Quantum Mechanics: mysteries and solutions

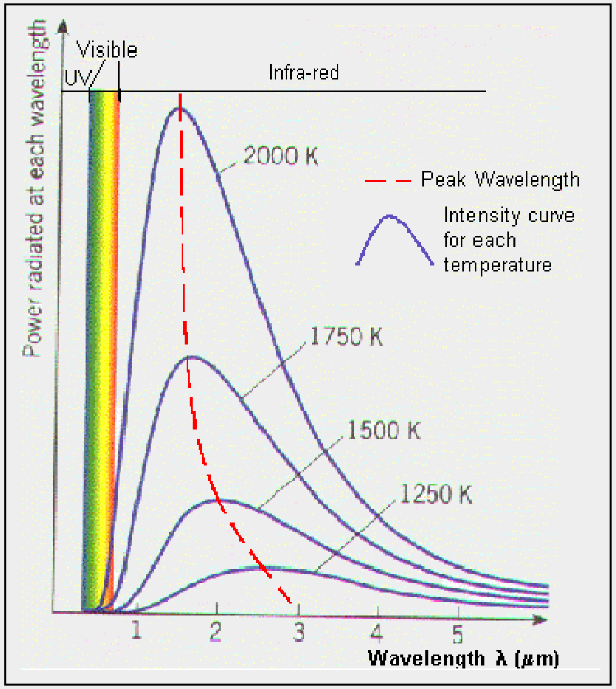
ANGELO BASSI

Department of Theoretical Physics, University of Trieste, Italy

and

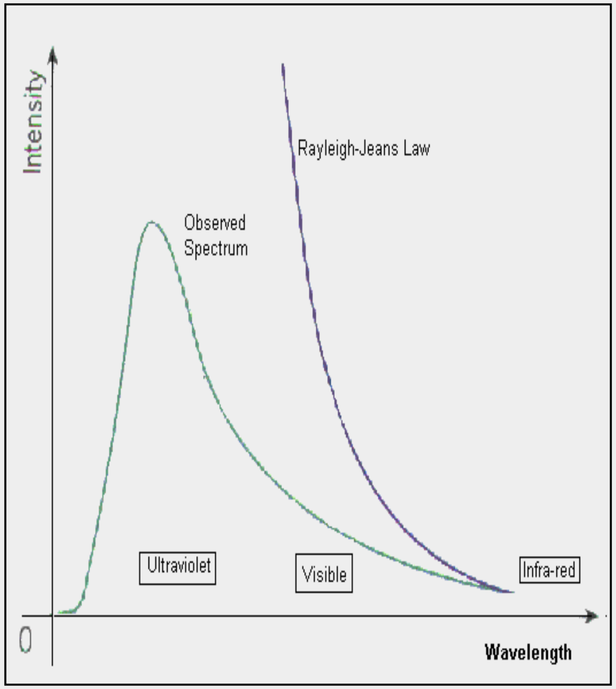
INFN - Trieste

Quantization of light: Planck’s hypothesis (1900)



All bodies emit radiation in the whole spectrum. Black bodies are special.

