Modern Physics

Lecture notes by
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The crisis of “classical” physics

What is Modern Physics?

Modern Physics is usually regarded as the enormous revolution in our view of the physical universe that began just prior to 1900.

At that time, most physicists believed that everything in physics was completely understood. Normal intuition and all experiments fit into the context of two basic theories:

1. Newtonian Mechanics for massive bodies;
2. Maxwell’s Theory for light (electromagnetic radiation).

Consistency of the two required that there be a propagating medium (and, therefore, a preferred reference frame) for light.

However, even a little thought made it clear that there was trouble on the horizon. And then came many new experimental results that made it clear that the then-existing theoretical framework was inadequate to describe nature.

Changes imposed by experiments

In a relatively short period of time, physicists were compelled to adopt:

1. the theory of special relativity based on the idea that there was no propagating medium for light (so that light traveled with the same speed regardless of the “frame” from which the light was viewed);
2. the theory of quantum mechanics, according to which the precise position and precise momentum of a particle cannot both be determined simultaneously. In fact, one must think of particles not (only) as particles, but as waves, much like light.
3. At the same time, experiments made it clear that light comes in little quantum particle-like packets called photons (so waves behave like particles).
4. In short, both particles and light have both a particle-like and wave-like nature.

Our vision of the phenomena happening at microscopic scales and/or at speeds comparable with the speed of light changed in a relatively short elapse of time.

Microscopic world

In these lectures we shall focus our attention on the initial developments leading to the new paradigm for the microscopic world: quantum mechanics.

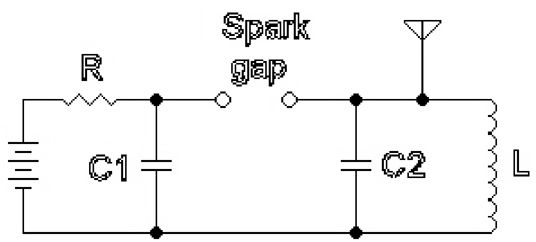
In fact, physical phenomena on a microscopic scale (dimensions, energy...) required new concepts for the interpretation of the observables processes depending on interactions at those scales.

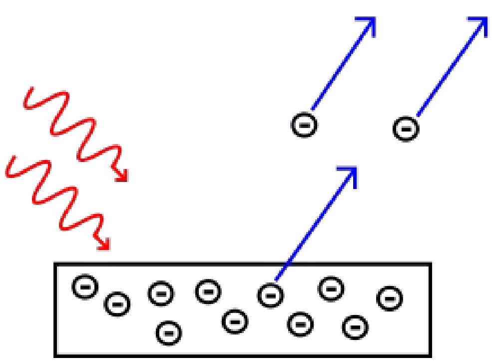
1. In this microscopic world physical quantities (like mass, energy, momentum) exist only as multiples of minimal quantities, named “quanta”.
2. The first example of a pure quanto-mechanical entity is the photon, introduced by Einstein in 1905 to explain the “photo-electric effect”, which is the quantum of electromagnetic radiation.
3. The photon energy is related to the frequency of the corresponding electromagnetic wave but a simple relationship: $E=h\nu$
4. The constant h is a very small quantity: $h = 6.63 \cdot 10^{-34}$ J·s = $4.14 \cdot 10^{-15}$ eV·s (1 eV = $1.6 \cdot 10^{-12}$ erg)

