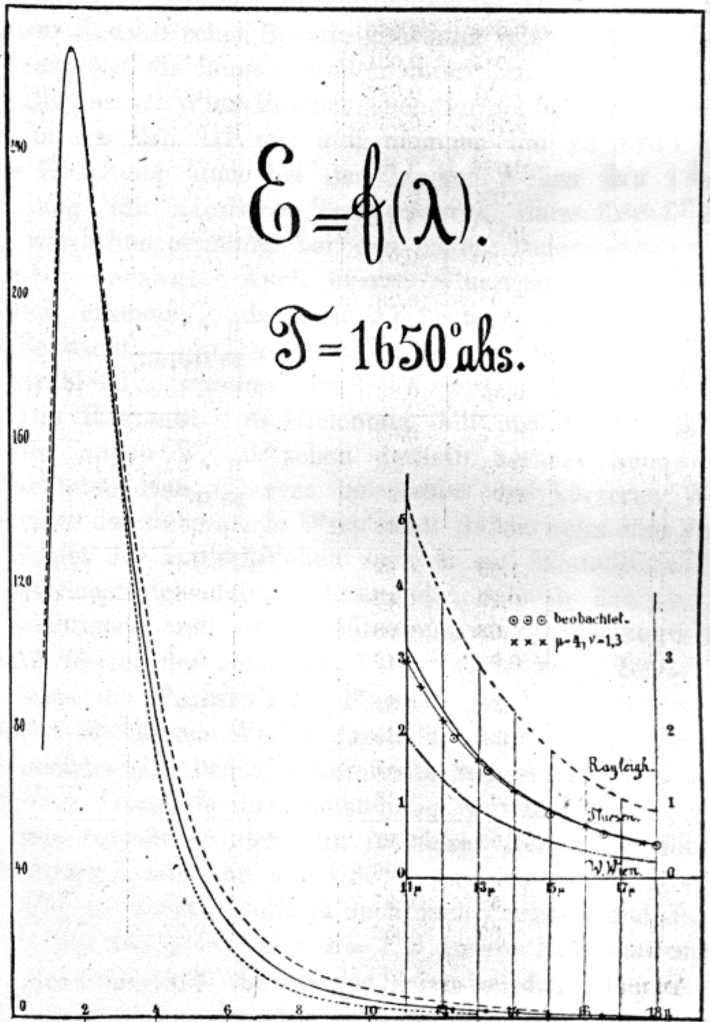

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Rethinking Light

8.225 / STS.042, Physics in the 20th Century
Professor David Kaiser, 30 September 2020

"Old Quantum Theory" (~ 1900 – 1924*)

Rethinking Light

1. Blackbody radiation# (1900)

2. Photoelectric effect (1905)

3. Compton scattering# (1922)

Rethinking Matter

1. Rutherford scattering (1911)

2. Bohr atom (1913)

3. de Broglie hypothesis (1924)

today's topic

See *Lecture Notes* on "Blackbody radiation and Compton scattering"

* dates are approximate! As we will see, physicists debated and revisited each of these topics over a span of years.

Blackbody Radiation

Physikalisch-Technische Reichsanstalt
(PTR), Berlin, ca. 1900
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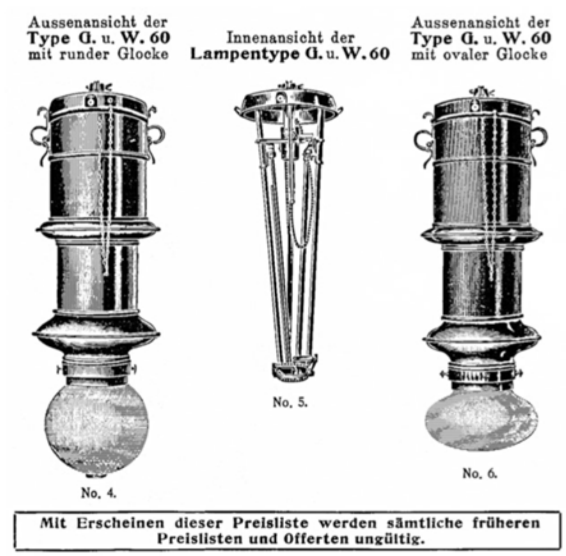
Germany became a united country in 1871, and accelerated a program of rapid industrialization. In 1887, at the urging of scientists and engineers, the government founded the *Physikalisch-Technische Reichsanstalt** (PTR) to foster research at the intersections of basic science, applied research, and industrial development. (Akin to the U.S. Bureau of Standards, now the National Institute of Standards and Technology [NIST].)

Early, pressing challenge: evaluate competing proposals for large-scale electric street lighting.

*Imperial Physical-Technical Institute



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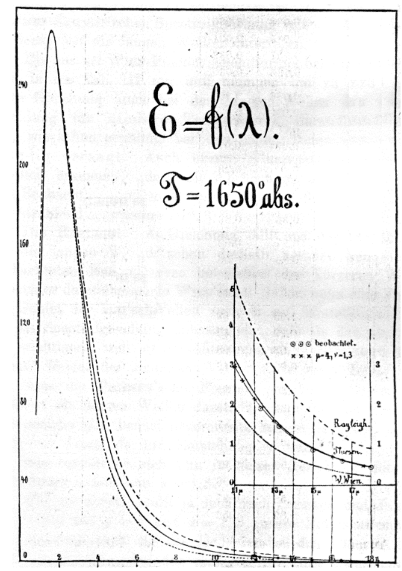
Blackbody Radiation

Glowing embers in a fireplace

When an object is heated to a high enough temperature, it will *glow*. The color of the emitted light shifts with the temperature to which the object has been heated.

