Il gatto di Schrödinger entrerà nelle nostre case?

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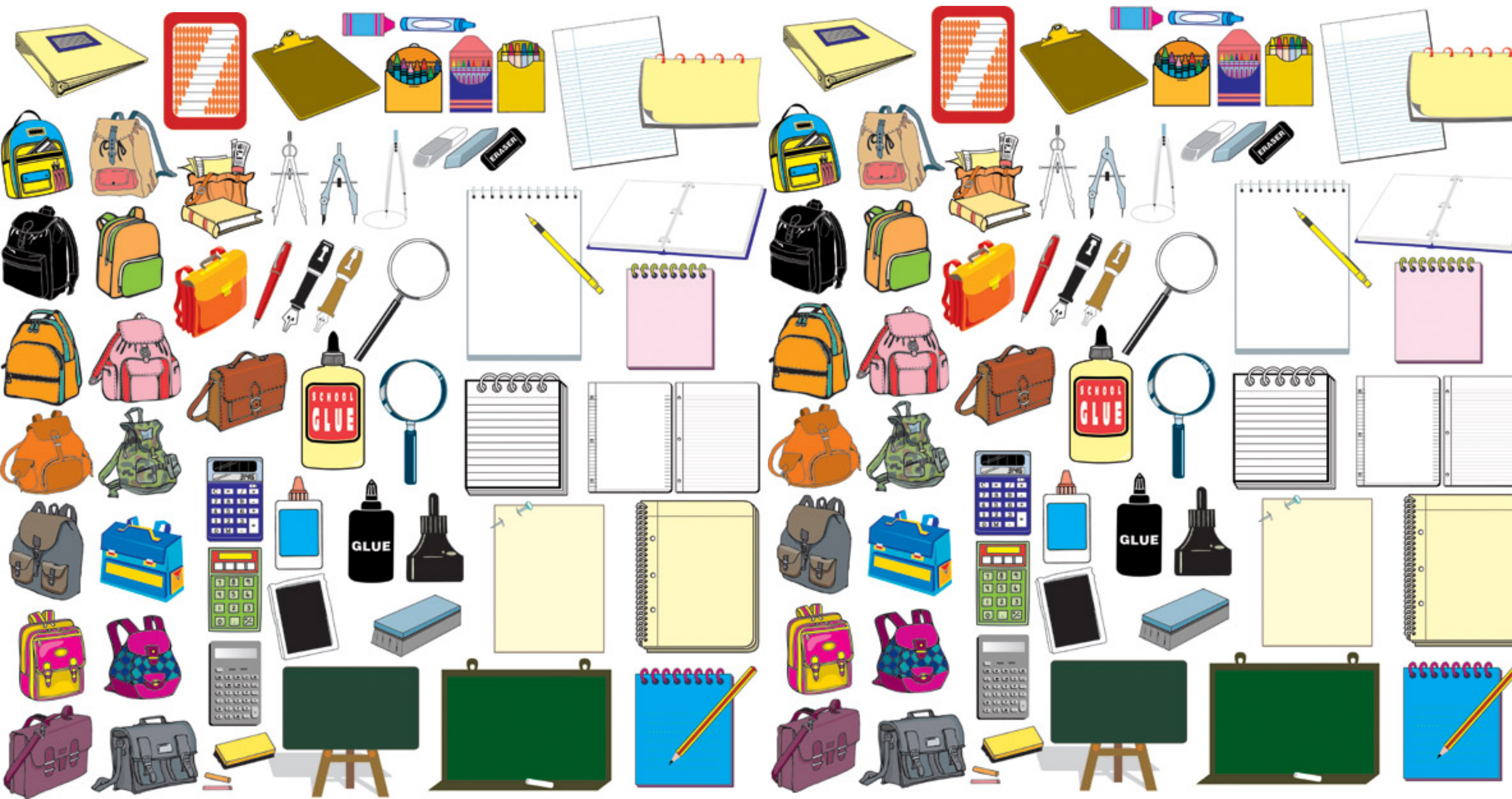
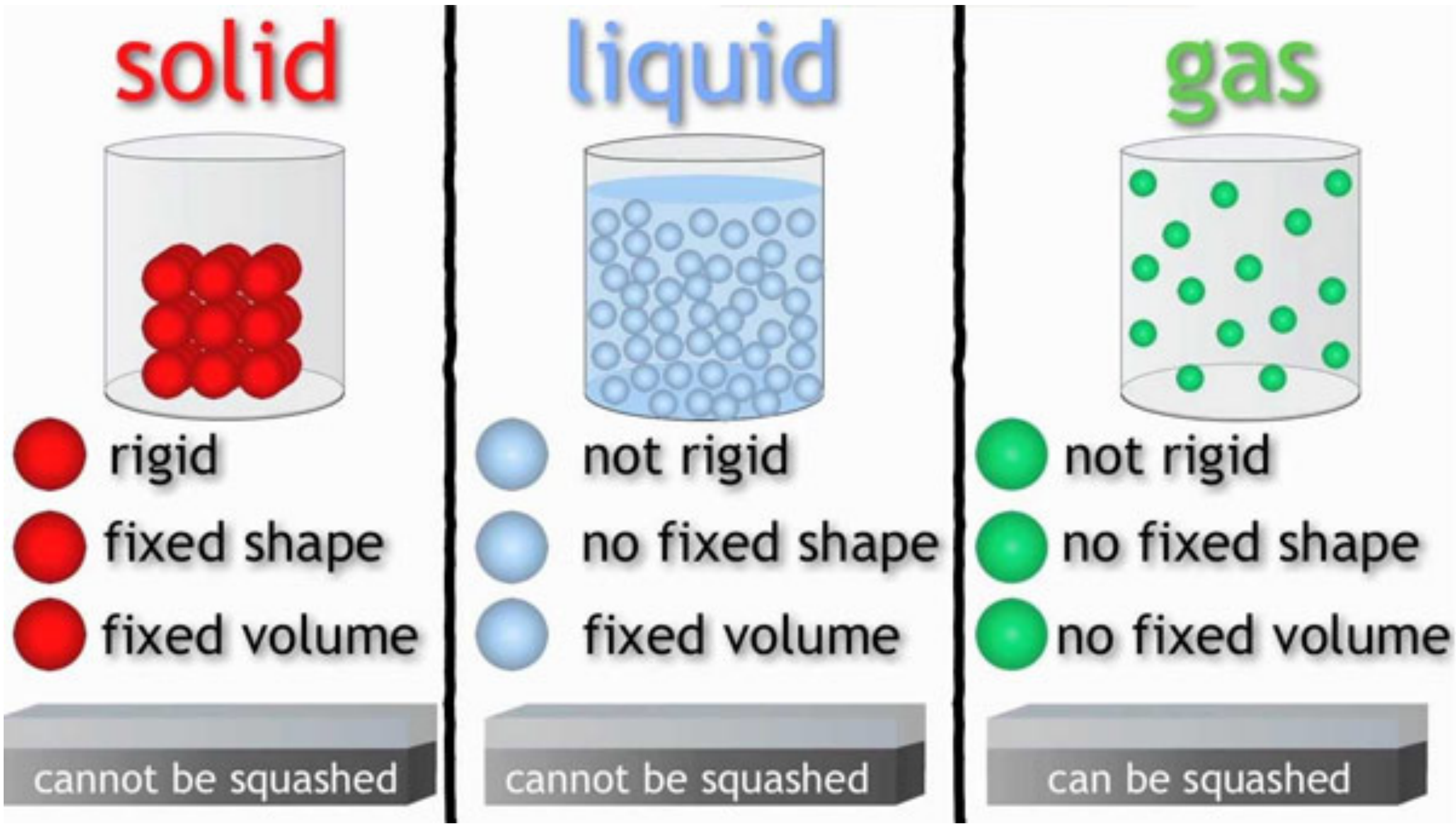
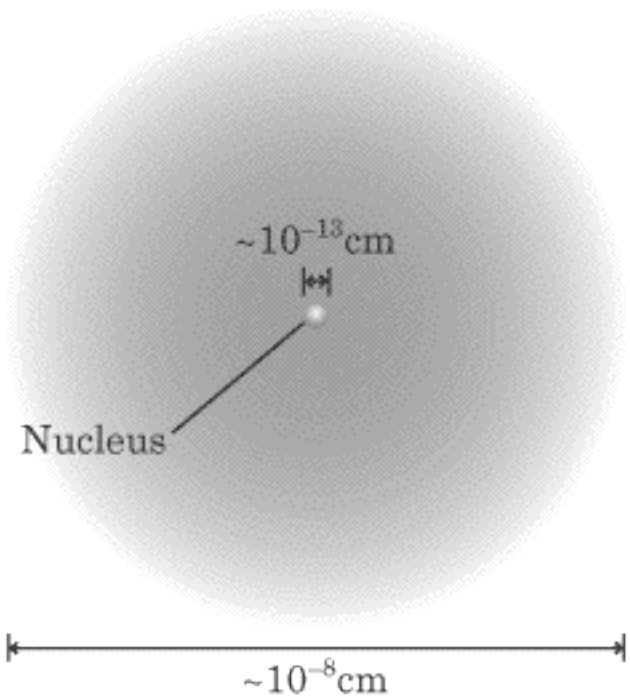
MATTER