Classical electromagnetic theory does not reproduce the spectrum

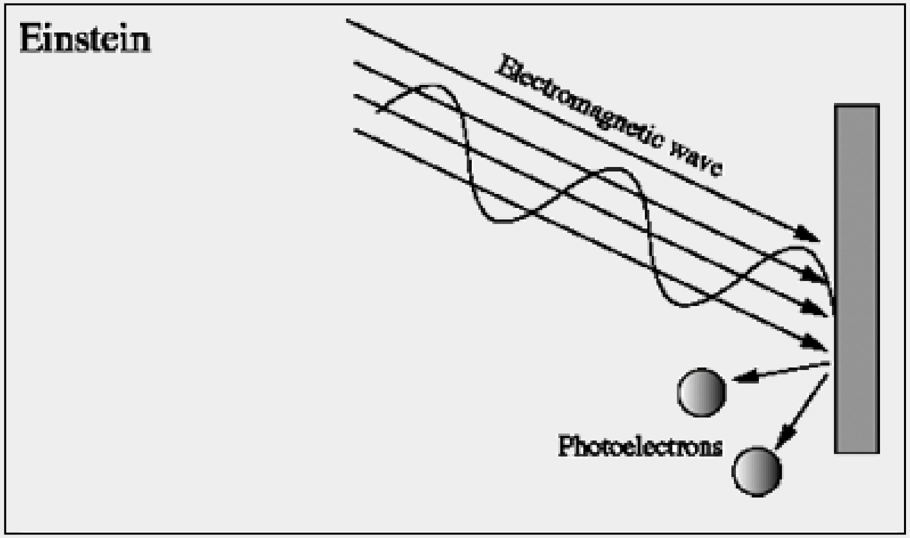


According to **Planck**, the exchanges of energy between light and matter are not continuous, as implied by classical electrodynamics, but **discrete.** They can be only multiples of the quantity

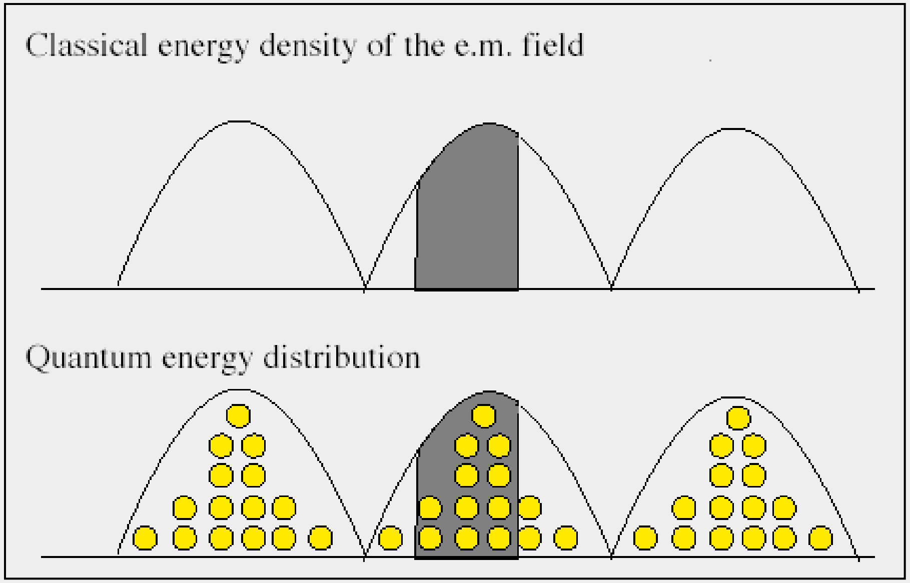
$$\mathbf{E = h\upsilon}$$

the quantum of light (radiation).

Quantization of light: photoelectric effect (1905)

