df \longrightarrow \frac{8\pi f^2}{c^3} \frac{hf\,df}{1+\frac{hf}{kT}-1} = \frac{8\pi f^2}{c^3} kT\,df$$ R.J.

let: $\frac{hf}{kT} \gg 1$ $\left\{ \begin{array}{l} f \text{ large} \Rightarrow \lambda \text{ small} \\ T \text{ small} \end{array} \right.$

$$u(f,T)\,df \longrightarrow \frac{8\pi f^2}{c^3} \frac{hf}{e^{hf/kT}} = \frac{8\pi f^2}{c^3} e^{-hf/kT}$$ Wien

Reconciling R.J. w/ Planck . . .



lots of "corpuscles" each small ε

few corpuscles each of high ε

turns over at high f
harder to make them

blackbody from....something ;)

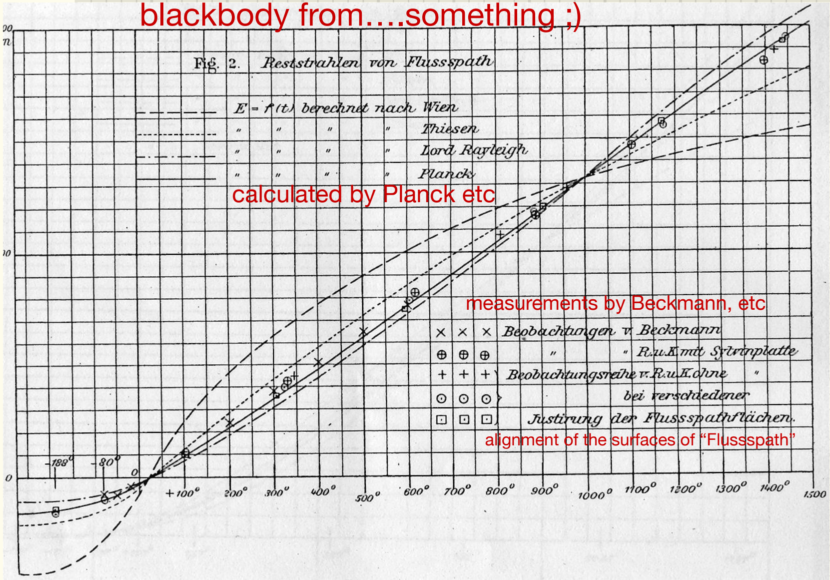
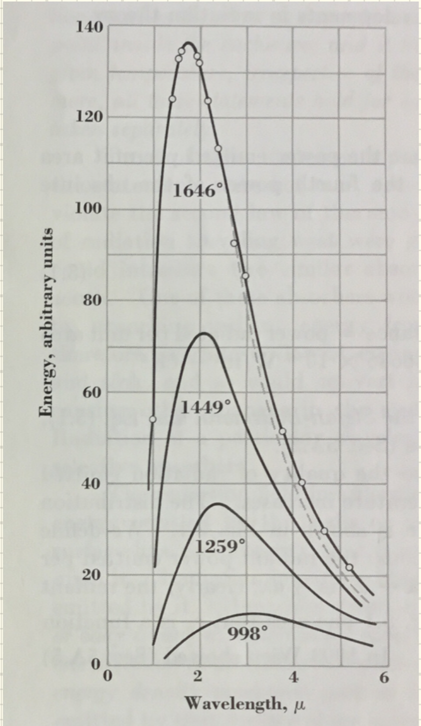


Fig. 2. Reststrahlen von Flussspath

calculated by Planck etc

measurements by Beckmann, etc

alignment of the surfaces of "Flussspath"



↑

1900 - Planck's colleagues

measurements done at 1 λ

and multiple temperatures

What Did Einstein Do?

Calculated the u of a gas of corpuscles of light – a gas of quanta

get's Planck's $u(f,T)$.