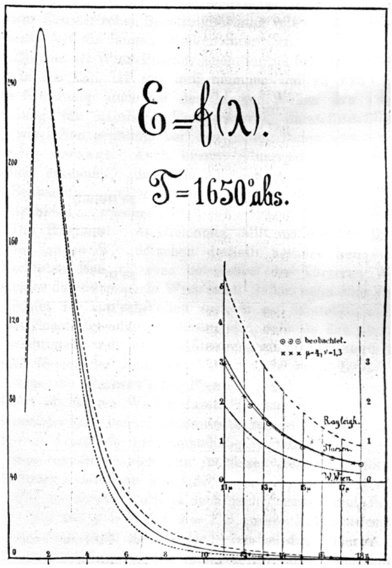
While working on calibrations for various electric lighting proposals, researchers at the PTR noted a "universal glow": the pattern of light emitted from various objects when they were heated to sufficiently high temperatures seemed to be *independent* of the composition of those materials.

They postulated that for an ideal "blackbody" — an object that absorbed all light that fell upon it, reflecting none — there might exist a single, universal *spectrum*, or pattern of the intensity of light emitted at various wavelengths.



Lummer and Pringsheim, blackbody spectrum, 1890s

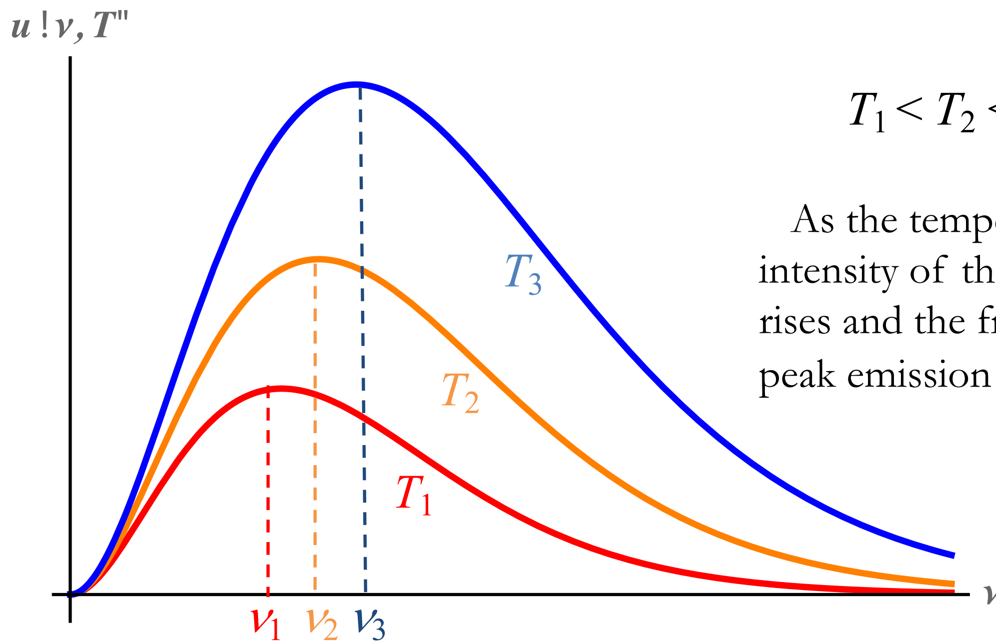
Blackbody Radiation



Lummer and Pringsheim,
blackbody spectrum, 1890s

The universal blackbody spectrum seemed interesting for at least two reasons: it could be useful for *industrial calibrations and standardization*, and it might offer clues about *fundamental interactions* between light and matter. So PTR researchers collected more and more data on emissions from (near) blackbodies throughout the 1880s and 1890s.

u (ν, T): energy density, how much energy was radiated per volume per frequency ν.

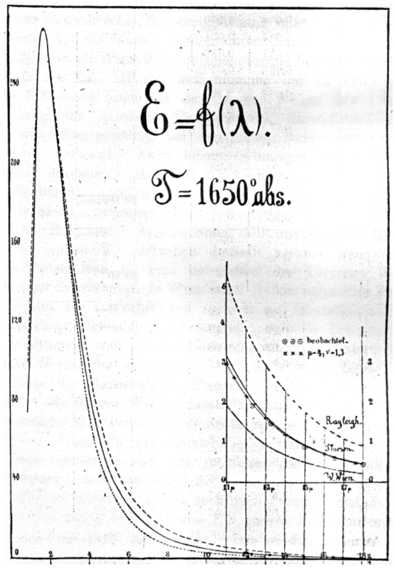


$T_1 < T_2 < T_3$

As the temperature rises, the intensity of the emitted light rises and the frequency of the peak emission rises.