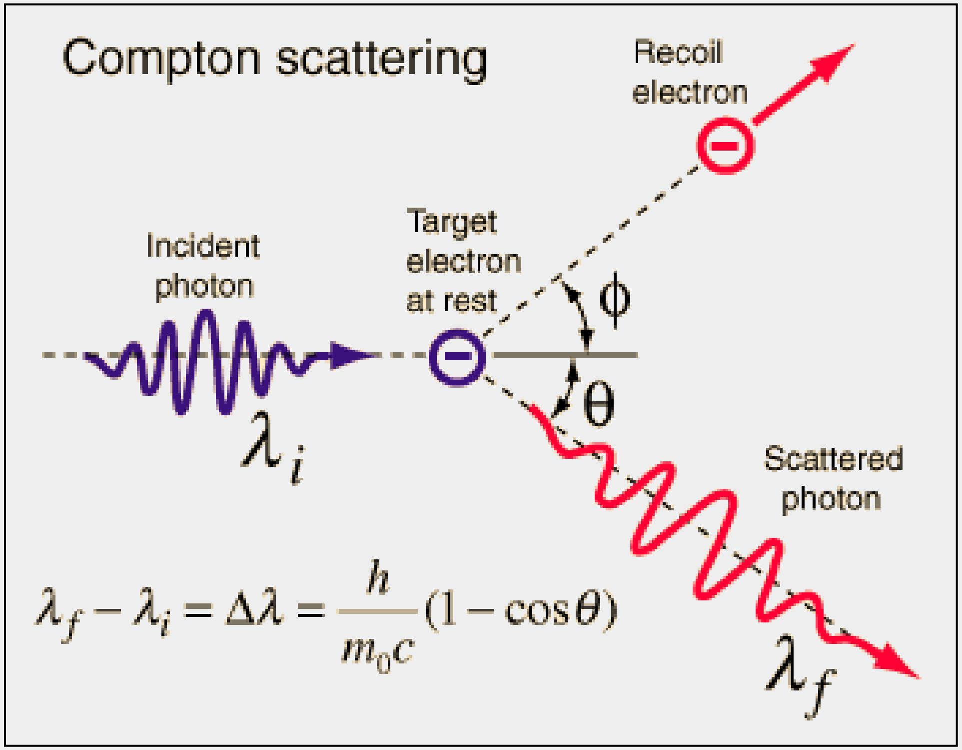


Classically, light is a **wave** propagating in space in a continuous manner



According to **Einstein**, light travels in space in small **quanta** of energy **E = hυ**

Quantization of light: Compton effect (1923)

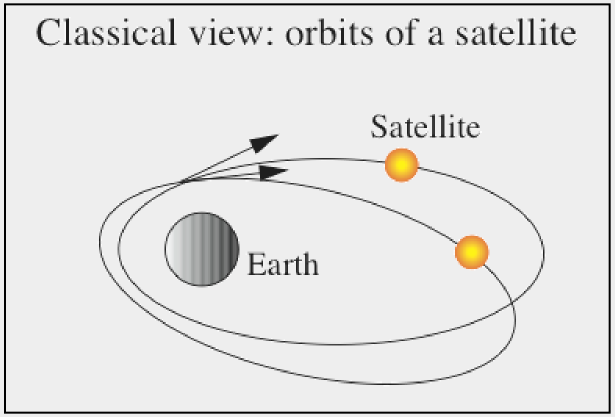


It is about the diffraction of X and gamma rays from gas, liquids and solids.

Once more, the effect could not be explained classically

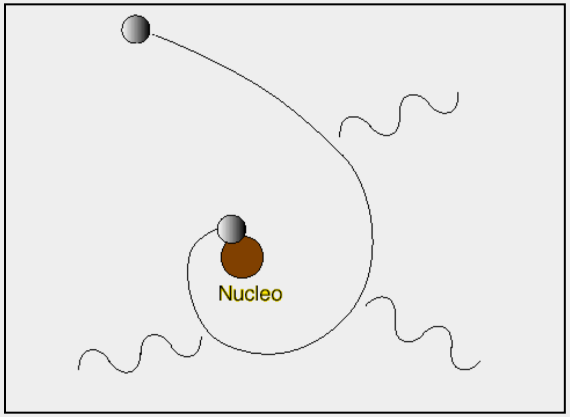
Solution: the ray behaves like a particle in all respects. Thus the interaction between the ray and an electron of the atom is like the (relativistic) interaction between two particles.

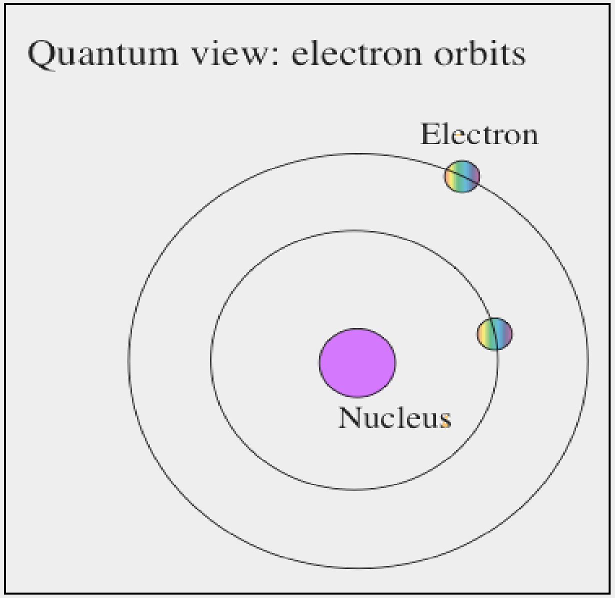
Quantization of matter: Bohr's atom (1911-13)