EINSTEIN'S TOTALLY DIFFERENT FROM PLANCK'S

↑ light behavior

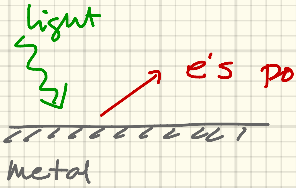
↑ only oscillator behavior

$$S = k \ln W$$

$$W = \left(\frac{f}{f_0}\right)^{E/hf}$$

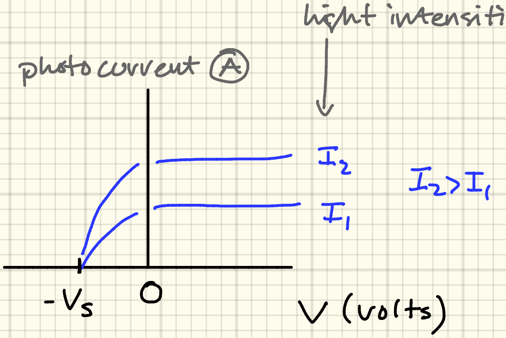
.. by "gas"... I mean a gas ala' Boltzmann

then: he solves photoelectricity.



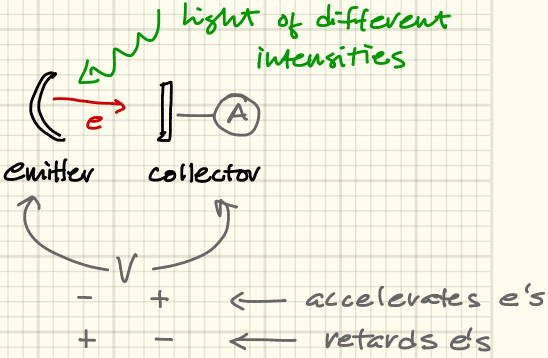
e's pop out.. "photocurrent"

Lenard:



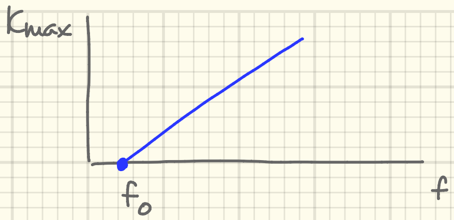
overcomes the fastest electrons

K_{max}



− + ⟵ accelerates e's

\+ − ⟵ retards e's



$$K_{max} = \frac{1}{2} m_e v_e^2 = eV_s = hf - hf_0$$

E's model: billiard balls

remember $E^2 = p^2c^2 + m^2c^4$

$$\overset{\uparrow}{= 0 \text{ for light}}$$

$$E = pc$$

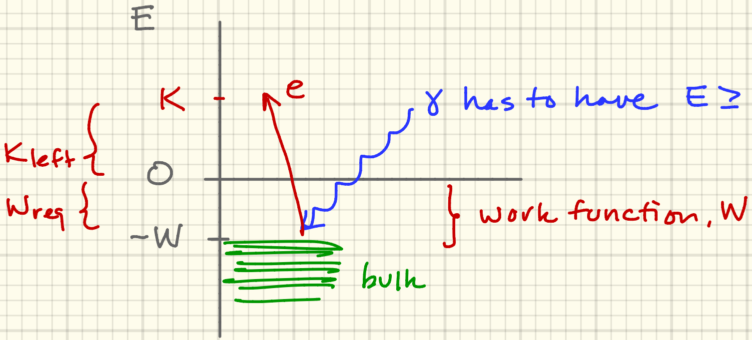
$$p = E/c = \frac{hf}{c} = \frac{h}{\lambda}$$

γ are momentum-carrying particles

↑

light quanta

(1926: "photons")



γ has to have $E \geq W$ to liberate e

$$hf = W + \tfrac{1}{2} m_e v_e^2$$

when $hf = W$ -- electron free w/ no K

$hf > W$ -- K_e depends on f

I_{photo} independent of I_γ

just # γ's

A DIRECT PHOTOELECTRIC DETERMINATION OF PLANCK'S "h."[1]

By R. A. Millikan.

I. Introductory.

Quantum theory was not originally developed for the sake of interpreting photoelectric phenomena. It was solely a theory as to the mechanism of absorption and emission of electromagnetic waves by resonators of atomic or subatomic dimensions. It had nothing whatever to say about the energy of an escaping electron or about the conditions under which such an electron could make its escape, and up to this day the form of the theory developed by its author has not been able to account satisfactorily for the photoelectric facts presented herewith. We are confronted, however, by the astonishing situation that these facts were correctly and exactly predicted nine years ago by a form of quantum theory which has now been pretty generally abandoned.

no!