$$\text{Recall : } \nu = \frac{c}{\lambda}$$

Blackbody Radiation

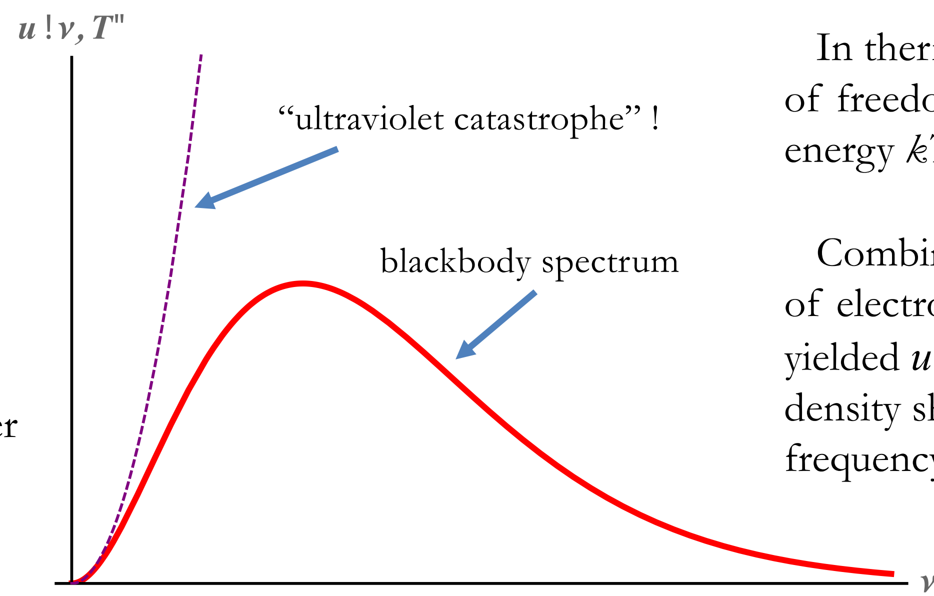


Lummer and Pringsheim,
blackbody spectrum, 1890s
Image is in the public domain.

As the empirical pattern of the blackbody spectrum was becoming more clear, how to *explain* that pattern was becoming more *puzzling*.

Max Planck was following the developments at the PTR closely. He became the new *Ordinarius* professor of theoretical physics in Berlin in 1892, and was an expert in *statistical mechanics*.

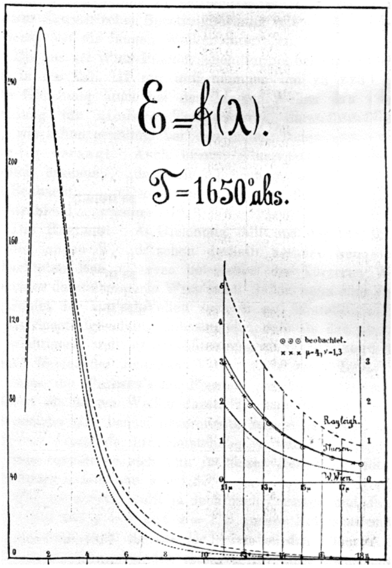
$u\,(\nu,\, T)$: energy density, how much energy was radiated per volume per frequency ν.



In thermal equilibrium, each degree of freedom should have average energy kT ("equipartition theorem").

Combined with Maxwell's treatment of electromagnetic radiation, that yielded $u\,(\nu,\, T) \sim kT\nu^2$: the energy density should *rise without limit* as the frequency of emitted light increased!

Blackbody Radiation



Lummer and Pringsheim, blackbody spectrum, 1890s

Given his proximity to the PTR, Planck had access to better, more up-to-date data on blackbody spectra than most of his colleagues. He knew not only that the $u(\nu,T)$ curve *must* fall with increasing ν; he had empirical evidence about how *sharply* the curve actually fell. *So he began to tinker.*

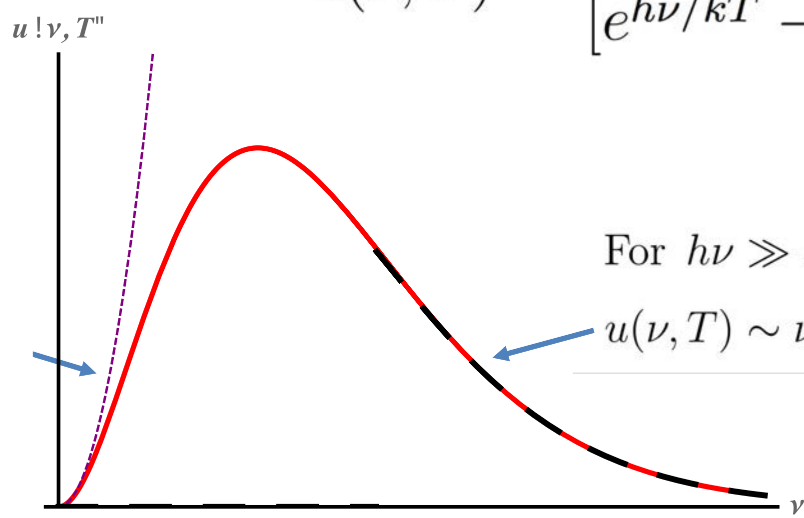
On December 14, 1900, he presented a paper to the German Physical Society:

$$u(\nu, T) \sim \frac{\nu^3}{[e^{h\nu/kT} - 1]}$$

h: a new, universal constant, now known as "Planck's constant."