Matter is made of atoms

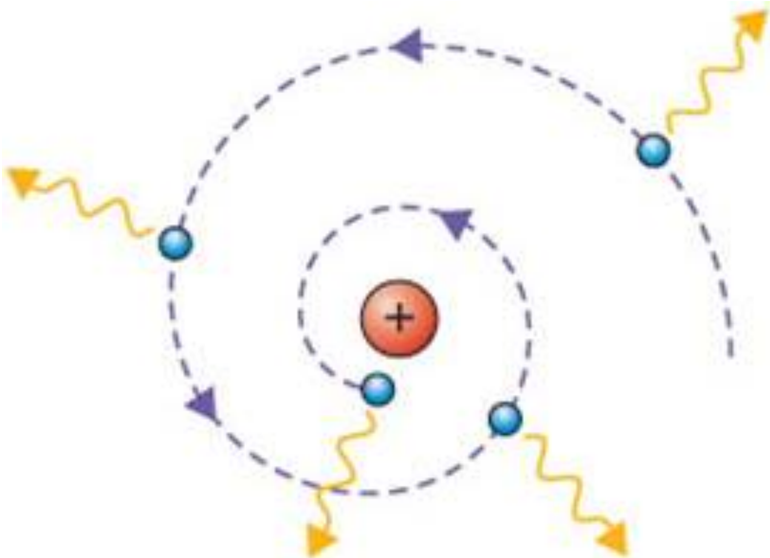


The atom



A compact nucleus with positive charge, surrounded by electrons with negative charge

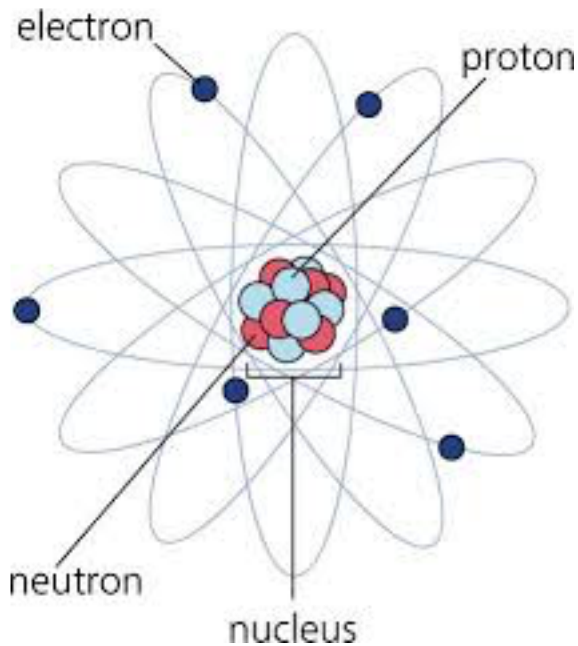
But there is a problem



So says the theory

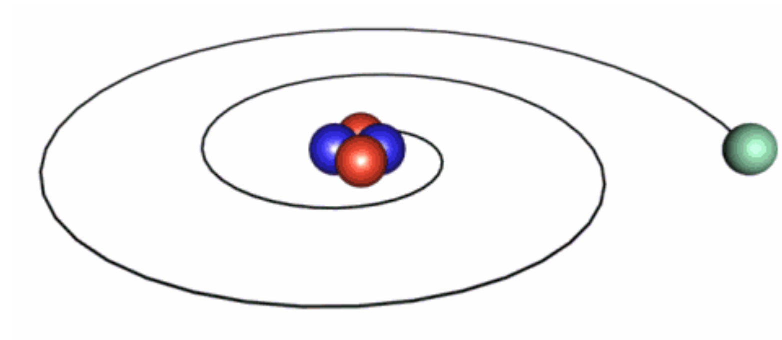
Electrons should fall on the nucleus in a fraction of a second. But this does not happen

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



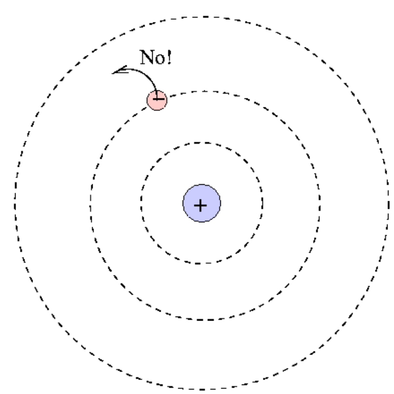
Classical Atom

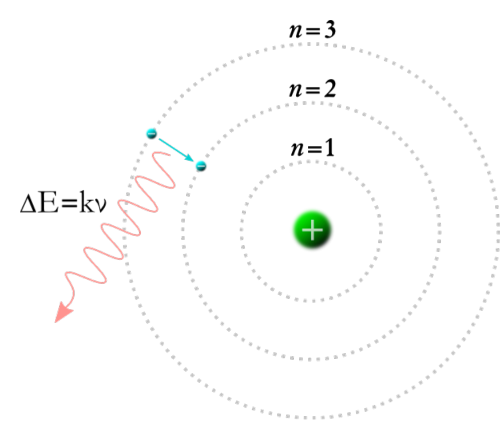
Like the solar system.
However… it is unstable (why?)
($t = 10^{-11}$s)



Bohr's atom

Only specific (= **quantized**) orbits are allowed. On these orbits, electrons are **stable**. **Jumps** are possible, with the **emission** of radiation.



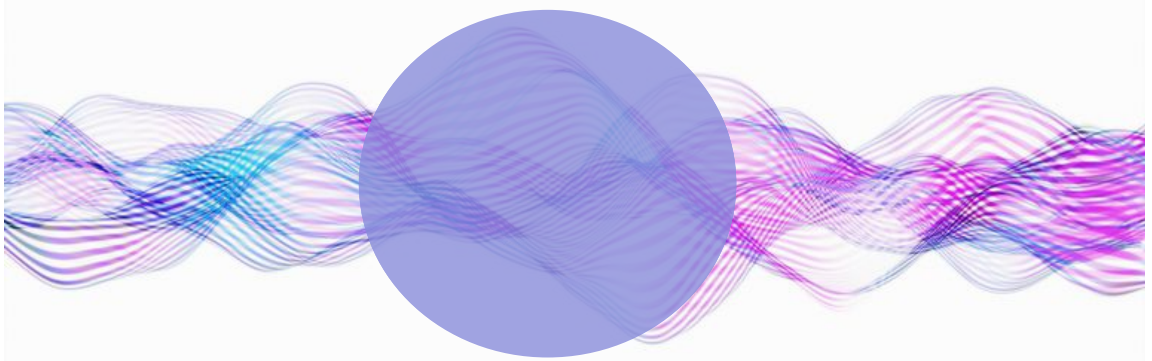


Quantization of matter: de Broglie's hypothesis (1924)

Motivation: Light seems to have a double nature, particle and wave.