Classical atom:

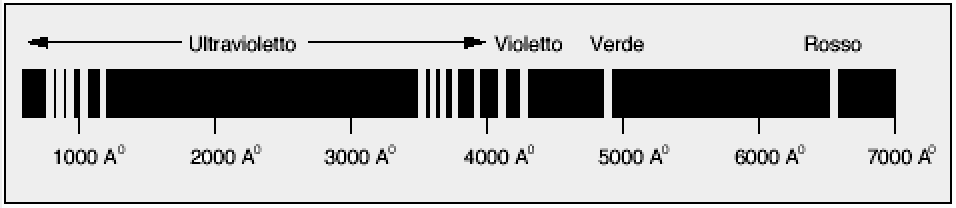
electrons should radiate and loose energy.
Instability of matter.





Bohr's atom

According to Bohr, only certain (discrete) energy level are permitted; on those levels, electrons do not radiate. **Quantum jumps** between different levels: this explains line spectra.



Quantization of matter: de Broglie's hypothesis (1924)

Observation: Light has a double nature, wavy and corpuscular.

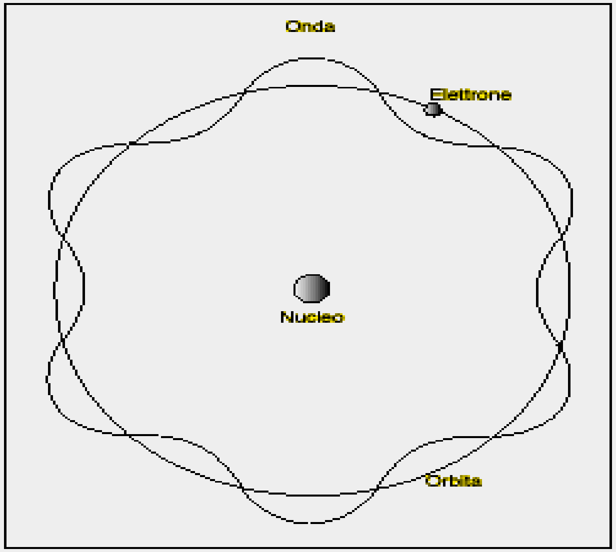
Assumption: Also matter has a double nature. A particle of mass **m**, traveling with speed **v**, has to be associated to a wave of wavelength:

$$\lambda = h/p = h/mv$$

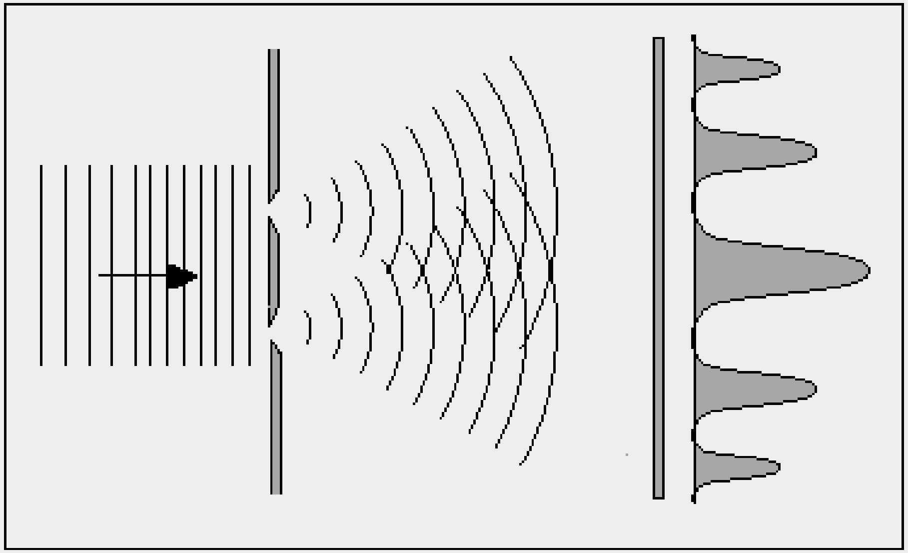
h is so small that at the macroscopic level the wave nature cannot been seen.