It was in 1905 that Einstein[2] made the first coupling of photo effects and with any form of quantum theory by bringing forward the bold, not to say the reckless, hypothesis of an electro-magnetic light corpuscle of energy $h\nu$, which energy was transferred upon absorption to an electron. This hypothesis may well be called reckless first because an electromagnetic disturbance which remains localized in space seems a violation of the very conception of an electromagnetic disturbance, and second because it flies in the face of the thoroughly established facts of interference. The hypothesis was apparently made solely because it furnished a ready explanation of one of the most remarkable facts brought to light by recent investigations, viz., that the energy with which an electron is thrown out of a metal by ultra-violet light or X-rays is independent of the intensity of the light while it depends on its frequency. This fact alone seems to demand some modification of classical theory or, at any rate, it has not yet been interpreted satisfactorily in terms of classical theory.

While this was the main if not the only basis of Einstein's assumption, this assumption enabled him at once to predict that the maximum energy

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[1] An abstract of this paper was presented before the Am. Phys. Soc. in April, 1914. (Phys. Rev., IV., 73, '14.) The data on lithium were however first reported at the meeting of the Am. Phys. Soc. in April, 1915. (Phys. Rev., VI., 55, '15.)

[2] Ann. d. Phys. (4), 17, 132, 1905, and (4), 20, 199, 1906.

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sumed to travel along the ether strings are proportional to the impressed frequency and (2) that they are transferred upon absorption as wholes to an electron. This being the case, the objections to an ether-string theory, that is, to any theory in which the energy remains localized in space instead of spreading over the entire wave-front, must hold for the Einstein theory. Lorenz[1] and Planck[2] have pointed out some of these. Despite these objections, however, Sir J. J. Thomson[3] and Norman Campbell[4] still adhere to it. I wish to call attention to one more difficulty which in itself seems to me to be very serious.

If a static electrical field has a fibrous structure, as postulated by any form of ether-string theory "each unit of positive electricity being the origin and each unit of negative electricity the termination of a Faraday tube,"[5] then the force acting on one single electron between the plates of an air condenser cannot possibly vary *continuously* with the potential difference between the plates. Now in the oil-drop experiments[6] we actually study the behavior in such an electric field of one single, isolated electron and we find, over the widest limits, exact proportionality between the field strength and the force acting on the electron as measured by the velocity with which the oil drop to which it is attached is dragged through the air.

When we maintain the field constant and vary the charge on the drop, the granular structure of electricity is proved by the discontinuous changes in the velocity, but when we maintain the charge constant and vary the field the lack of discontinuous change in the velocity disproves the contention of a fibrous structure in the field unless the assumption be made that there are an enormous number of ether strings ending in one electron. Such an assumption takes all the virtue out of an ether string theory.

Despite then the apparently complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it. But how else can the equation be obtained?

Before attempting to answer this question, let us consider the energy relations which it imposes. It requires the absorption at some time or other by the escaping electron of at least the energy $h\nu$ from incident waves of frequency ν. The total luminous energy falling per second from

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[1] Phys. Zeit., 11349, 1910.

[2] Ann. der. Phys., 39, 1912. Berliner Ber., 723, 1911.

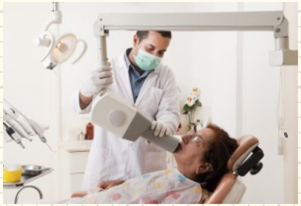
[3] Proc. Phys. Soc. London, XXVII., 105, December 15, 1914.

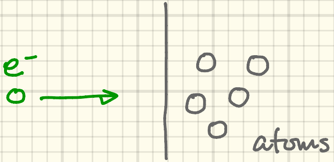
[4] Modern Electrical Theory, Cambridge Press, 1913, p. 248.

[5] J. J. Thomson's Electricity and Matter, p. 9.

[6] Phys. Rev., 2, 109, 1913.