Hypothesis: Also matter has a **double nature**, particle and wave. A particle moving with velocity **v** is associated a wave with wavelength

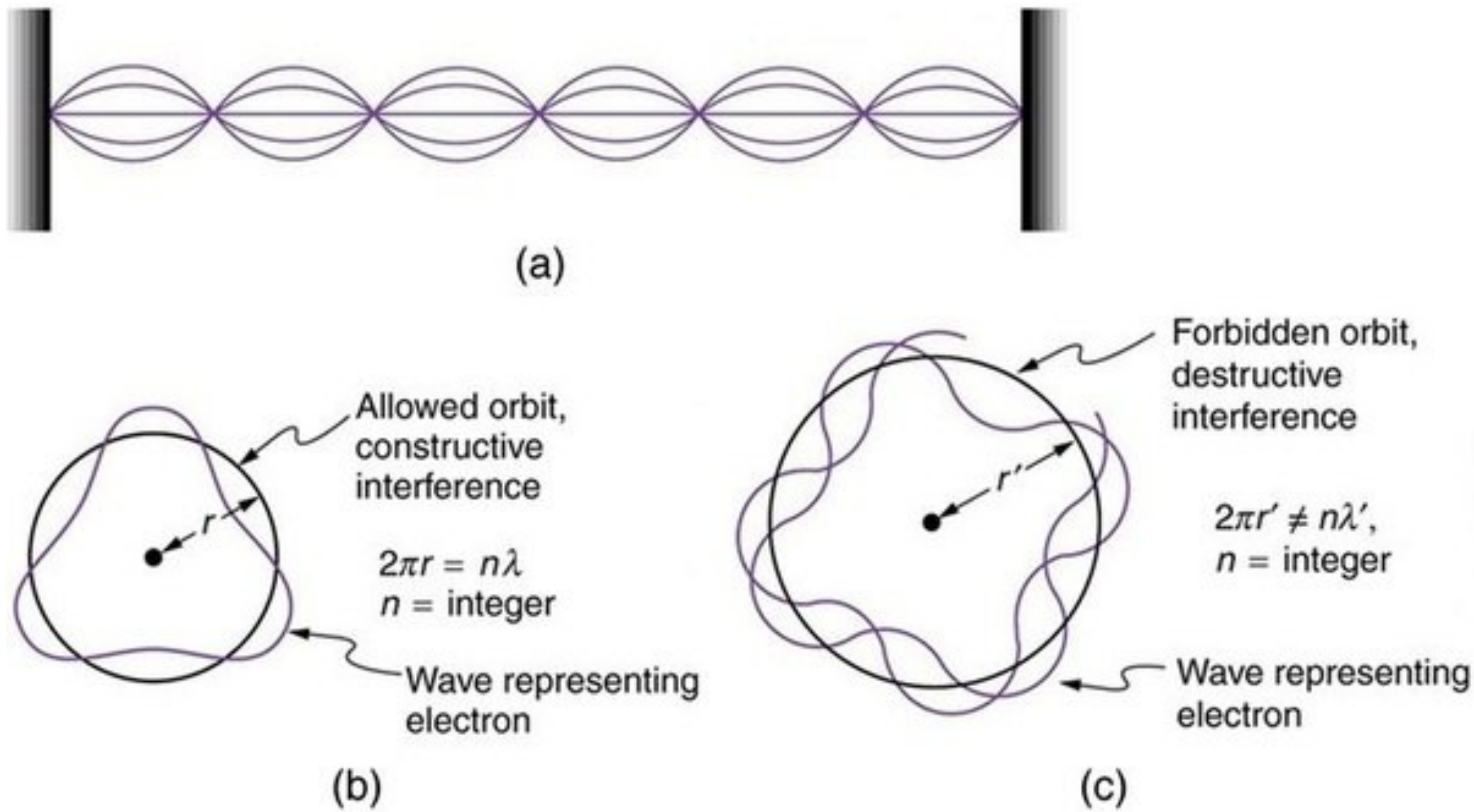
$$\lambda = h/p = h/mv$$



The de Broglie wave length of macroscopic matter is so small that it cannot be detected (classical behaviour). That of small particles, like electrons, can (quantum behaviour).

de Broglie and Bohr’s atom

De Broglie’s hypothesis explains why orbits in atoms are quantized



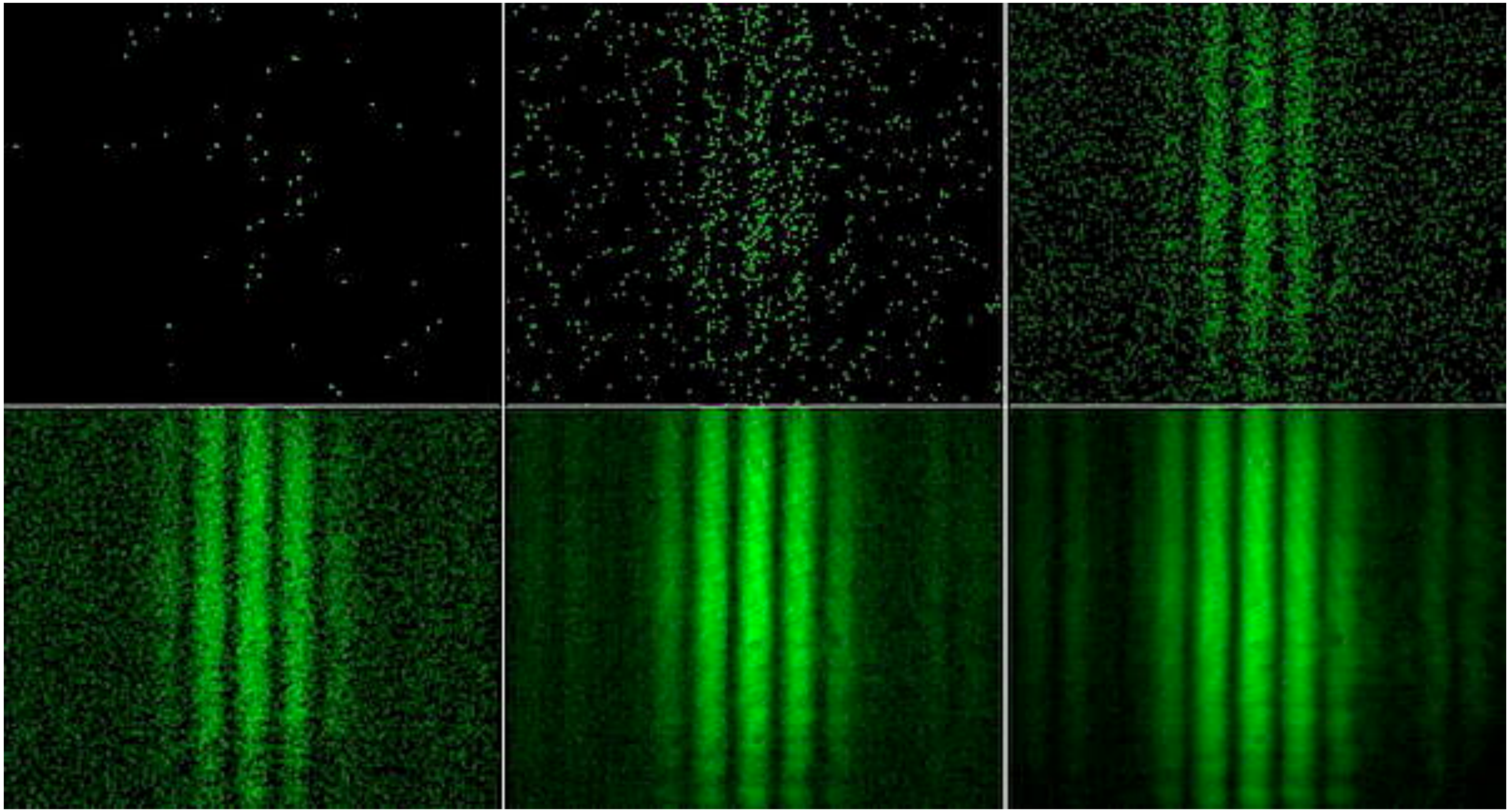
Quantization of matter: summary

Matter behaves like a **particle**

Matter behaves like a **wave**

What's going on? Is it a particle or a wave?