At the microscopic level, on the contrary, wave-effects become important.

De Broglie's assumption is fascinating because it explains Bohr's atom.



Wave-particle duality: experiment (1927)

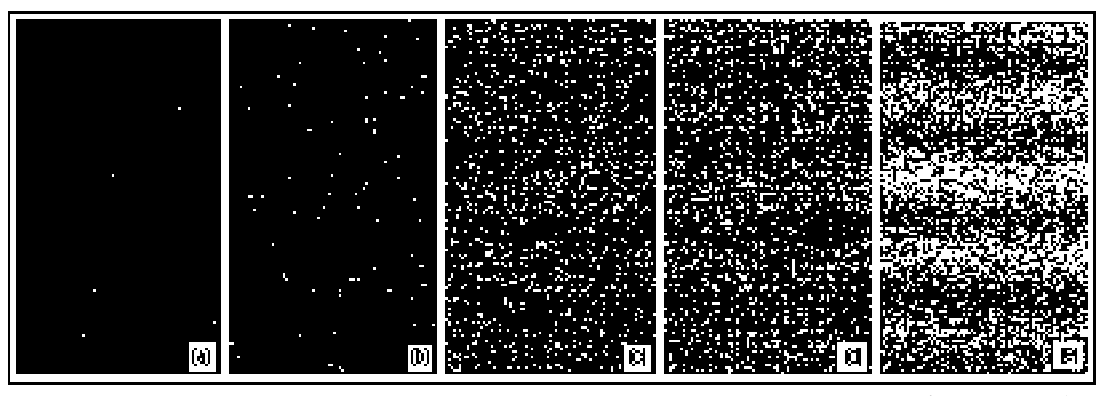


Two-slit experiment

Screen with two slits. Electrons are sent through the screen, behind which there is a photographic plate which registers their final position.

One sends **one particle at a time**.

Points are randomly distributed but they display an **interference pattern**.



C. Jonsson, 1961.

To summarize

Quantization.

At the microscopic level, physical processes are not continuous.

Wave-particle duality.

Radiation, besides its classical-wave nature, has a particle-like nature which shows up at the microscopic level; only in this way it seems possible to explain certain microscopic phenomena.

Matter, besides its classical-particle nature, has a wave-like nature which appears only at the microscopic level.

Schrödinger equation (1926)

Schrödinger first formulated an equation which describes **all microscopic quantum phenomena**. The heuristic models and partial descriptions of microscopic events finally find place into one theory (subsequently, the equation has been generalized to include also relativistic effects - Dirac equation, Klein-Gordon equation, …)

$$i\,(h/2\pi)\,(d/dt)\psi = H\,\psi$$

Each physical system is associated to a wave. The Schrödinger equation describes the evolution in space and time of such a wave.

Problem: the wave function **diffuses** in space, but when one measures where a particle is, the particle turns out always to have a **precise position.**

Then, what is that wave? What does it represent?