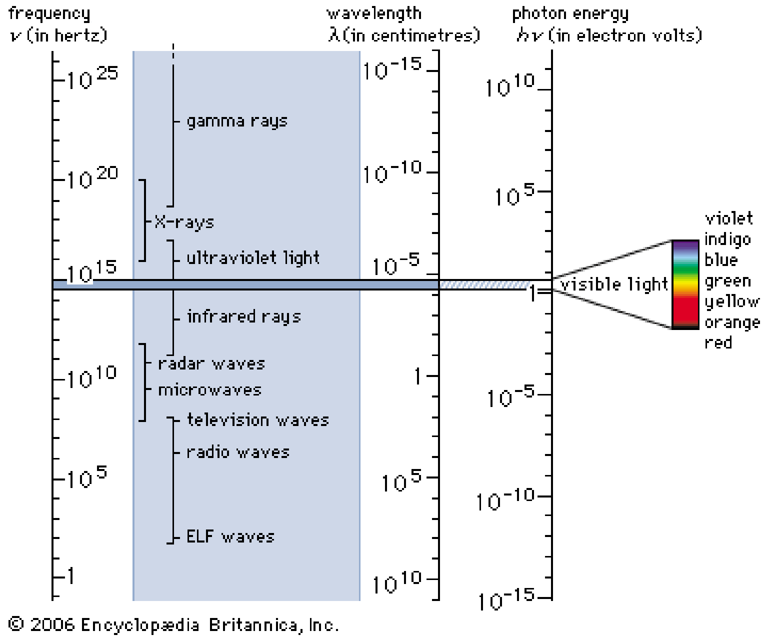
Photoelectric effect

- The photoelectric effect consists in the observation of an electric current induced by exposing a metal surface to electromagnetic waves.

- The effect was discovered experimentally Heinrich Rudolf Hertz in 1887 while investigating his “spark gap” transmitter/receiver of electromagnetic waves. The spark was considerably increased in presence of a source of ultraviolet radiation.

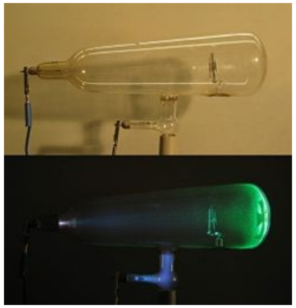


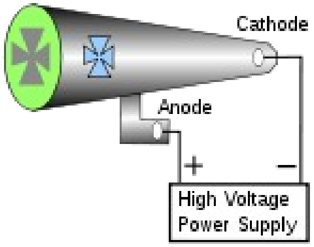




Photoelectric effect – hystorical perspective

- Before Hertz's observations, Becquerel measured a current flow in an electrode immersed in a solution (1839), and induced by light exposure . W. Smith found that Selenium was photoconductive (1874). These experiments showed already that was possible to induce electric currents by electromagnetic radiation.
- The Russian physicist A. Stoletov build an improved version of the Hertz's experimental setup and measured that the electric current was proportional to the intensity of the incoming electromagnetic field (1888-1891). W. Hallwacks, an Hertz collaborator, showed that the photocurrent was of negative charges.
- J. J. Thomson (Nobel for the discovery of the electron, 1906) investigated UV light in modified Geissler tubes, the Crookes tubes. In those tubes gases were evacuated to a modest residual pressure (10^{-6}-10^{-8} atm), to be compared to the 10^{-3} atm of the Geissler (Neon-like) tubes. Thomson discovered that the exposure to UV light of the cathode produced a current between cathode and anode whose intensity depends on colour and intensity of the incoming radiation.

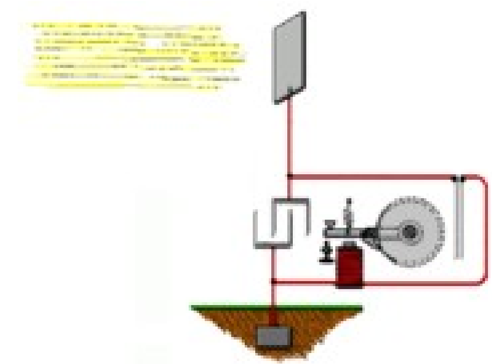




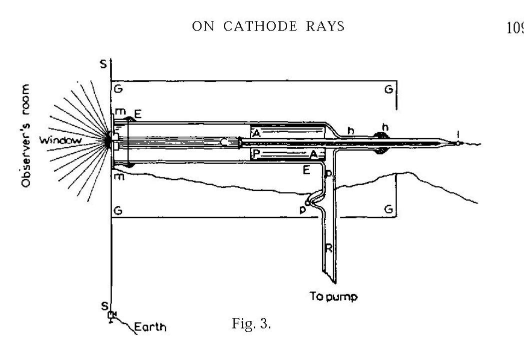
- Using this kind of tubes Thomson studied the so-called cathode-rays travelling toward the anode, showing that they were particles called *electrons.*

Photoelectric effect – hystorical perspective

- Nikola Tesla described and deposited a patent in 1901 for a device able to charge and discharge a conductor by “radiant energy”. Tesla used this effect to charge a capacitor by means of a conductive plate: in our language the electrons emitted by the surface of a metal plate shined by radiation induce a current for replacing the missing electrons and are able to charge a capacitor with the “solar energy”. It was a prototype of a “solar cell”.