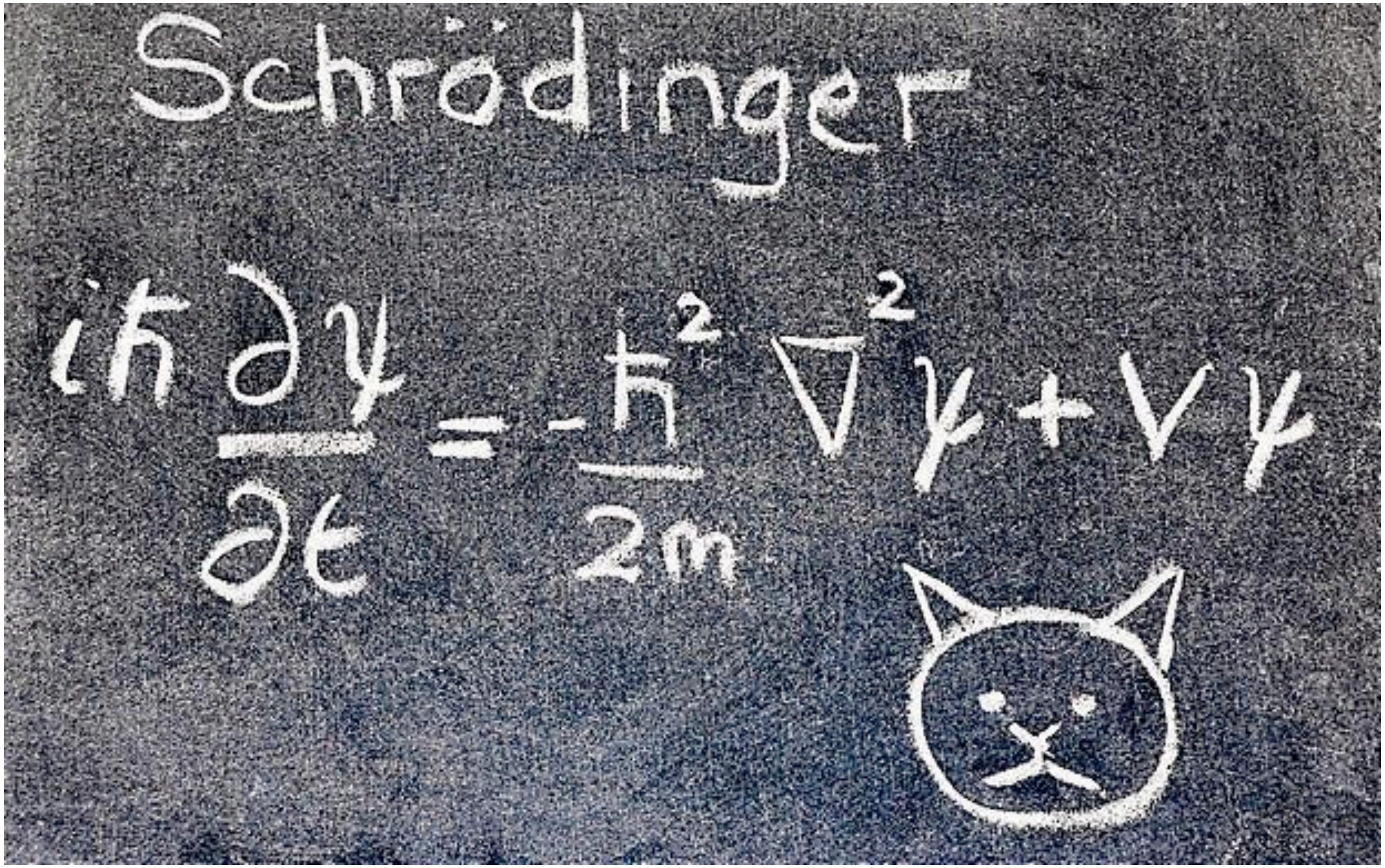
Particle and Wave



Each single atom atom hits the screen in a precise point and one can count them (➔ **particle**) but at the same time they arrange themselves according to an interference pattern (➔ **wave**). How do we describe this?

Birth of Quantum mechanics (1926)

In 1926, Schrödinger suggests to associate a wave function to every physical system. This wave function is solution of of an equation – the Schrödinger equation – which determines its time evolution.



… but there is a problem

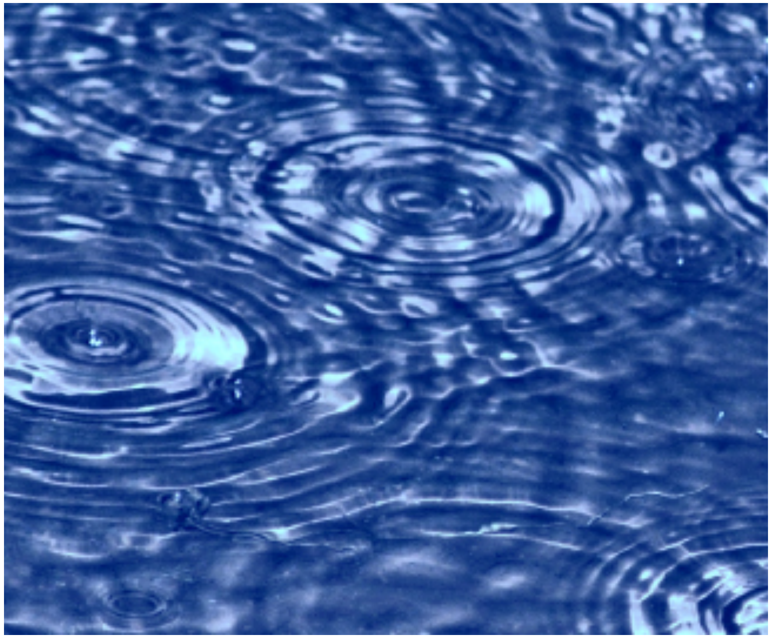
«At an early stage, [Schrödinger] had tried to replace ‘particles’ with wavepackets. But wavepackets diffuse. And the paper of 1952 ends, rather lamely, with the admission that Schrödinger does not see how, for the present, to account for particles tracks in track chambers … nor, more generally, for the definiteness, 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 Schrödinger wave function explains all properties of matter.

But when measured, particles are always found in a precise location in space, not spread out like waves!

The particle properties are not explained.



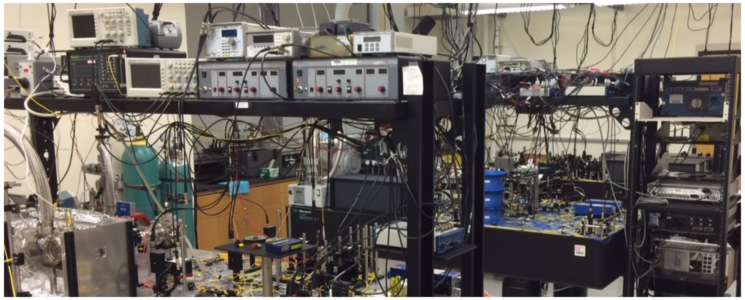
The official solution (Born - 1926)

One cannot ask where particles are, or what properties they have. One can only speak only of **outcomes of measurements**, the only thing one has access to. The wave function therefore does not describe the particle and its properties, but only the probability of outcomes of measurements (through the square modulus)