For $h\nu \ll kT$,

$$u(\nu, T) \sim kT\nu^2$$



For $h\nu \gg kT$,

$$u(\nu, T) \sim \nu^3 e^{-h\nu/kT}$$

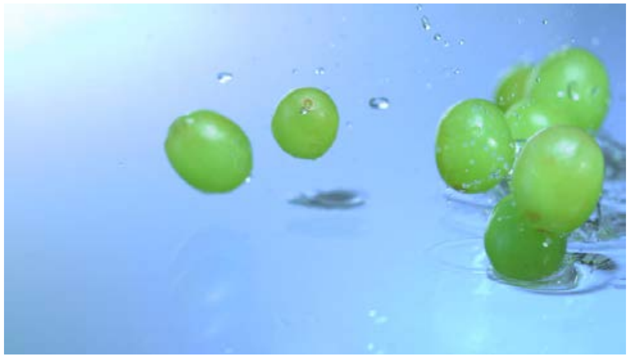
The Quantum Scale

In his 1900 treatment of blackbody radiation, Planck introduced a new universal constant, h. It set the *scale* for departures from physical descriptions based solely on Newton's or Maxwell's equations.

$$h = 6.261 \times 10^{-27} \text{ erg-seconds}$$

erg: a unit of energy
$1 \text{ erg} = 1 \text{ g cm}^2 / \text{s}^2$

On the scale of human-sized objects, h is *incredibly small*:



Drop a grape from 5 cm: $E \,\Delta t \sim 10^{28}\, h$

Fly buzzing your head: $|\mathbf{L}| \sim 10^{28}\, h$

The Origin of Quantum Theory?

Scientists typically say that Planck launched a new "quantum revolution" with his work in 1900. In *modern* derivations, we arrive at Planck's expression for $u(\nu,T)$ by stipulating that the energy exchanged between matter and radiation must be *quantized*, in units $E = h\nu$, rather than treated as continuous. *Is that what Planck thought he was doing?*

Kuhn: In Planck's 1900 derivation, he fixed the *total energy of the system* to be an integer number of units of $h\nu$,

$$E_{\text{total}} = \sum_i E_i = Nh\nu$$

but he did *not* require $E_i = h\nu$. In fact, in Planck's description, the energies for sub-systems fell "in the *range* $(E_i, E_i + \Delta E_i)$." Planck used *bins* of size $\varepsilon = h\nu$ for his accounting, but then counted how many oscillators of *continuous* energy fell within bins $[0, \varepsilon]$, $[\varepsilon, 2\varepsilon]$, and so on.

In his 1906 lectures, Planck *still* spoke of continuous (rather than quantized) energy exchange.

(The debate continues: see M. Nauenberg, *American Journal of Physics* 84 (2016): 709-720.)

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Planck letter to a colleague, 1931: "What I did can be described as simply an act of desperation. ... [Introducing bins $\varepsilon = h\nu$] was purely a formal assumption and I really did not give it much thought ..."

Kuhn. In Planck's ... to be an integer number of units of $h\nu$,

$$E_{\text{total}} = \sum_i E_i = Nh\nu$$

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Questions?

Photoelectric Effect

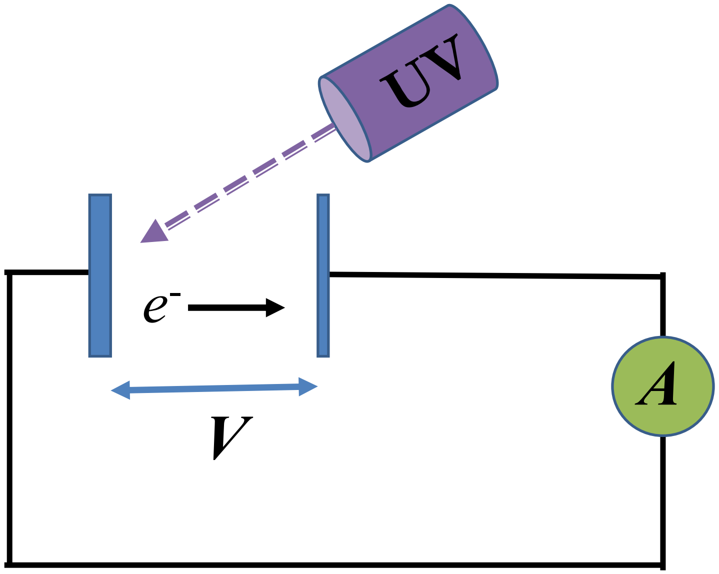
Einstein at the Patent Office, 1905

In 1900, Planck had been concerned with the *interaction* between light and matter, not the propagation of light on its own. In 1905, Einstein began to think about the nature of light itself.

March 1905: light quanta
May 1905: Brownian motion
June 1905: special relativity
September 1905: $E = mc^2$

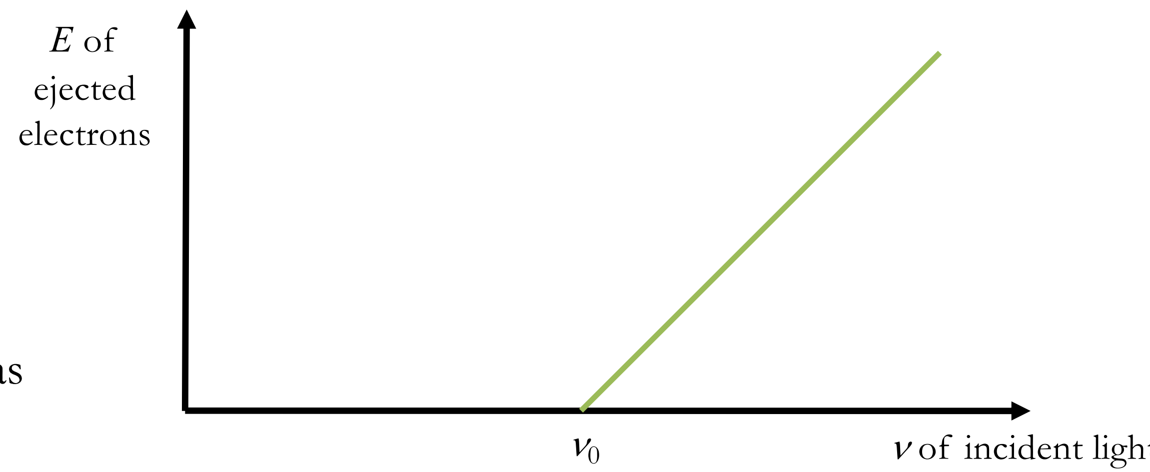
In particular, he was trying to make sense of recent experimental results (1902) from *Philipp Lenard* on the ejection of electrons from a metal plate, when high-energy radiation shines on it.

