Quantum optics

Photoelectric effect: [discovered late 19th century]

electrons are ejected from metallic surfaces when exposed to short wavelength visible or UV light

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Key features:

1) kinetic energy of the ejected electrons increases with the frequency of the light

2) no electrons ejected unless frequency exceeds a certain critical frequency f_0 depending on the type of metal

3) number of ejected electrons proportional to the intensity of light

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Features 1 + 2 were puzzling because energy imparted by a classical electromagnetic wave is given by its intensity $I = \frac{1}{2}\epsilon_0 c |A|^2$ which depends on its <u>amplitude</u> not its <u>frequency</u>

In 1900, Max Planck proposed that the energy of an electromagnetic wave is emitted + absorbed in discrete chunks, or quanta, called photons

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The energy of a photon is proportional to its frequency

$$\boxed{E = hf}$$

Constant of proportionality h = Planck's constant

$h = 6.625 \times 10^{-34}$ J·s or 4.14×10^{-15} eV·s

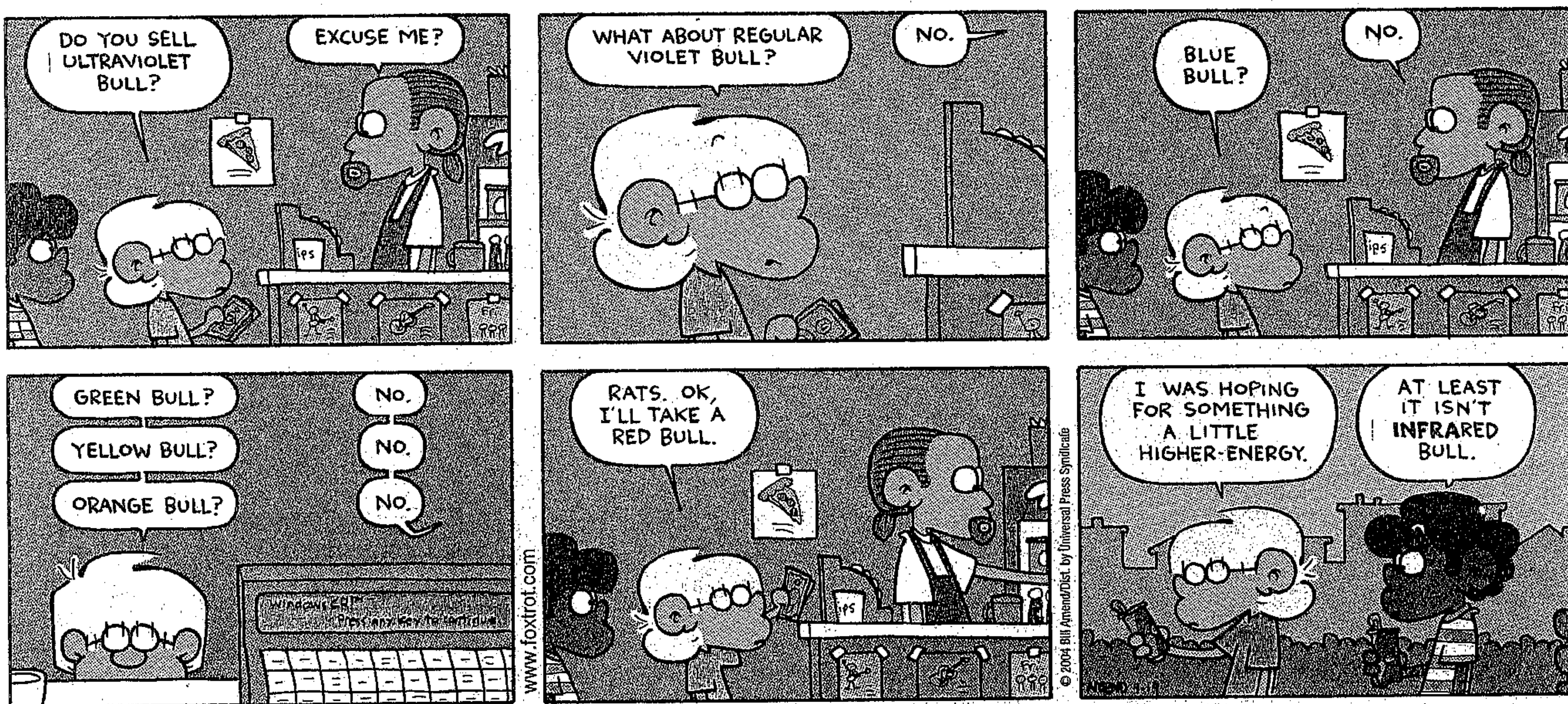
Since $f = \frac{c}{\lambda}$ $\Rightarrow$ $E = \frac{hc}{\lambda} = \frac{1240 \text{ nm}\cdot\text{eV}}{\lambda}$