Classical Physics

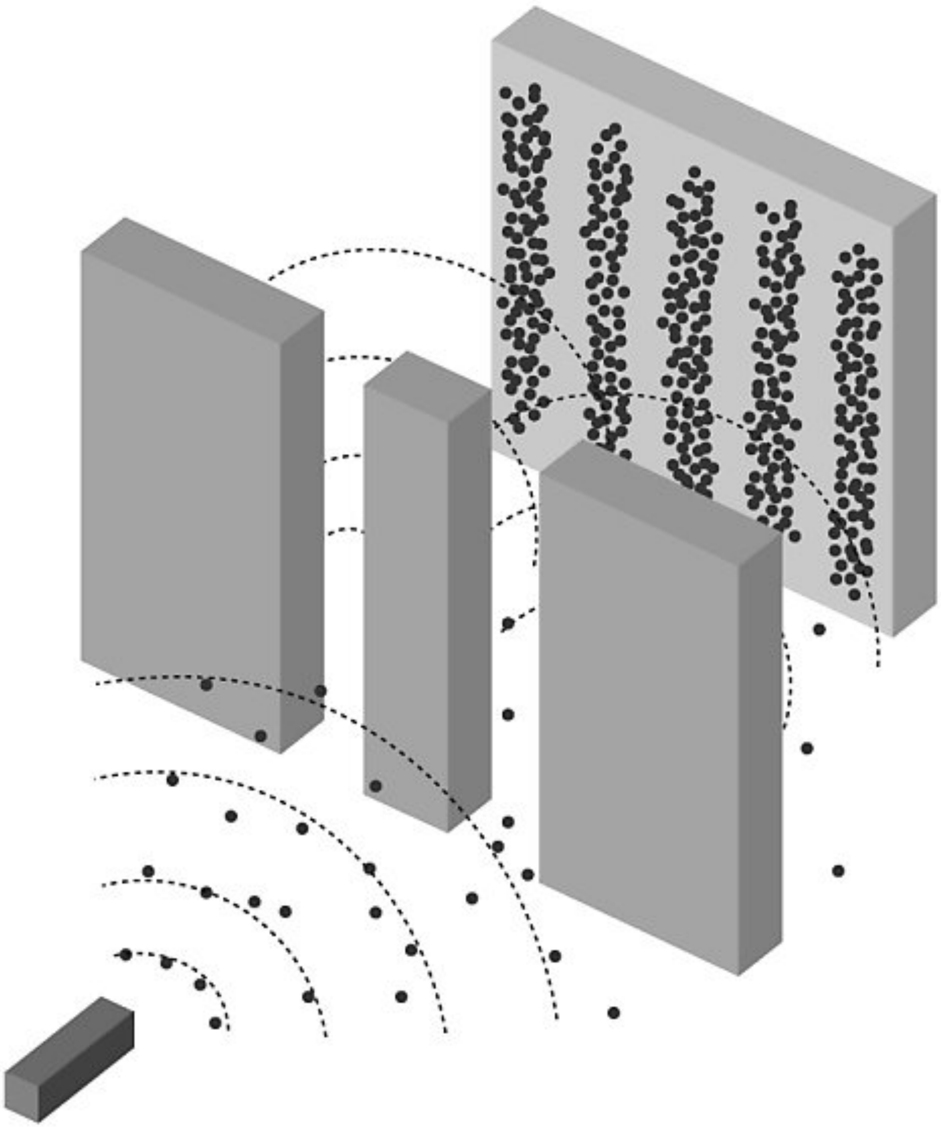
Direct access to the system under study

Quantum Physics



No direct access to the system under study

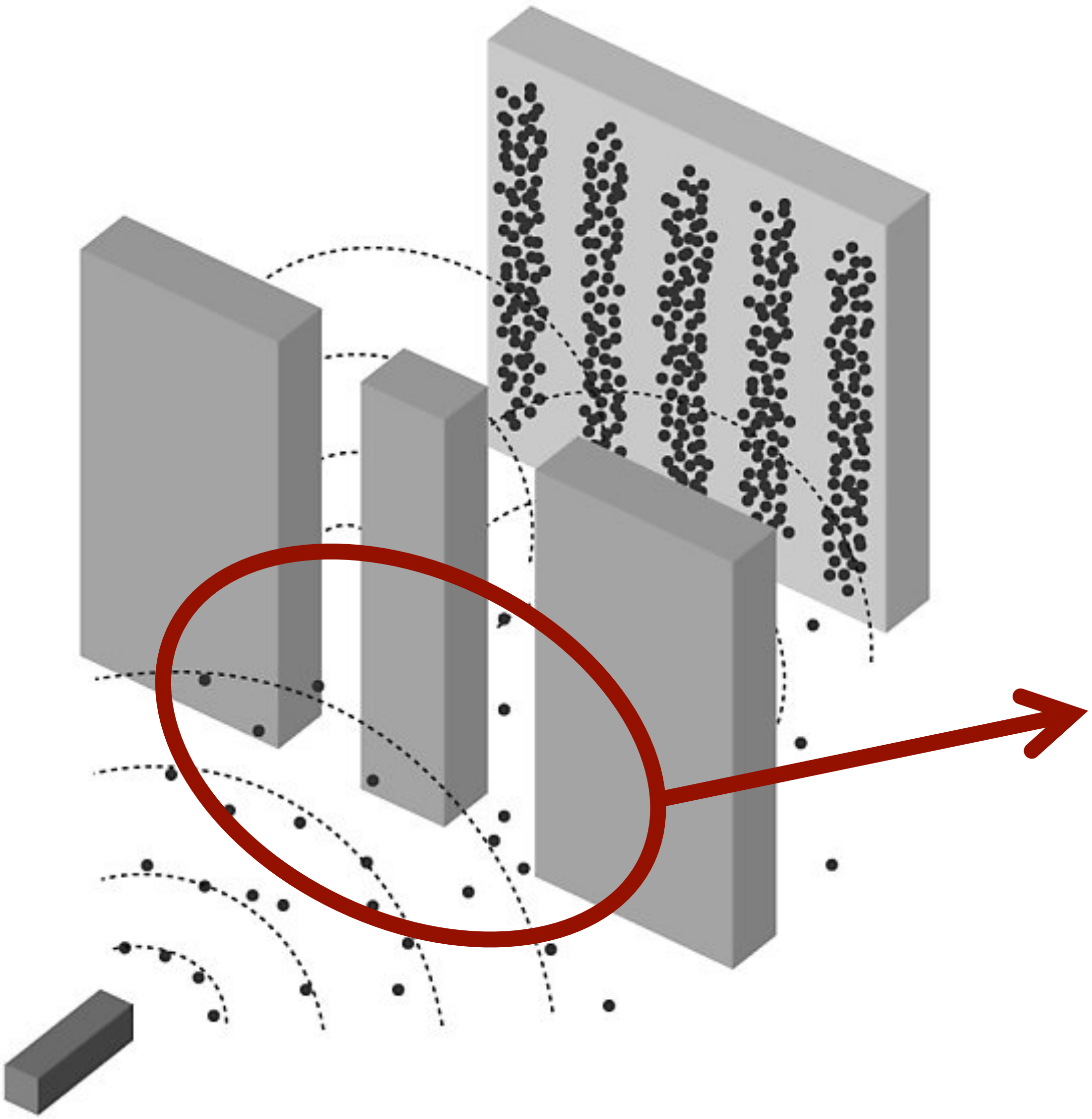
In other words



Measurement: particles, but distributed like waves

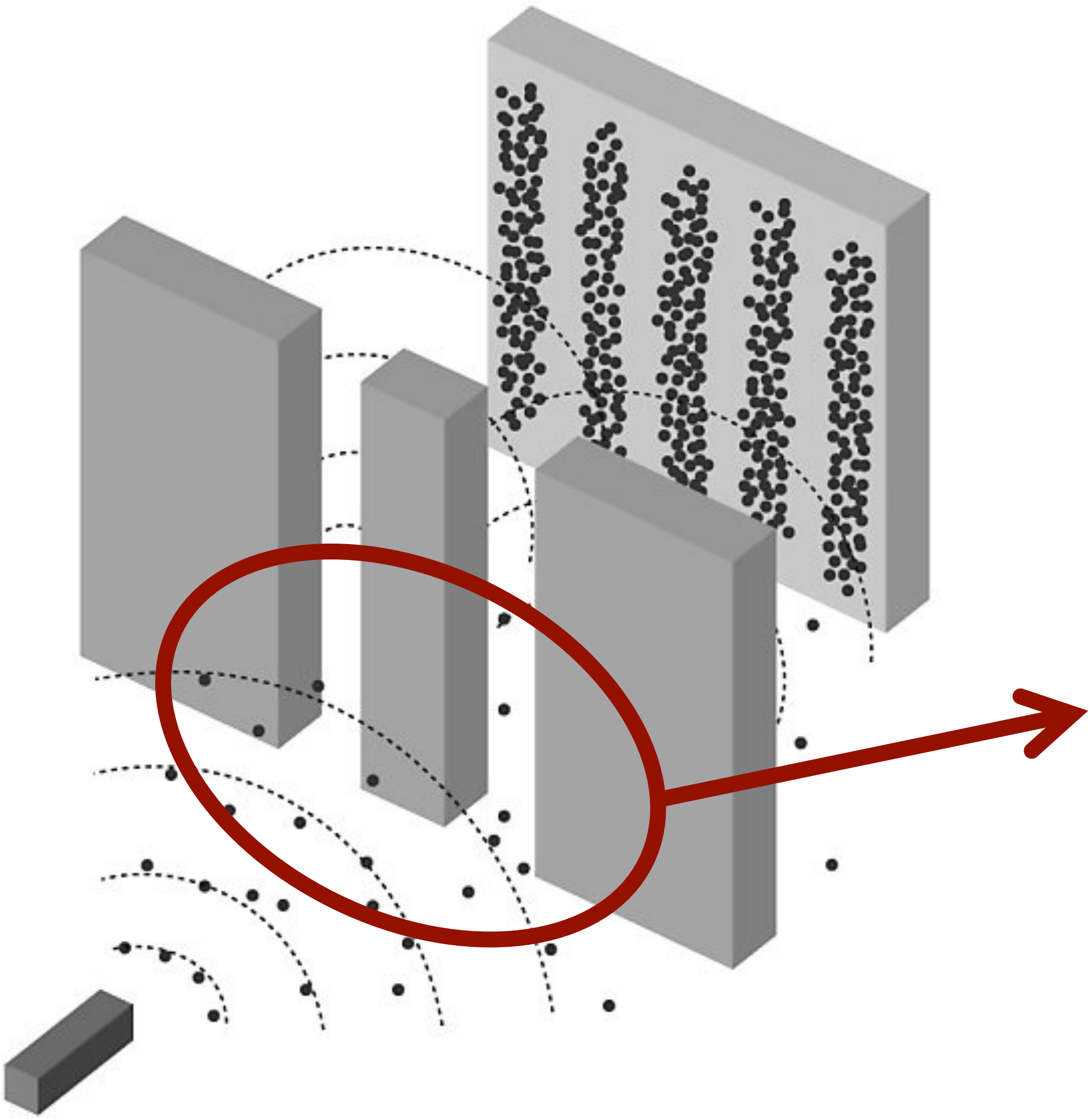
Wave probablity propagating

There is still a problem