Photoelectric Effect

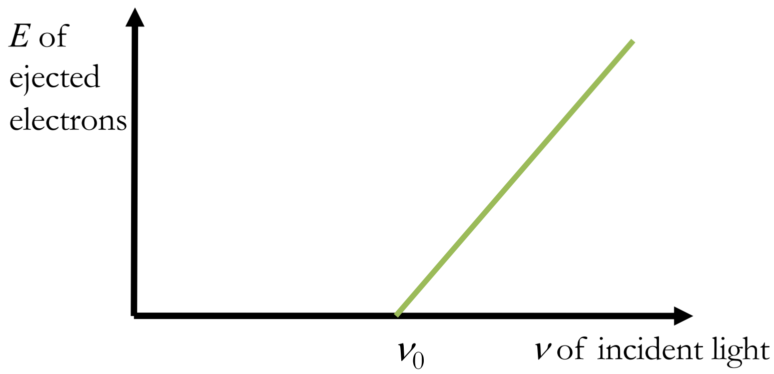


In his experiments, Lenard applied a tunable voltage $\boldsymbol{V}$ across conducting plates. When one of the plates was irradiated with ultraviolet light (**UV**), electrons were ejected and traveled to the other plate, completing a circuit (hence current was measured in the ammeter $\boldsymbol{A}$). By adjusting the voltage, Lenard could measure *how much energy* the electrons had upon being ejected from the plate ("stopping voltage"), and compare that with the *frequency* of the radiation that had shone onto the plate.

Lenard's data indicated that there was some *threshold frequency*, below which no electrons were ejected. Above that frequency, the electrons' energy *rose linearly* with the frequency of incident light, but was *independent* of the *intensity* of the light.



Photoelectric Effect



Why were Lenard's results puzzling?

According to Maxwell's work, the *energy* carried by a light wave is proportional to its *intensity*:

$$E \sim I \sim |\mathbf{E}|^2 + |\mathbf{B}|^2$$

So why couldn't Lenard's device eject electrons with *high-intensity* light of *low frequency*? If light acted like Maxwellian waves, there should be *no threshold frequency* ν_0 in the photoelectric experiments.

Likewise, according to Maxwell's work, the energy imparted to the electrons that *were* ejected should have been proportional to the light wave's *intensity*, with no particular dependence on the light's *frequency*.

Photoelectric Effect

6. ***Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt;***
von A. Einstein.

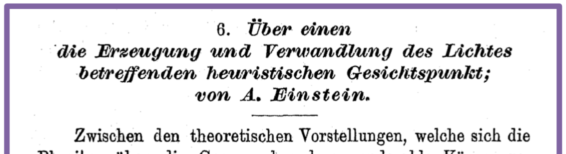
Zwischen den theoretischen Vorstellungen, welche sich die Physiker über die Gase und andere ponderable Körper gebildet haben, und der Maxwellschen Theorie der elektromagnetischen Prozesse im sogenannten leeren Raume besteht ein tiefgreifender formaler Unterschied. Während wir uns nämlich den Zustand eines Körpers durch die Lagen und Geschwindigkeiten einer zwar sehr großen, jedoch endlichen Anzahl von Atomen und Elektronen für vollkommen bestimmt ansehen, bedienen wir uns zur Bestimmung des elektromagnetischen Zustandes eines Raumes kontinuierlicher räumlicher Funktionen, so daß also eine endliche Anzahl von Größen nicht als genügend anzusehen ist zur vollständigen Festlegung des elektromagnetischen Zustandes eines Raumes. Nach der Maxwellschen Theorie ist bei allen rein elektromagnetischen Erscheinungen, also auch beim Licht, die Energie als kontinuierliche Raumfunktion aufzufassen, während die Energie

In what he considered the "most radical" of his papers of 1905, Einstein offered a "heuristic"* explanation of the photoelectric effect: *What if light itself were quantized?*

"It seems to me that the observations about [...] the production of cathode rays by ultraviolet light [...] are more readily understood if one assumes that the energy of light is *discontinuously distributed* in space. [As suggested here,] the energy of a light ray spreading out from a point source is not continuously distributed over an increasing space but consists of *a finite number of energy quanta* which are localized at points in space, which *move without dividing*, and which can only be produced and absorbed as *complete units*."

* heuristic means "suggestive," worth considering, not definitive.

Photoelectric Effect



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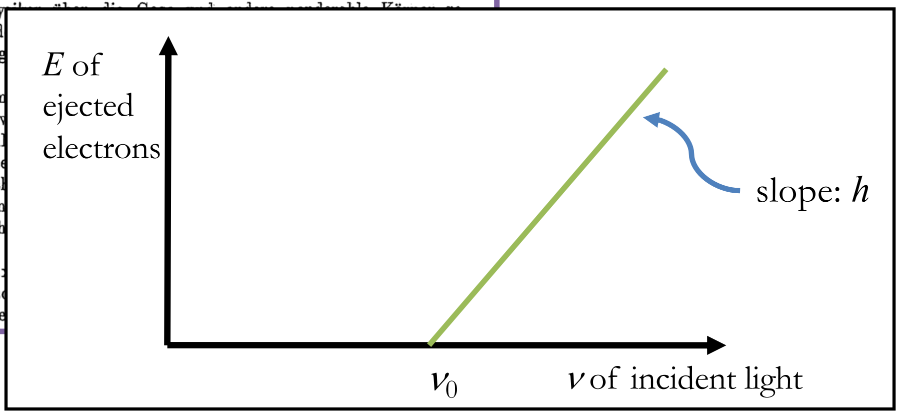


ν was very close to Planck's new constant, h.