X-rays



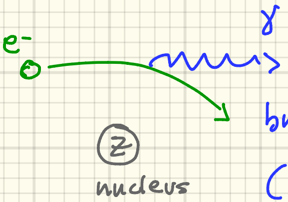


high Z material... Z effects

1. Continuous radiation spectrum:

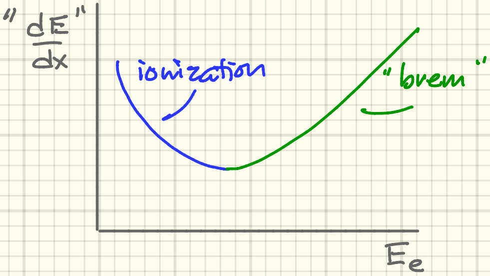
$$\frac{\Delta E}{\Delta x} \propto \frac{K_e}{m_e}$$ brem

so electrons lose a lot

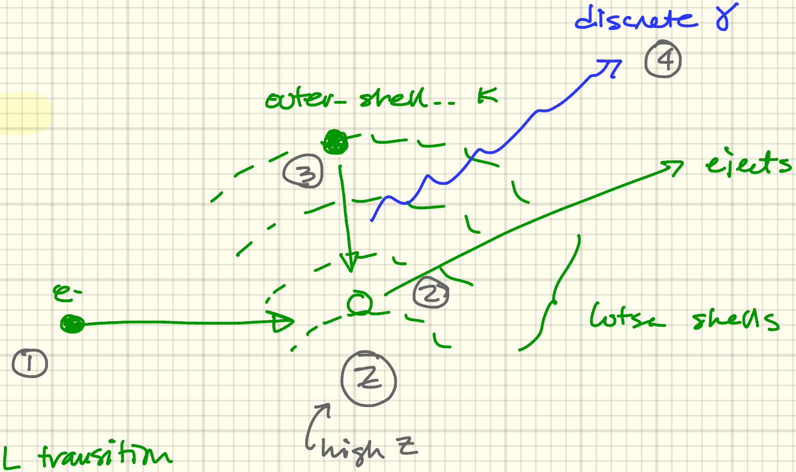


bremsstrahlung

(braking radiation)



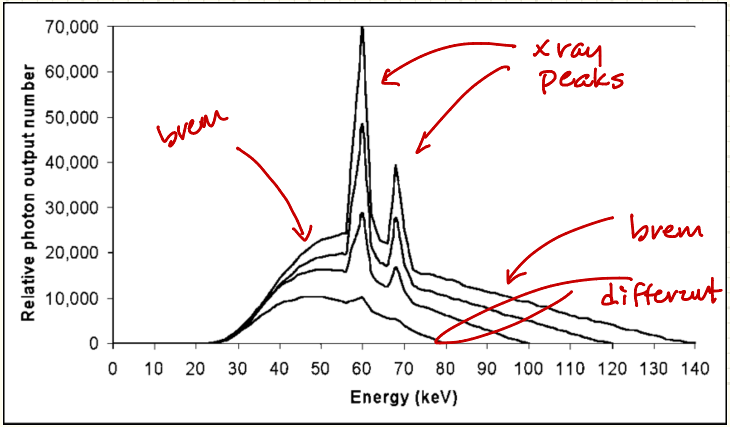
2. Discrete emission



most x-ray machines
also Mo

Tungsten:

K → L transition



Tungsten wavelength?

AN ASIDE ON UNITS →

PLANCK'S CONSTANT IN MANY GUISES:

$h = 6.6261 \times 10^{-34}\ \underset{\overset{\uparrow}{eV}}{J} \cdot s$ ⟶ more useful in physics: $\cancel{J}$

$$h(eV \cdot s) = (6.6261 \times 10^{-34}\ J \cdot s)\left(\frac{1}{1.6 \times 10^{-19}\ J/eV}\right) = 4.14 \times 10^{-15}\ eV \cdot s$$

also, hc happens frequently

$$hc = (6.6261 \times 10^{-34}\ J \cdot s)(3 \times 10^{8}\ m/s) = 1.99 \times 10^{-25}\ J \cdot m$$