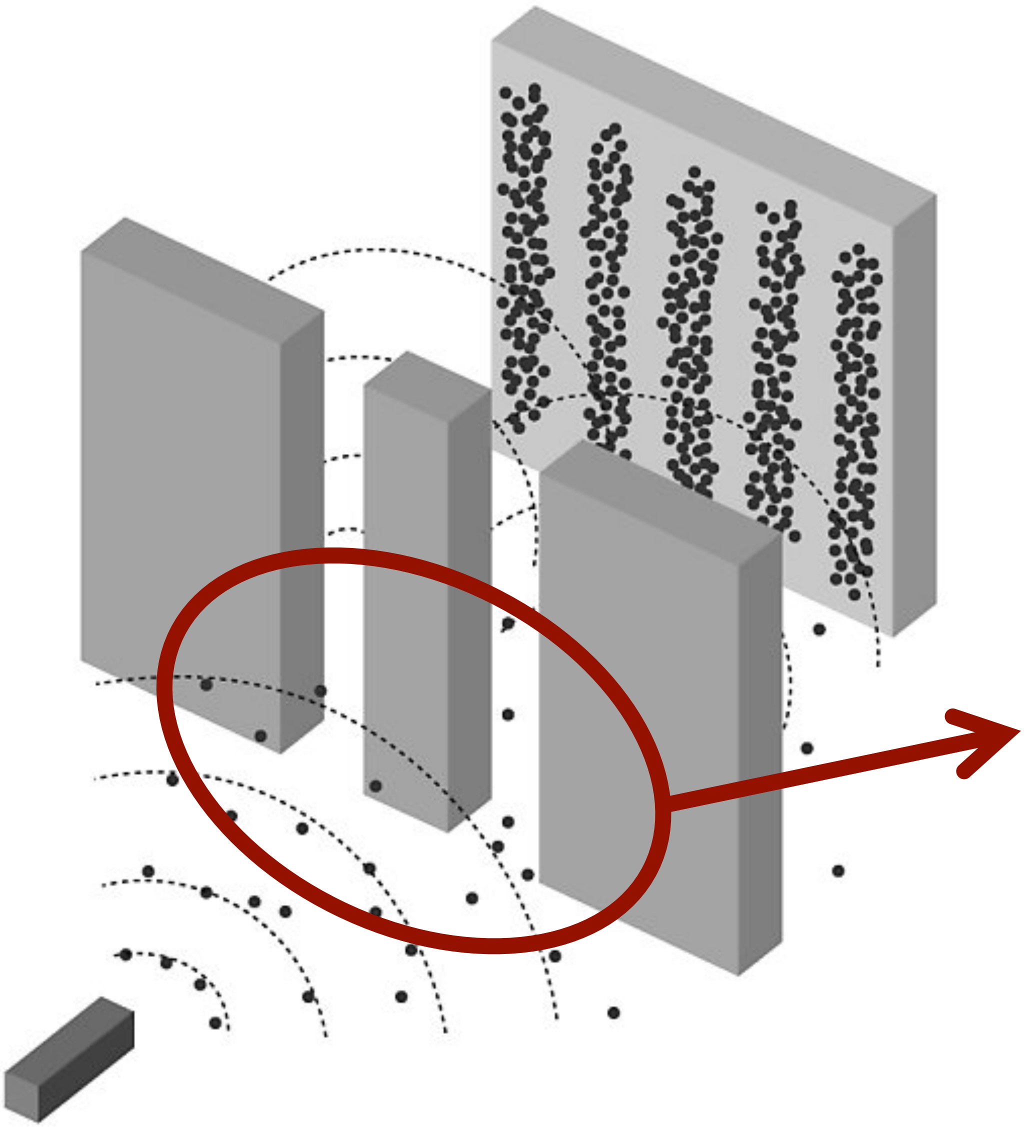
What happens to the particle when it goes through the two slits?

The answer is…



The particle is in a superposition state. Wa cannot say anything more

The problem is still there!



What does it mean that the particle is in a superposition state?

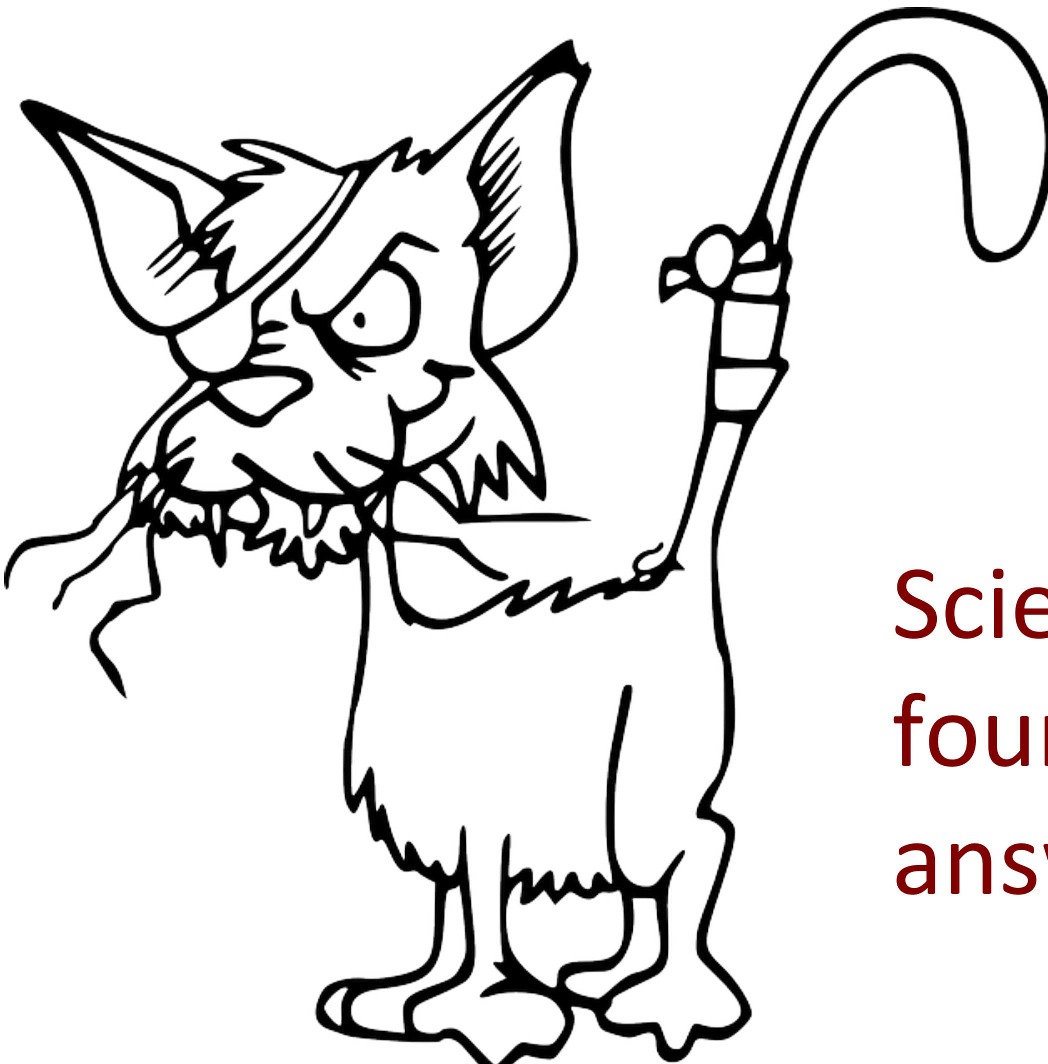
No unique answer yet (there are many…)