The interpretation of Quantum Mechanics

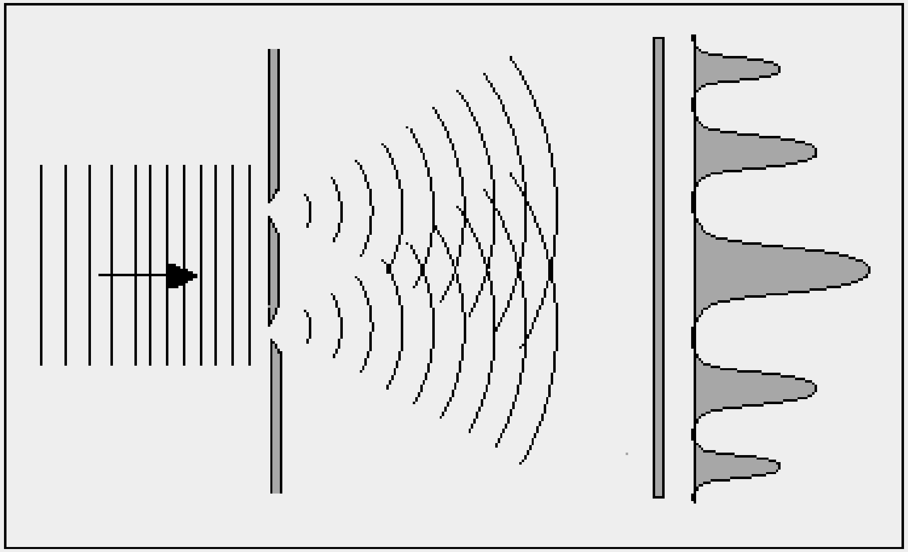
J.S. Bell

«At an early stage, [Schrödinger] had tried to replace 'particles' with wavepackets. But wavepackets diffuse. And the paper of 1952 ends, rather lamely, with the admission that Schrödinger does not see how, for the present, to account for particles tracks in track chambers … nor, more generally, for the definetness, the particularity, of the world of experience, as compared with the indefiniteness, the waviness, of the wavefunction».

(*"Are there quantum jumps*?", in: J.S. Bell, "*Speakable und unspeakable in quantum mechanics"*, Cambridge University Press, 1987, p. 201).

The two-slit experiment again

Which slit does each electron go through?



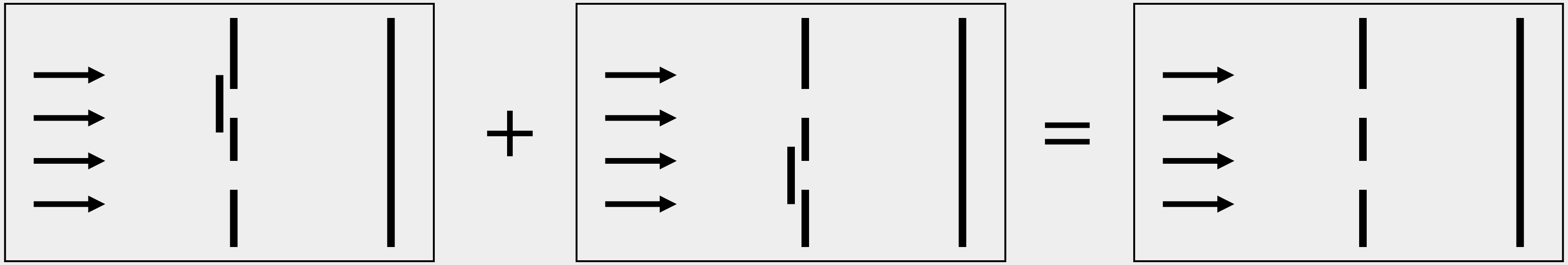
“Obvious” answer: each electron goes through **one of the two slits,** even though we don’t know which one. On the average, half of them go through the upper slit and the other half through the lower slit.