or

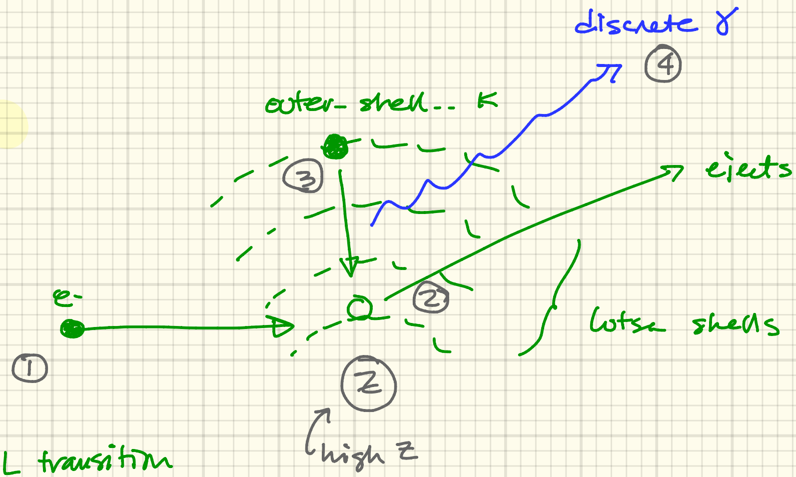
$$hc = (4.14 \times 10^{-15}\ eV \cdot s)(3 \times 10^{8}\ m/s)\left(\frac{1\ nm}{1 \times 10^{-9}\ m}\right) = 1241\ eV \cdot nm$$

"reduced Planck's constant"

$\frac{h}{2\pi}$ happens frequently ⇒ $\hbar = 1.05 \times 10^{-34}\ J \cdot s = 6.58 \times 10^{-22}\ MeV \cdot s$

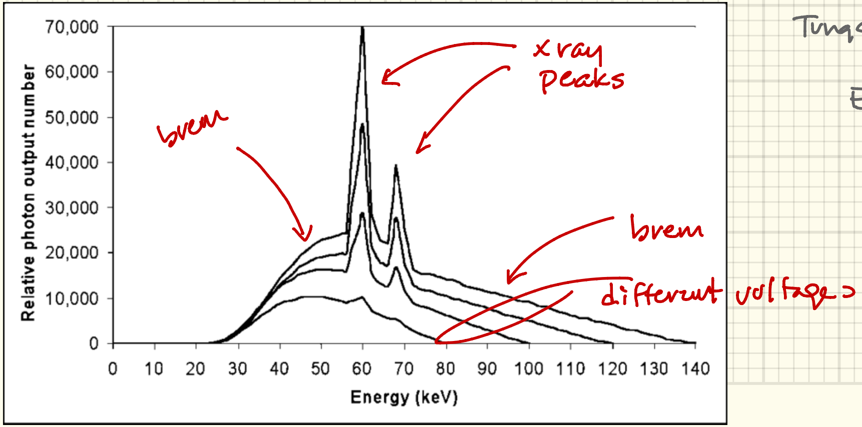
"h-bar"

2. Discrete emission



Tungsten:

K → L transition



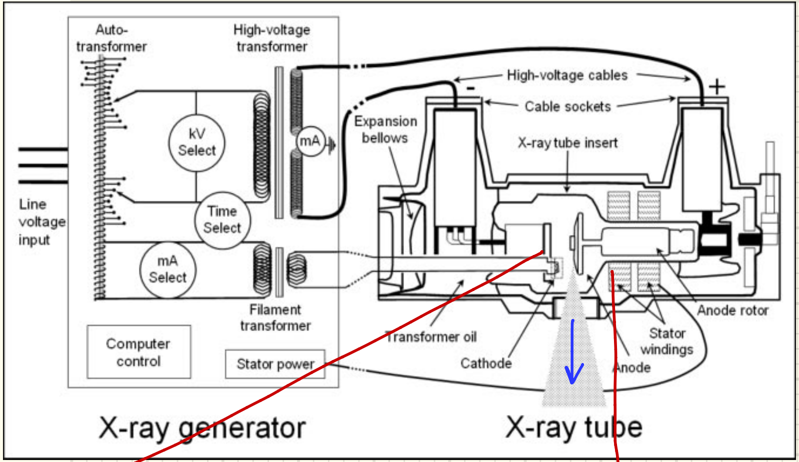
Tungsten wavelength?