If *each* light quantum carried energy

$$E_{\text{light quantum}} = h\nu$$

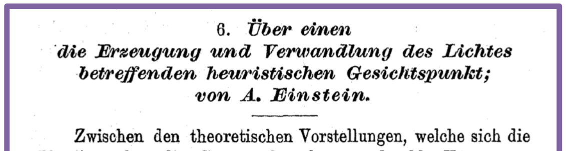
then following a collision with an electron in the metal plate, the electron would acquire energy

$$E_{\text{electron}} = h\nu - \Phi$$

where Φ (the "work function" of the metal) characterized how tightly electrons were bound to their atoms in the plate.

The threshold frequency was then given by $\nu_0 = \Phi/h$: only when *each* incoming light quantum had sufficient energy would electrons overcome the work function and be ejected.

Photoelectric Effect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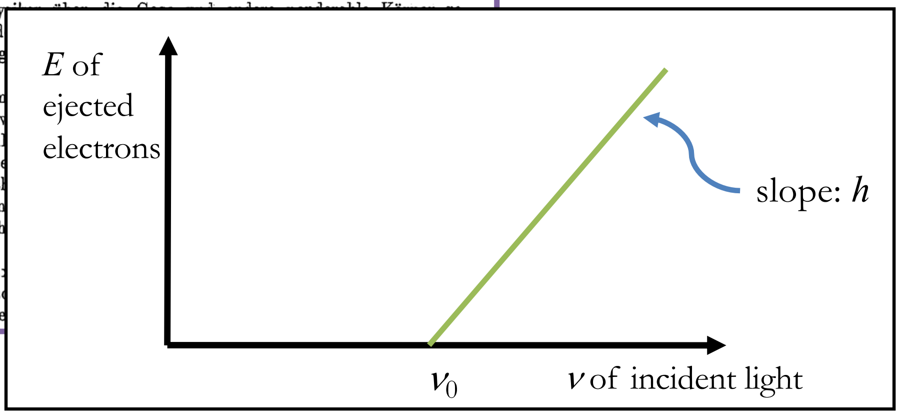
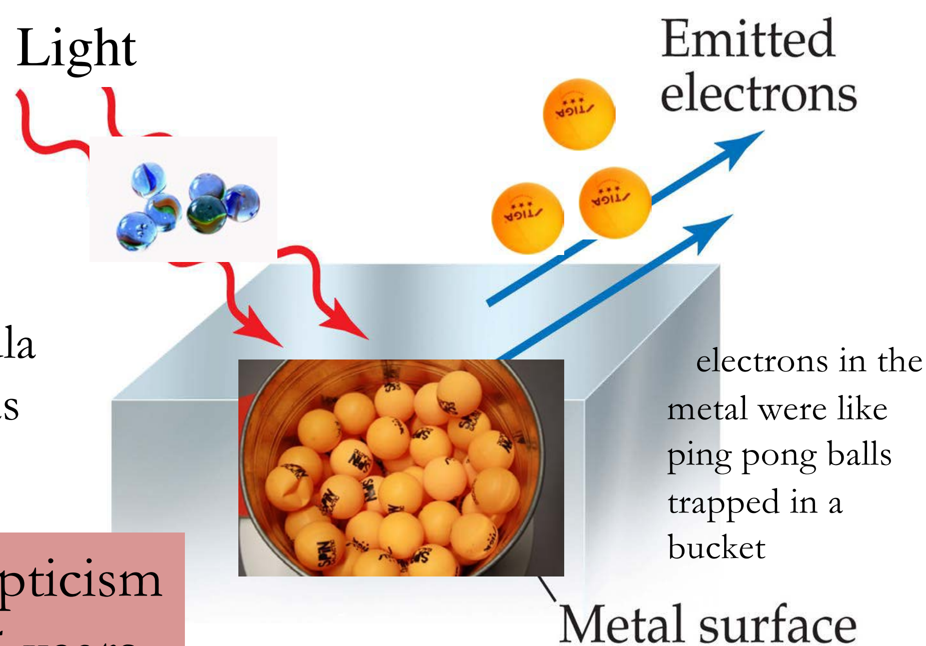


Einstein suggested: the light shining on the metal plate was *not* like an extended, continuous wave washing up on shore, but like a shower of marbles, each of which could collide with electrons in the metal.



Einstein also re-derived Planck's blackbody formula for $u(\nu, T)$, assuming the radiation consisted of a gas of individual particles with energies $E = h\nu$.

So: everyone was convinced, right? Enormous skepticism about the light-quantum hypothesis for ~15 years.