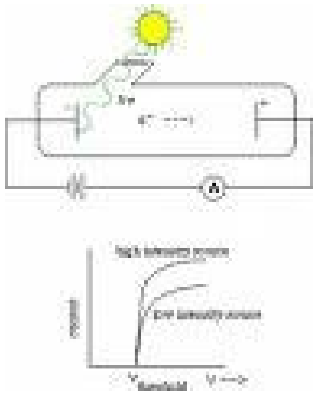


- In 1902 Philippe Von Lenard (Nobel, 1905) executed his systematic studies of the cathod rays by building metal windows able to sustain vacuum on one side and to show the effect of the rays on a fluorescent screen, ultimately showing that their absorption depended on the density and thickness of the window and that they were diffused by air, differently by electromagnetic radiation. They were charged particles confirming Thomson's results. Moreover he showed that the cathode rays produced by electromagnetic radiations on the cathode were of the same nature and had more energy depending on the frequency of the electromagnetic field.



Crucial Experiments on the photoelectric effect

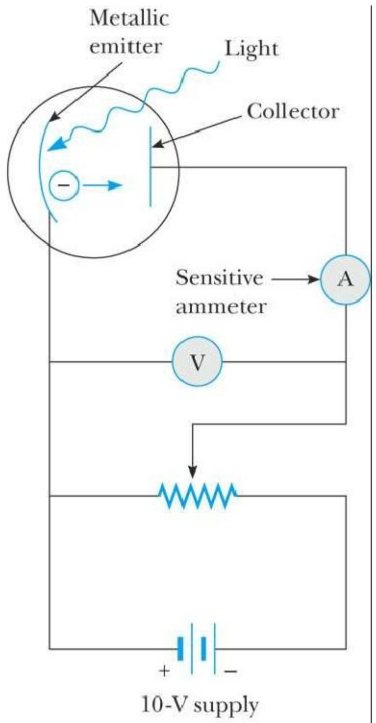
- P. Von Lenard set-up was able to measure potential differences in a way similar to what depicted here.



- The variable resistor is used to tune a negative potential to the collector of “electrons” C, with respect to the target T. This potential is able to slow down and eventually stop the electrons ejected by the target according to the law:

$$K_{max} = q\Delta V = -e\Delta V = eV_{stop} \qquad (1)$$

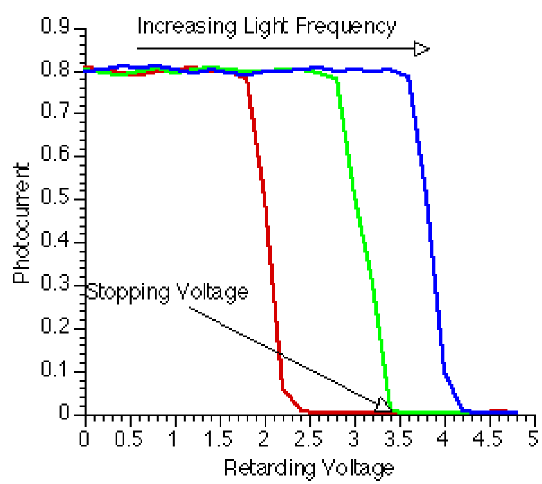
$$V_{stop} = -\Delta V > 0 \qquad (2)$$

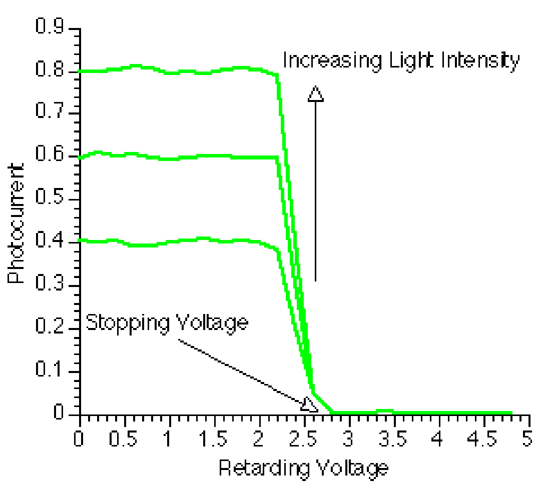


- In eq. (1) we wrote energy balance (Kinetic and Potential energy) for the ejected electrons and the in equation (1) and (2) the definition of the “stopping” potential. “e” is the elemental charge of the ejected particles later called “electrons”.
- The response of the device to the light is determined only by the time constant of the circuit (can be reduced to 10^{-8} sec).

Crucial Experiments on the photoelectric effect

- The measurements indicate that:
- 1) for a given frequency of the optical or UV light, the stopping potentials and therefore the maximal Kinetic energy of the electrons, is constant.
- 2) for increasing frequency the stopping potential increases linearly
- 3) there is a minimal frequency for which a current of electrons is generated and this is not dependent upon the intensity of light.