red photons $\lambda \sim 700$ nm $\Rightarrow$ $E \sim 1.8$ eV

green photons $\lambda \sim 550$ nm $\Rightarrow$ $E \sim 2.25$ eV

violet photons $\lambda \sim 400$ nm $\Rightarrow$ $E \sim 3$ eV

[The main purpose of a physics education is to understand xkcd and Foxtrot cartoons.]



www.foxtrot.com

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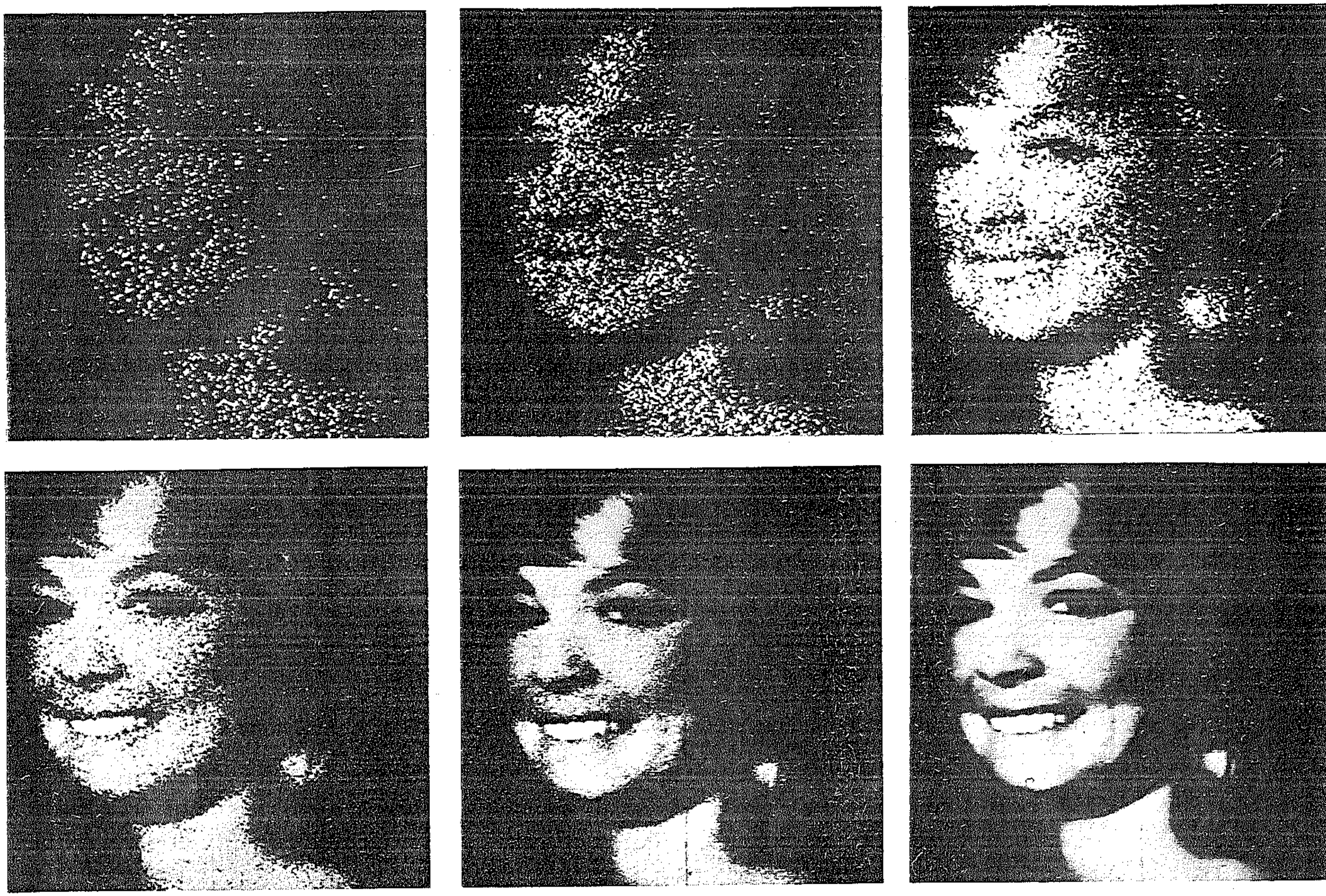