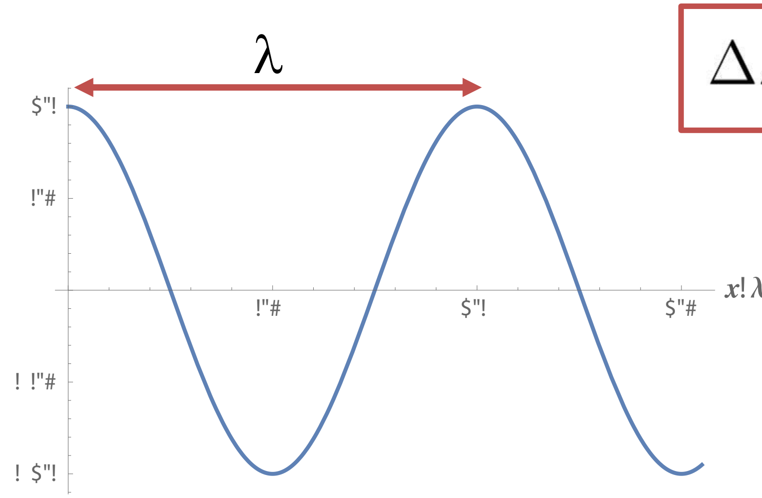
Questions?

Compton Scattering

Arthur H. Compton with his apparatus, early 1920s

More physicists began to take Einstein's light-quantum hypothesis seriously after experiments by *Arthur Compton* at the University of Chicago in 1922.

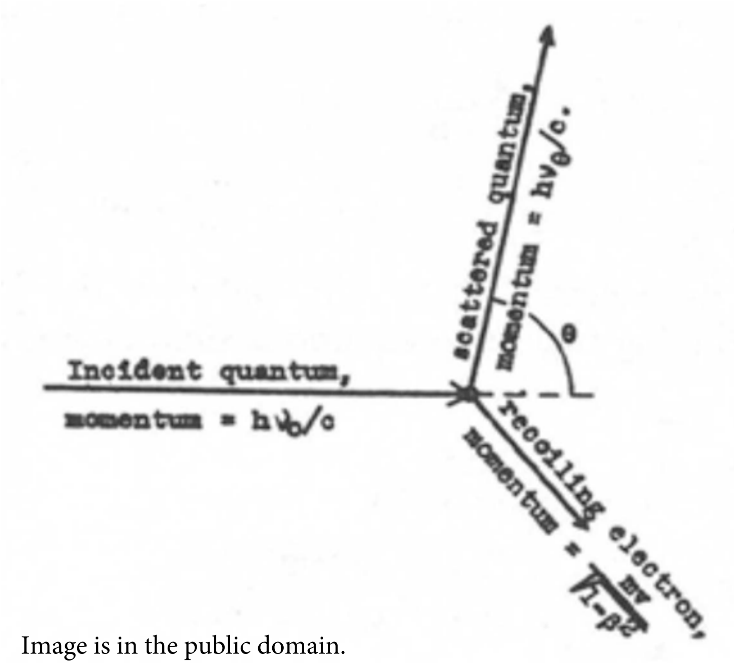
Compton scattered high-energy X rays off of electrons in graphite and measured the *change in wavelength* of the X rays after scattering.



$$\boxed{\Delta\lambda = \lambda' - \lambda \propto (1 - \cos\theta)}$$

Compton could only make sense of his results by thinking in terms of two-body scattering among *particles*: light-quantum and electron.

Compton Scattering



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Before collision

$$p_{\text{light}} = \frac{E}{c} \qquad \text{(Maxwell)}$$

$$E_{\text{photon}} = h\nu = \frac{hc}{\lambda} \qquad \text{(Einstein)}$$

$$p_{\text{photon}} = \frac{h\nu}{c} = \frac{h}{\lambda}$$

$$p_{\text{electron}} = 0 \qquad \text{(at rest)}$$

$$E_{\text{electron}} = mc^2 \qquad \text{(Einstein)}$$

After collision

$$p'_{\text{photon}} = \frac{h}{\lambda'}$$

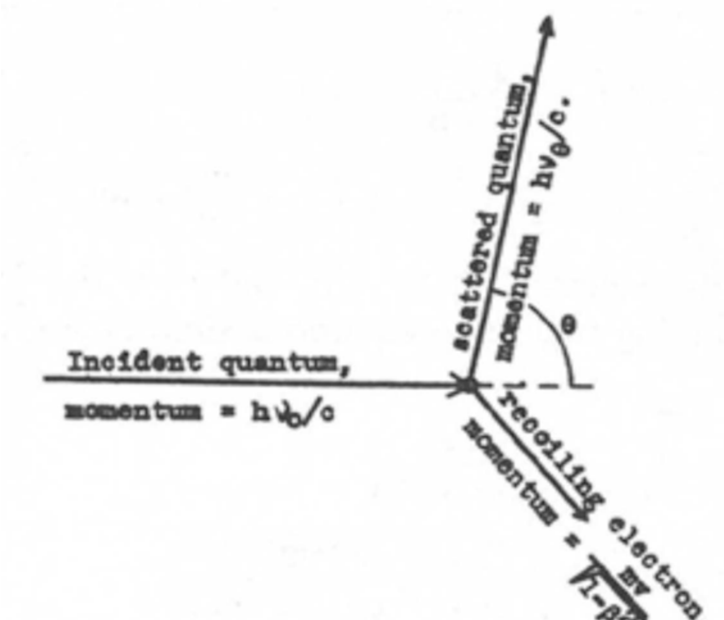
$$E'_{\text{photon}} = \frac{hc}{\lambda'}$$

$$p'_{\text{electron}} = \gamma m v$$

$$E'_{\text{electron}} = \gamma m c^2$$

$$\left(\gamma \equiv \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\right)$$