Implications

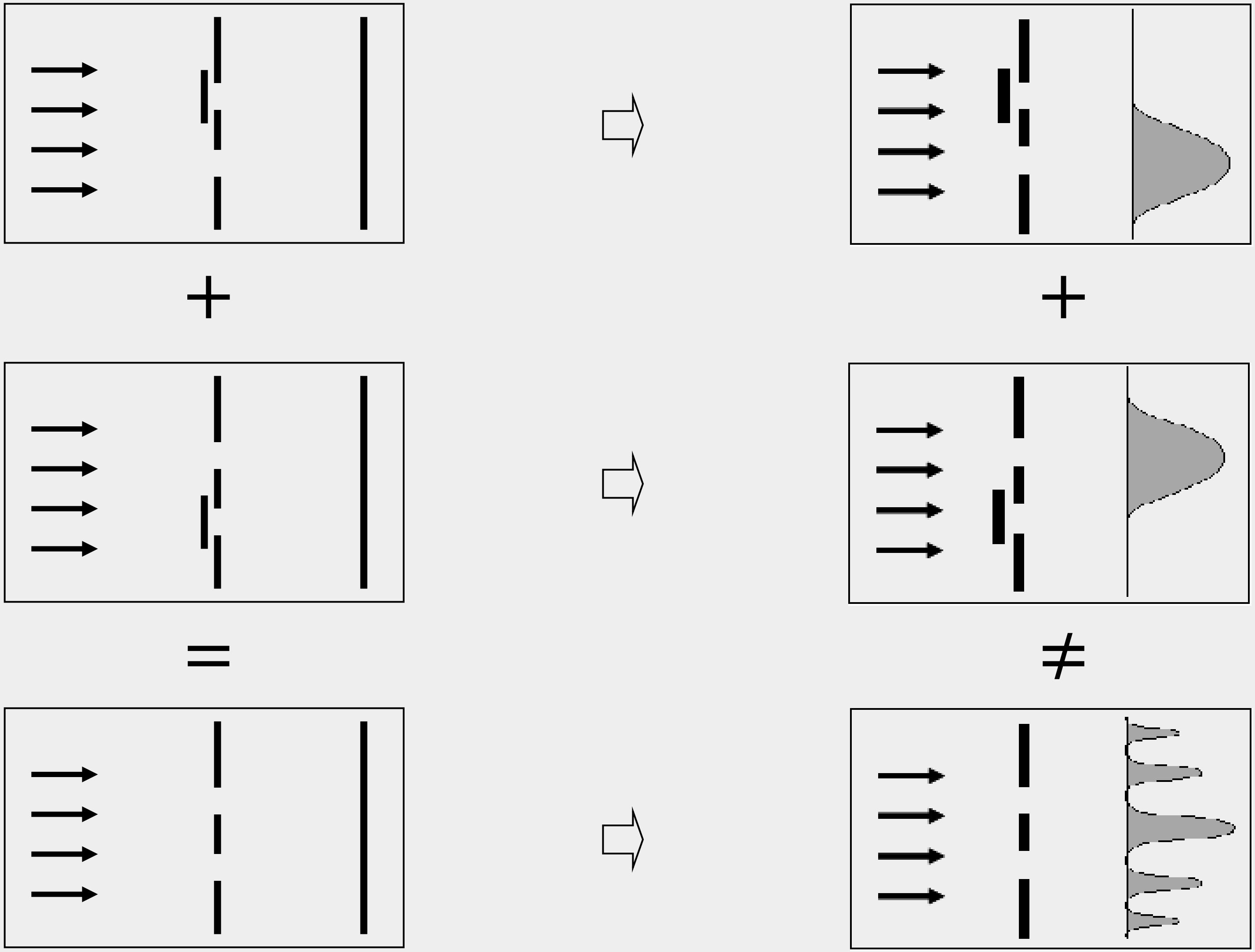
Then, if we perform the following experiment:

1. We close the upper slit, leave the lower one open, and run the experiment N times;
2. We open the upper slit, close the lower one, and run the experiment other N times,

we should get **the same result** as if both slits were open and we had run the experiment N times.