Fig. 1.9 These photos, which were made using electronic amplification techniques, are a compelling illustration of the granularity displayed by light in its interaction with matter. Under exceedingly faint illumination the pattern (each spot corresponding to one photon) seems almost random, but as the light level increases the quantal character of the process gradually becomes obscured. (See *Advances in Biological and Medical Physics* V, 1957, 211–242.) Courtesy Radio Corporation of America.

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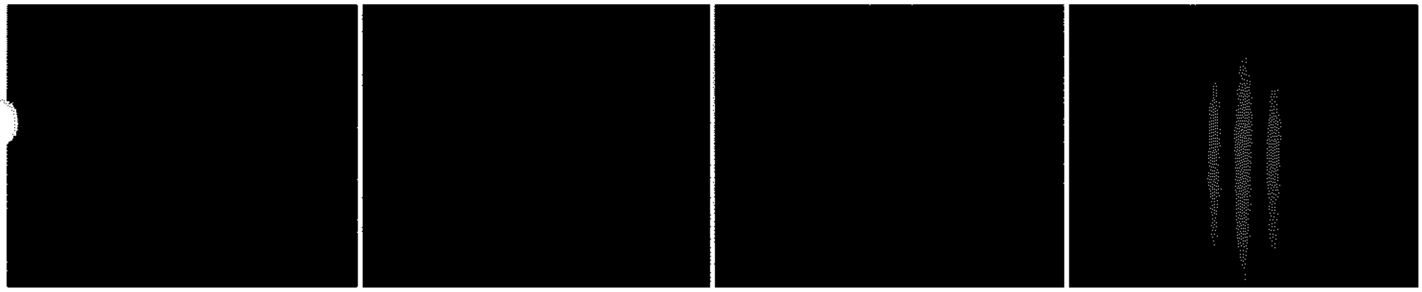
[show off of image of person]

[Evidence of "granularity" of light can be seen by reducing the intensity of light shining on a subject. As intensity goes down, image becomes dimmer]

$$\text{Intensity} \sim \left(\frac{\#\,\text{photons}}{s \cdot m^2}\right) \cdot (\text{energy per photon})$$

[Eventually only a small # of photons strike the camera. Can see individual photons]



w-p-doubleslit-light.jpg in public_html/1140scans
wave-particle.jpg

[Light is behaving like a particle.

But let's not get carried away.

It still behaves like a wave, as seen by interference in a double slit interference.]

[show "double slit photons" on 1140.html]

Wave-particle duality

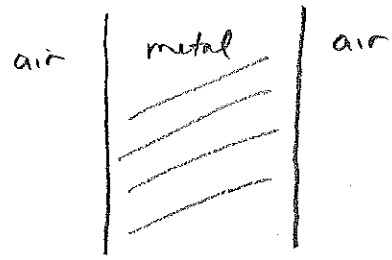
Light behaves as a particle when emitted + absorbed

but as a wave when travelling from source to observer.