Compton Scattering



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$$p_{\text{electron}} = 0 \quad \text{(at rest)}$$

$$E_{\text{electron}} = mc^2 \quad \text{(Einstein)}$$

After collision

$$p'_{\text{photon}} = \frac{h}{\lambda'}$$

$$E'_{\text{photon}} = \frac{hc}{\lambda'}$$

$$p'_{\text{electron}} = \gamma m v$$

$$E'_{\text{electron}} = \gamma m c^2$$

$$\left(\gamma \equiv \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}\right)$$

Conserve energy:

$$E_{\text{photon}} + E_{\text{electron}} = E'_{\text{photon}} + E'_{\text{electron}}$$

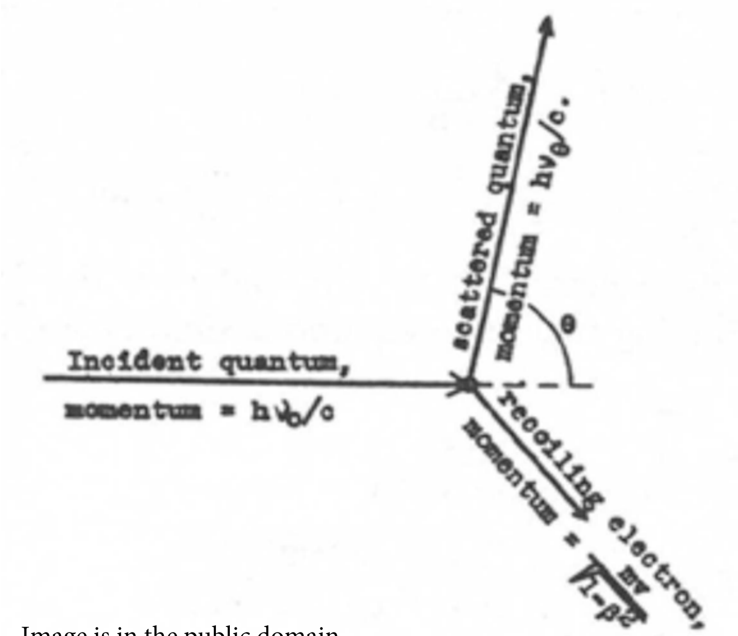
$$\longrightarrow \frac{hc}{\lambda} + mc^2 = \frac{hc}{\lambda'} + \gamma m c^2$$

Conserve momentum:

$$p_x: \quad \frac{h}{\lambda} + 0 = \frac{h}{\lambda'}\cos\theta + \gamma m v \cos\varphi$$

$$p_y: \quad 0 + 0 = \frac{h}{\lambda'}\sin\theta - \gamma m v \sin\varphi$$

Compton Scattering



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Conserve momentum:

$$p_x : \qquad \frac{h}{\lambda} + 0 = \frac{h}{\lambda'}\cos\theta + \gamma mv\cos\varphi$$
$$p_y : \qquad 0 + 0 = \frac{h}{\lambda'}\sin\theta - \gamma mv\sin\varphi$$

By treating the problem just like (ordinary) two-body scattering among particles, Compton now had three equations and three unknowns: λ', θ, φ.

$$\boxed{\Delta\lambda = \lambda' - \lambda = \left(\frac{h}{mc}\right)(1 - \cos\theta)}$$

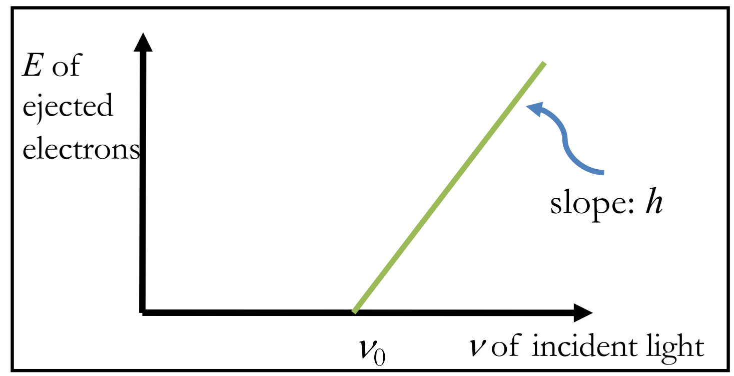
Compton treated light like *particles*, yet measured changes in *wavelength*: a *wave-particle duality!*

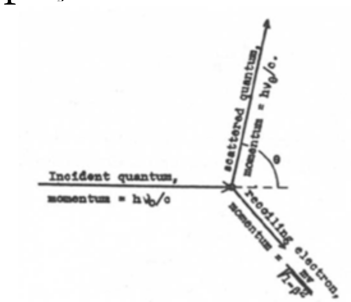
Rethinking Light: Summary

Physikalisch-Technische Reichsanstalt (PTR), Berlin, ca. 1900

A new priority upon industrialization led to investment in institutions like the PTR in the 1880s. Researchers studied *blackbody radiation* both to aid with industrial standardization and for clues about the universal behavior of light and matter. *Max Planck* found a way to characterize the energy of the emitted radiation by *avoiding* the usual calculation and inserting a new fundamental constant ***h***.

Albert Einstein took Planck's work more seriously than even Planck did, and offered a "heuristic" suggestion that light was *quantized*. Then he could account for the photoelectric effect. Most physicists remained deeply skeptical.





Arthur Compton studied the scattering of X rays off of electrons. He could only make sense of the *change in wavelength* by invoking Einstein's light-quantum hypothesis, which suggested a *wave-particle duality*.