The problem is serious

Small particles can be in superposition states. But matter is made of particles, therefore also matter should behave the same way.

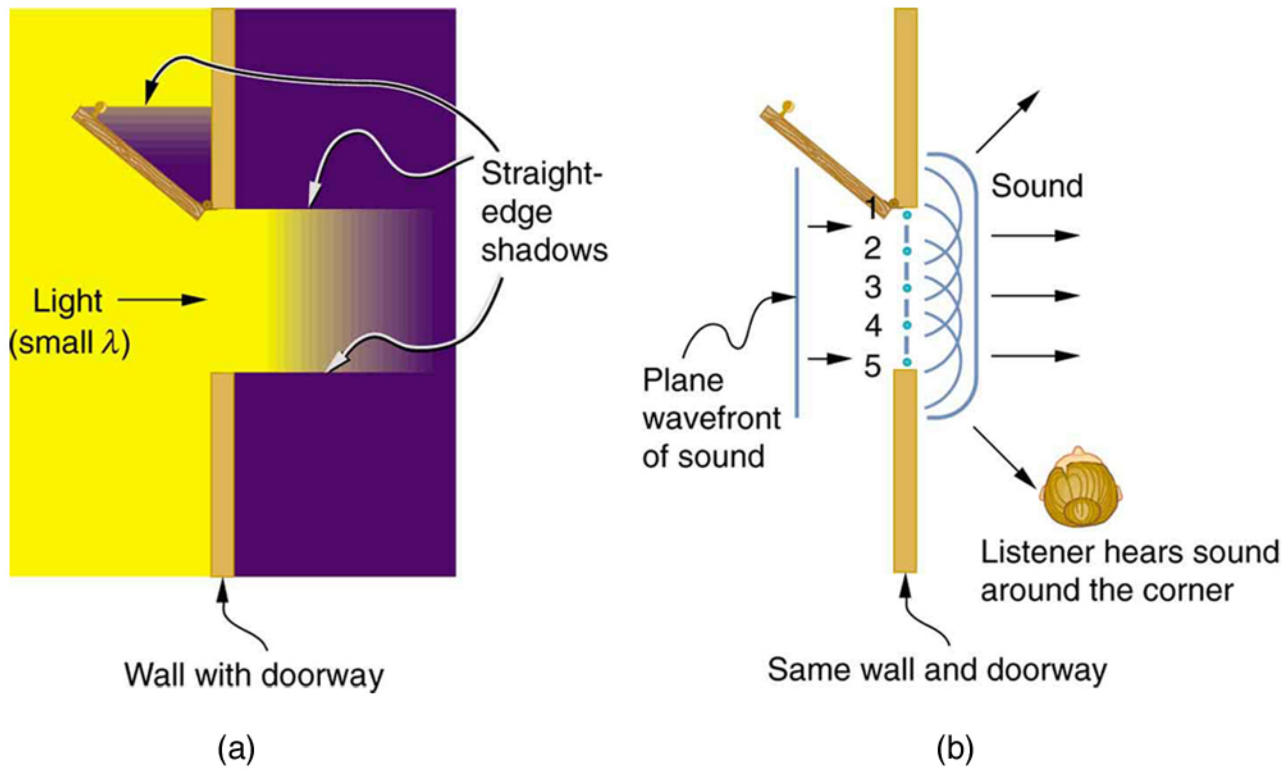
How can it be?

The debate is still open



Scientist still haven't found a convincing answer

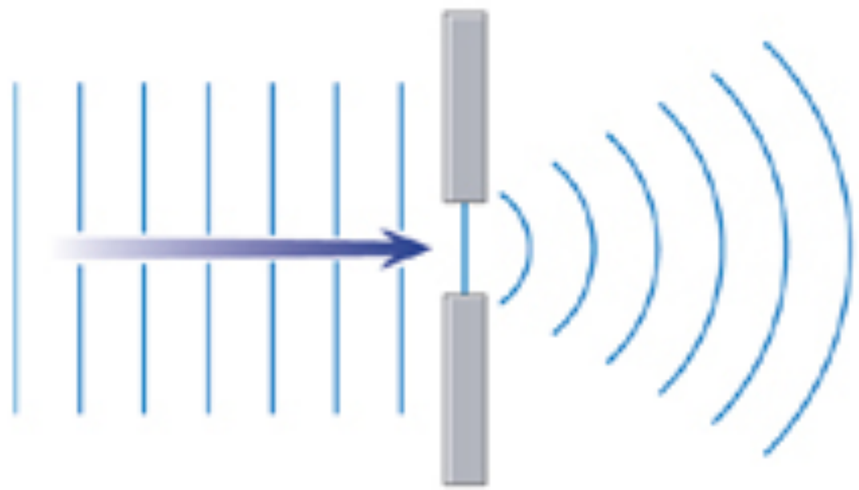
How do we see a wave behaviour?



Light: λ = 400-700nm, much smaller than the width of the doorway ➔ No diffraction

Sound: λ = 0.33m (1000Hz), comparable to the width of the doorway ➔ Diffraction

Condition for Diffraction



Diffraction occurs when

$$\frac{F^2}{L\lambda} \ll 1$$

F = Size of the slit / dimension of the diffracting object

L = Distance from the aperture

λ = wavelength

Two examples

Macroscopic system: m = 1g, v = 1m/s

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} J \cdot s}{1 \times 10^{-3} Kg \times 1 m/s} = 6.63 \times 10^{-31} m$$

L = 10m (max for a lab). Then F < 10^{-15} m (size of proton). Impossible!

Very small, impossible to detect!

Microscopic system: electrons (m = 9.11 x 10^{-31} Kg),

E = 54 eV = 8.65 x 10^{-18} J.

Then v = $(2E/m)^{1/2}$ = 4.36 x 10^{6} m/s

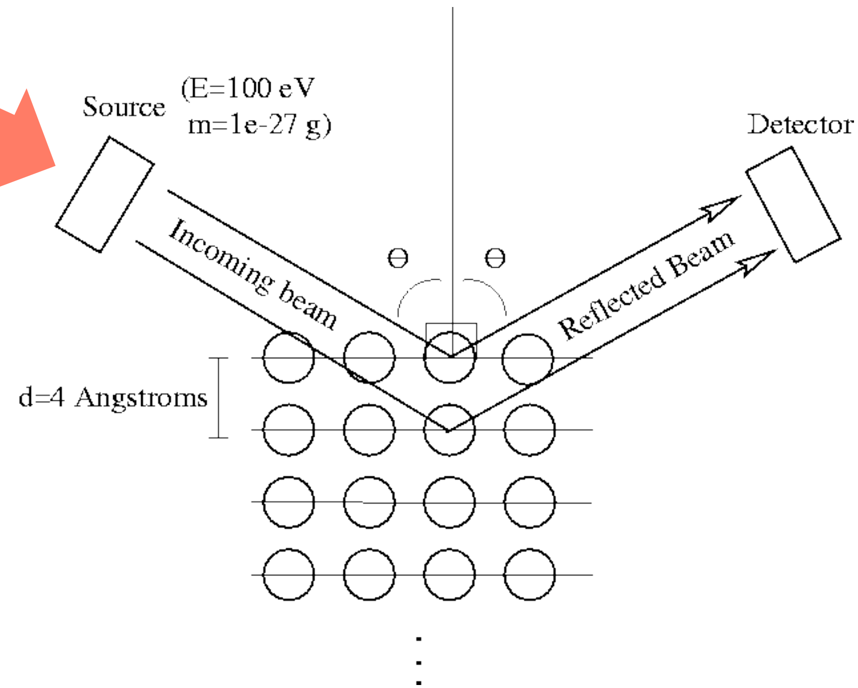
L = 1m. Then F < 10^{-5} m. Easy F = 10^{-10}m (crystals)