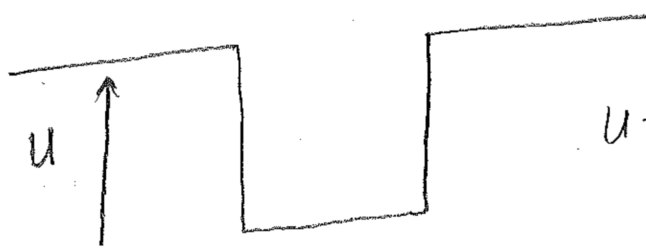
Photons interfere w/ themselves
+ ∴ do not travel along well-defined paths

[later we'll see electrons behave the same way.]

[Back to photoelectric effect]



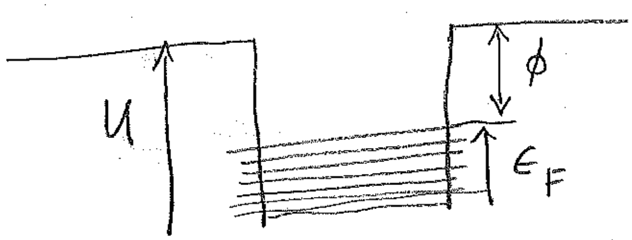
Conduction electrons confined to interior of metal
[though free to move within it, causing electrical conductivity]



U = potential energy of conduction electrons

Electrons in the metal have various allowed energy levels.
[later: particle in a box]

Pauli exclusion principle: different electrons occupy diff. levels



Highest occupied energy level called Fermi energy E_F.

Region outside metal is forbidden ($E_F < U$).

Difference between U and E_F is called the work function ϕ.

	ϕ
Na	2.3 eV
Al	4.1 eV
Cu	4.7 eV
Pt	6.3 eV

If provided with energy $\geq \phi$,
a conduction electron can escape the metal.

A photon with this energy has frequency f_0
where $E_{photon} = hf_0 = \phi$

$$f_0 = \frac{\phi}{h}$$

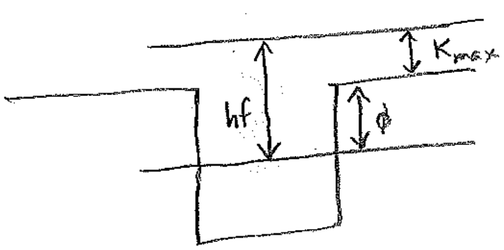
$$\lambda_0 = \frac{c}{f_0} = \frac{hc}{\phi} = \frac{(1240\,\text{nm}\cdot\text{eV})}{\phi}$$

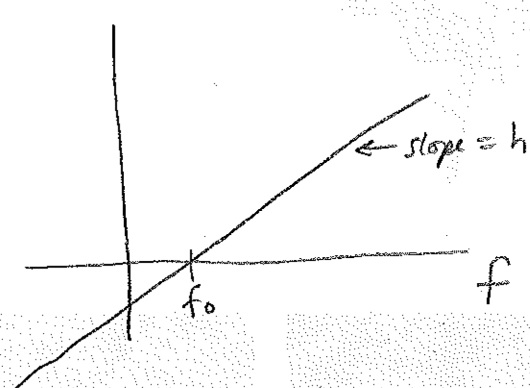
Example: Na: $\phi = 2.3\,\text{eV} \Rightarrow \lambda_0 = 540\,\text{nm}$ (green)

[Q: will violet light work too?]

If $f > f_0$, the ejected electron will have kinetic energy

$$K_{max} = hf - \phi = h(f - f_0)$$





[use slope to measure h]

All features explained!

1) K_{max} ↑ as f ↑
2) no emission unless $f > f_0$
3) # electrons ejected ~ # photons absorbed ~ intensity of light

[physics jeopardy]

In 1921, Albert Einstein was awarded the Nobel prize for the development of the theory of relativity.

T or F?