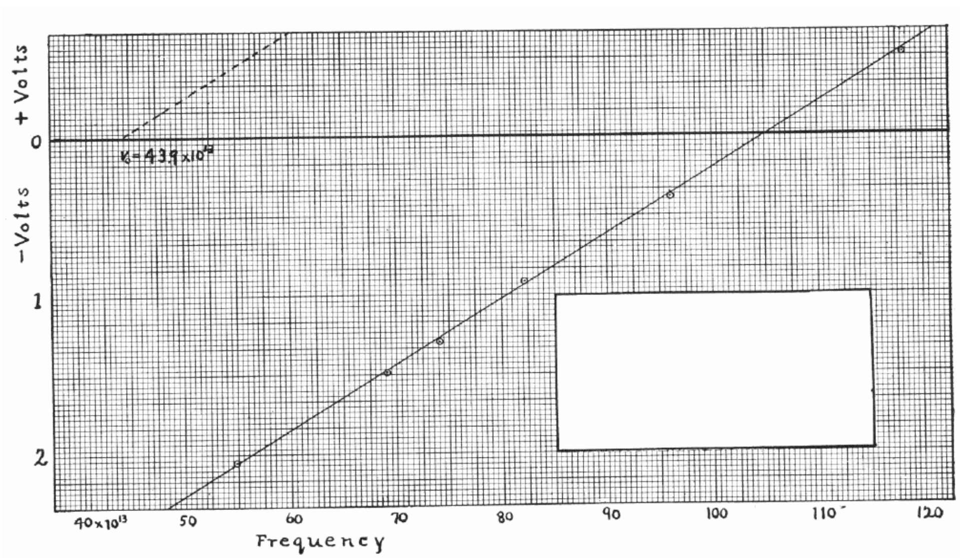


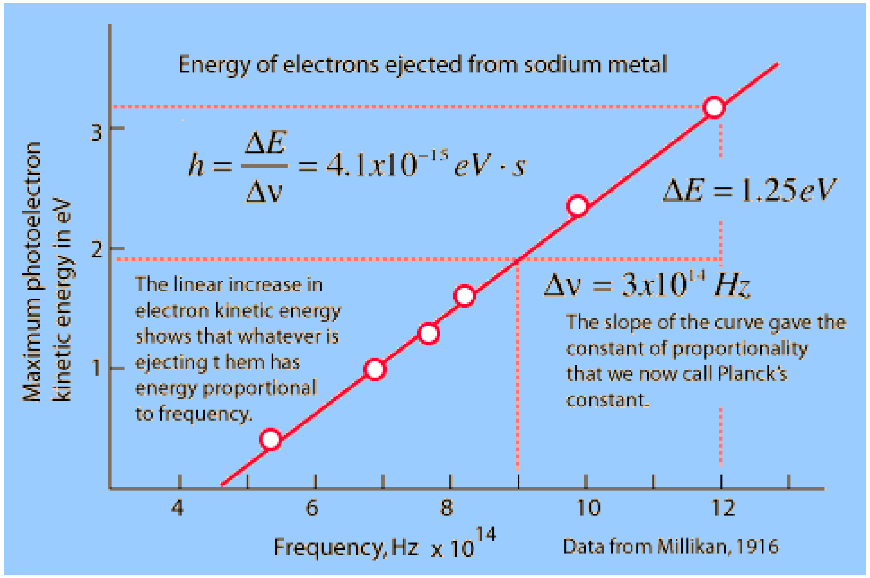


- Experimental conditions for this experiment were the realization of an high vacuum and the possibility to a have fresh-cut polished metal surfaces.

Results of the experiments

- Experiments aimed to understand the nature of the photoelectric effect were performed by various scientists in the 1900-1920 years confirming the basic phenomena for a wide range of clean metals and different radiation sources.
- Original Millikan's (Nobel 1923, electron charge) data (1916) on Na targets showed a clear linear dependence for the stopping voltage – frequency relationship.





Puzzling Results using classical physics

- The fact that *the energy of the ejected electrons is not dependent on the intensity of the incident light* can not be understood by classical physics: the intensity (and total Energy flux) is proportional to the square of the amplitude of an electromagnetic wave so an increased amplitude should transfer more energy to the electrons.
- The existence of *a minimal frequency for inducing the photoelectric effect* is also in contrast with classical physics. In fact, the energy carried by an electromagnetic wave and possibly transferred to the electrons is proportional to the intensity of the EM field, not to its frequency or wavelength.
- The inadequacy of classical concepts are evident also using the Thompson atomic model, in which the electrons (mass m=9 10^{-31} Kg, charge e=1.6 10^{-19} C) are elastically bonded to nuclei in a range of 1-3 10^{-10} m:

$$m\ddot{x} = -kx - \eta\dot{x} - eE$$

- A simple calculation shows that for e.m. Power flux of 100 W/m2 the energy transfer to the electron should be of the order of 10^{-27} J (~ 10^{-8} eV), much less of that of the thermal energy (KT~ 26 meV). So potentials near to 0 should be enough to stop the electrons, which is in contrast with the measured experimental stopping voltages.

Radiation-voltage relationship

- By a complete set of experiments on different materials and under different conditions it was possible to infer the following set of expressions

$$c = \lambda \nu \qquad (3)$$

$$b\nu = a + eV_{stop} \qquad (5)$$

$$eV_{stop} = b\nu - a \qquad (4)$$

$$h\nu = \Phi + eV_{stop} \qquad (6)$$

$$V_{stop} = \left(\frac{h}{e}\right)\nu - \frac{\Phi}{e} \qquad (7)$$

$$\frac{h}{e} = 4.1x10^{-15} V \cdot s \qquad (8)$$

$$h = (4.1x10^{-15} V \cdot s) \cdot (1.6x10^{-19} C) = 6.6 \cdot 10^{-34} J \cdot s \qquad (9)$$

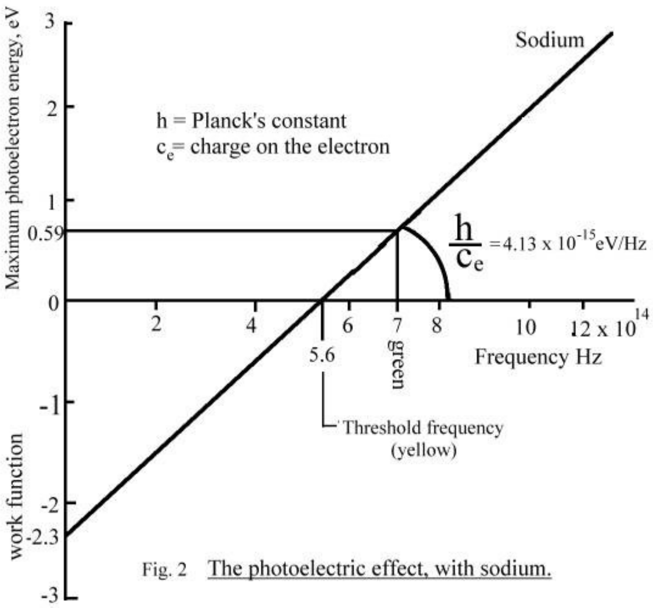


Fig. 2 The photoelectric effect, with sodium.