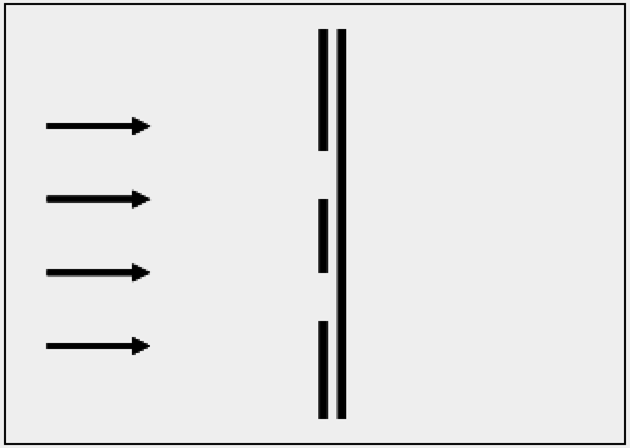
This answer is wrong



Alternative answer

An electron is not a particle. It is a **wave** which goes at the same time through **both** slits!

Also this answer is wrong



If one pushes the photographic plate towards the two slits, he finds the electron always either within the upper slit **or** within the lower slit, never in both places. If the electron were a wave, he would find half of it by the upper slit, and half by the lower slit.

What is the solution, then? (Born, 1926)

Copenhagen school: it is not legitimate to ask which slit each electron goes through. We can only ask where we can **find** an electron if we measure its position, and the answer is:

The probability of **finding** an electron around the position x is given by the square modulus of its wave function, computed at x.

This is the orthodox doctrine about Q.M.

N. Bohr

«There is no quantum world. There is only an abstract quantum mechanical description. It is wrong to think that the task of physics is to find out how Nature *is*. Physics concerns *what we can say* about Nature».

(in: M. Jammer, "*The philosophy of Quantum Mechanics*", p. 204)

The rules of Quantum Mechanics

Rule 1. To each physical system, one associates a wave function.

Rule 2. The wave evolves in time according to the Schrödinger equation:

$$i\,(h/2\pi)\,(d/dt)\psi = H\,\psi$$

Rule 3. The **probability of finding** the system at **x** at time t is:

$$P(t) = |\psi(t)|^2$$

Rule 4. After the measurement, the wave function collapses to the region where the particle has been found (**postulate of wave packet reduction**).

The atmosphere at those times

A. Pais:

«I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it».

(Reviews of Modern Physics LI, 863, 1979)

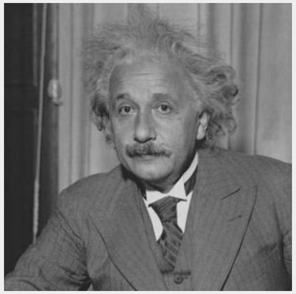
W. Pauli

«As O. Stern said recently, one should no more rack one's brain about the problem of whether something one cannot know anything about exists all the same, than about the ancient question of how many angels are able to sit on the point of a needle. But it seems to me that Einstein's question are ultimately always of this kind».

(from a 1954 letter to M. Born, in: "*The Born-Einsten Letters*" Walker, New York, p. 223)

Dissidents

A. Einstein



«What I dislike in this kind of argumentation is the basic positivistic attitude, which from my point of view in untenable».

(in: "*Albert Einstein: philosopher-scientist*", p. 668)

Realist School (Einstein, Schrödinger, Bell): A physical theory should be a mathematical model of physical phenomena, which is independent of any measurement. Since the quantum theory does not provide us with such a description, it is **incomplete**. Like statistical mechanics is built on Newtonian mechanics, in a similar way there must be a fundamental theory giving raise to quantum theory.

The “measurement problem”

Rule 1. To each physical system, one associates a wave function.

Rule 2. The wave evolves in time according to the Schrödinger equation.

Rule 3. The probability of **finding** the system at **x** at time t is:

Rule 4. After the **measurement,** the wave function collapses to the region where the particle has been found (postulate of w.p.r.).

Observation: There are **two different, opposite** evolution laws: the Schrödinger evolution which is linear and deterministic, and the w.r.p. which is non-linear and stochastic.

Problem: When does one law apply, and when does the other apply? W.r.p. applies only during measurements. But what is a measurement? Why is it different from all other physical interactions? What qualifies a system to be a measurement apparatus?