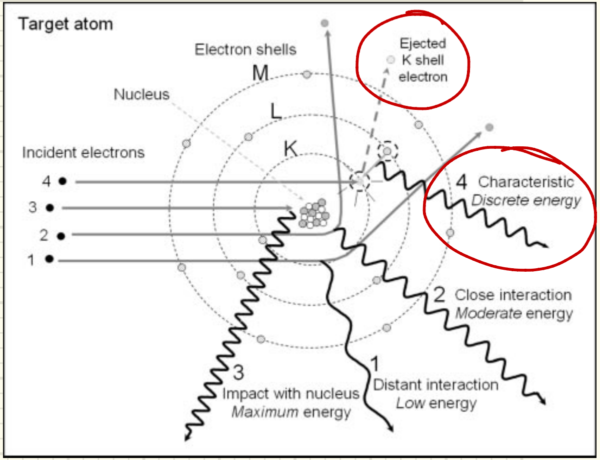
$$E = hf = \frac{hc}{\lambda}$$

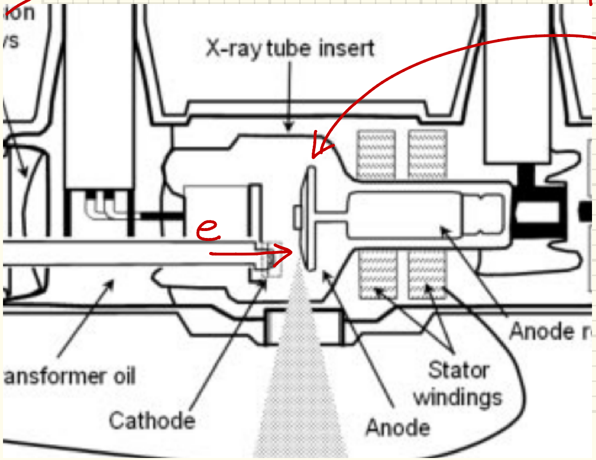
$$\lambda = \frac{hc}{E} = \frac{1241\ \text{eV}\cdot\text{nm}}{60 \times 10^{3}\ \text{eV}}$$

$$\lambda = 2.1 \times 10^{-2}\ \text{nm}$$

Seibert, James. (2004). X-ray imaging physics for nuclear medicine technologists. Part 1: Basic principles of x-ray production. Journal of nuclear medicine technology. 32. 139-47.



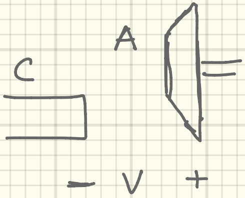




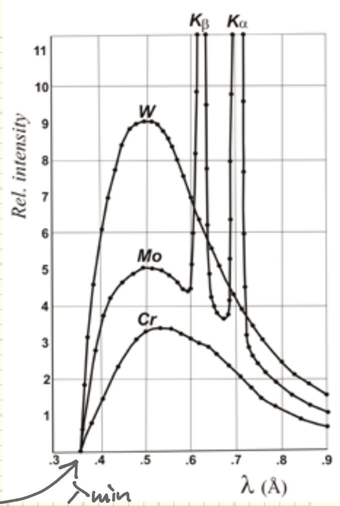
W anode rotates

Calculate voltage required

to



for electron to give up all KE to E_γ



λ_{min}

$0.35 \times 10^{-10}\ m$

$\sim\ 3 \times 10^{-2}\ nm$

$$K_e = eV = hf^{max}$$

$$eV_0 = \frac{hc}{\lambda^{min}}$$

$$V_0 = \frac{hc}{e\lambda_{min}}$$

HARD WAY

$$V_0 = \frac{(1.99 \times 10^{-25}\ J \cdot m)}{(1.6 \times 10^{-19}\ C)(3 \times 10^{-2} \times 10^{-9}\ m)}$$

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

EASY WAY

$$V_0 = \frac{1241\ \cancel{e}V \cdot \cancel{nm}}{\cancel{e}\ 3 \times 10^{-2}\ \cancel{nm}}$$

$$V_0 = 41,400\ V$$