Einstein's theory of photoelectric effect

- The photoelectric phenomenon discovered and studied by Hertz, Von Lenard and co-workers could be easily explained provided that:

  1) the incident light is regarded as composed of quanta (photons) of Energy proportional to the frequency ν (in the original Einstein's paper):

$$E = \left(\frac{R}{N}\right)\beta\nu = h\nu \qquad (10)$$

$$\left(\frac{R}{N}\right) = K_b; \beta = \left(\frac{h}{K_b}\right) \qquad (11)$$

  2) the simplest process is the absorption of a light quantum and transfer of its energy to kinetic electron energy. The kinetic energy must overcome the energy potential barrier, called "work function" Φ which corresponds to the work done by the electron in leaving the surface of the solid target. The kinetic energy must then be:

$$E_{kin} = h\nu - \Phi \qquad (12)$$

Einstein's theory of photoelectric effect

- As also stated in his original paper (Annalen Der Physik, 17, 144 (1905)), for which he got the Nobel prize in 1921, the quantization of light provides explanation also of the fact that (rarefied) gases can be ionized only by radiation above a minimum frequency. The Lenard's measurements available at the time said that the greatest effective wavelength for ionizing air with e.m waves was $\lambda \sim 1.9\ 10^{-5}$ cm. On the other hand a limit for the ionization potential can be derived from the minimum ionization voltages that were found by Stark to be around 10 V. The kinetic energy associated with electrons excited by the e.m. Radiation should be therefore of the same order of magnitude. This is exactly what happens:

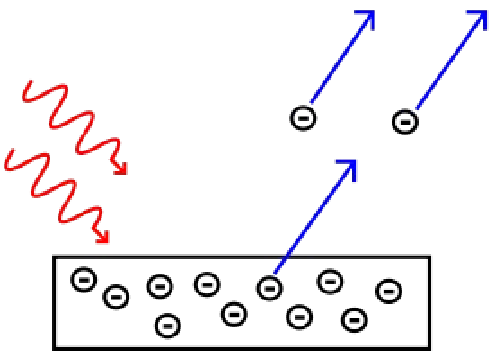
$$I_p + E_{kin} = h\nu = h\left(\frac{c}{\lambda}\right) =$$

$$= 4.14 \cdot 10^{-15} eV \cdot s \cdot \frac{3. \cdot 10^{8} m s^{-1}}{1.9 \cdot 10^{-7} m} \sim 6.6 eV \ (13)$$

- The cathod luminescence, as a consequence of electrons hitting the surface and observed for high potential energies 100-1000 eV was predicted to be composed by many light quanta. The relationship between absorption of photons in a gas and the amount of ionized molecules was predicted by Einstein as well.

Consequences

- Double-nature of the electromagnetic radiation: it behaves like a wave but it interacts with matter (electrons) as it would be composed by an ensemble of particles with well-defined energy. It is NOT possible to have radiation with energy content less than a specified quantum.
- Explanation of the photoelectric effect then requires the quantization of the electromagnetic field. Each particle of minimal energy is called “photon”.



Three-step model for photoemission

•The photoelectric effect in crystalline material is often decomposed into three steps:

•1) Inner photoelectric effect with excitation of bounded electrons.*

•2) Ballistic transport of half of the electrons to the surface. Some electrons are scattered elastically and inelastically.

•3) Electrons escape from the material at the surface.

•In the three-step model, an electron can take multiple paths through these three steps.**

.* The hole left behind can give rise to auger effect, which is visible even when the electron does not leave the material. In molecular solids phonons are excited in this step and may be visible as lines in the final electron energy. The inner photoeffect has to be dipole allowed. The transition rules for atoms translate via the tight-binding model onto the crystal. They are similar in geometry to plasma oscillations in that they have to be transversal.

**For surface states and molecules the three-step model does still make some sense as even most atoms have multiple electrons which can scatter the one electron leaving.