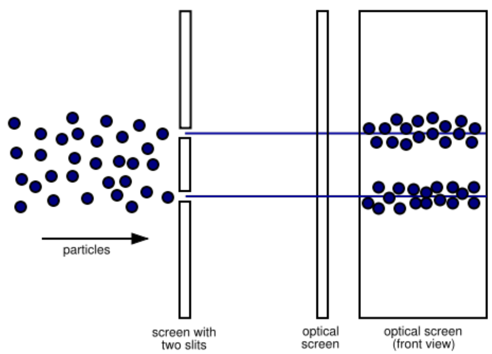
$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} J \cdot s}{9.11 \times 10^{-31} Kg \times 4.36 \times 10^{6} m/s} = 1.67 \times 10^{-10} m$$

Wave nature of matter: the experiment of Davisson & Germer (1927)

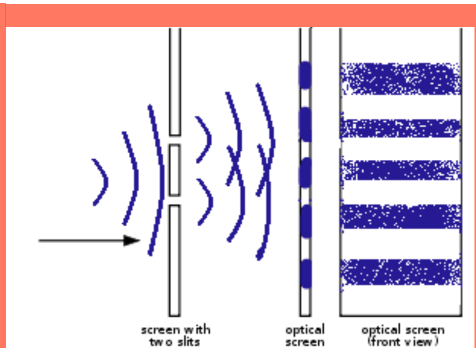
Diffraction of electrons by a crystal

A more complicated version of the **double-slit experiment**

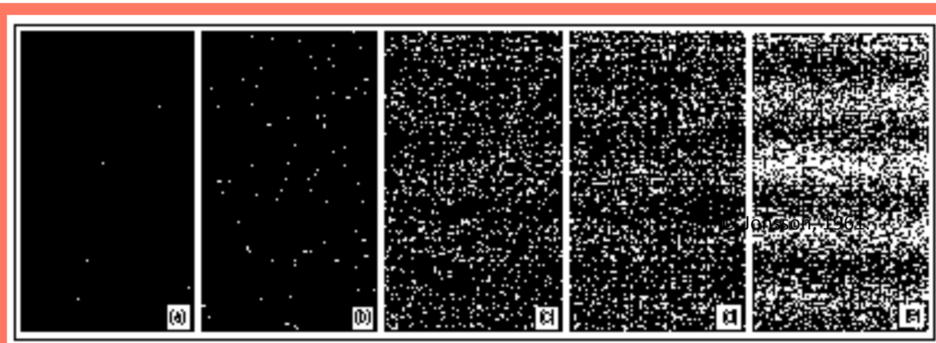




Particle behaviour

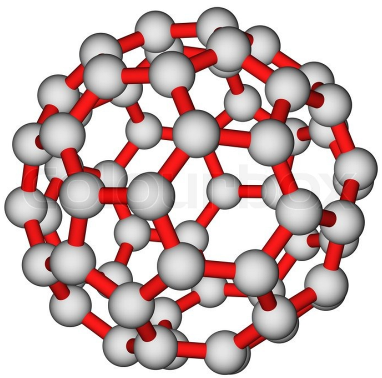


Wave behaviour

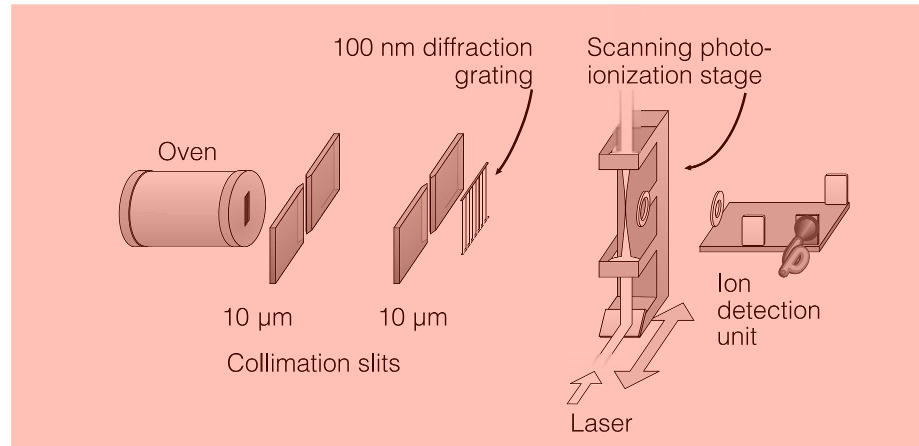


Modern Experiment with molecules (1999)

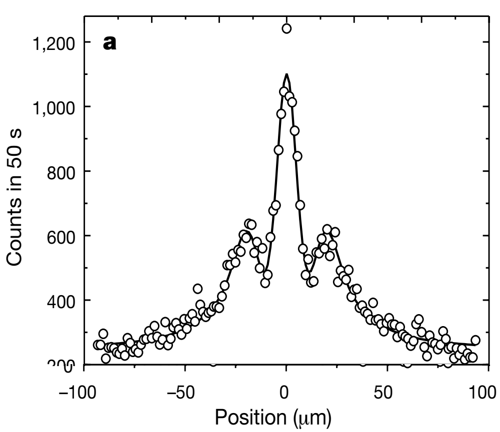
Diffraction of Fullerene (C_{60})



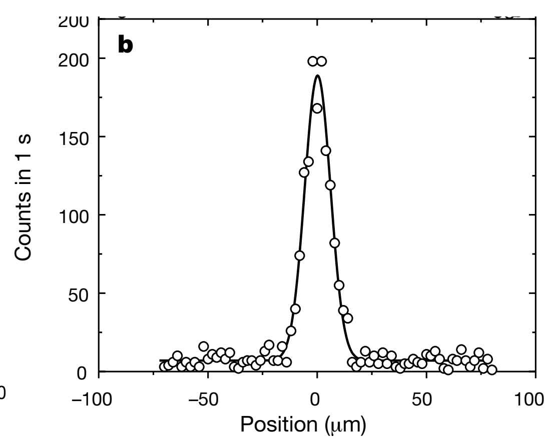
The experiment



The result



With grating



Without grating

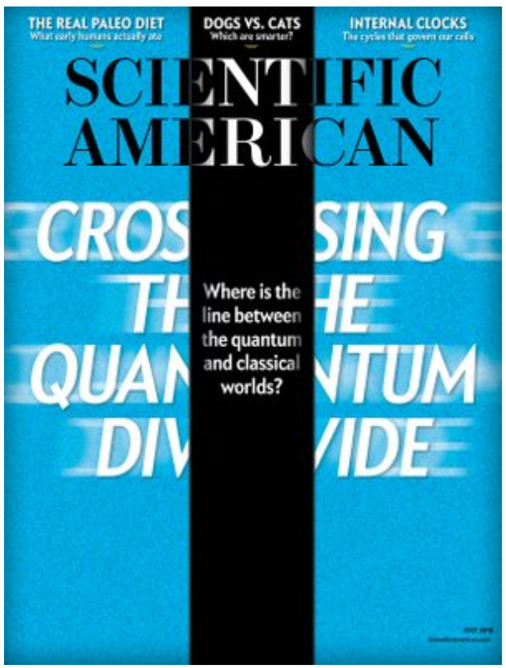
Some numbers

Mass = 60 x 12 x 1,68 x 10^{-27} Kg = 1,21 x 10^{-24}Kg = 10^{6} larger than the mass of the electron.

Velocity = 220 m/2

λ = 2.49 pm = 10^{-2} smaller than that of electrons

A hot topic



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October 2018

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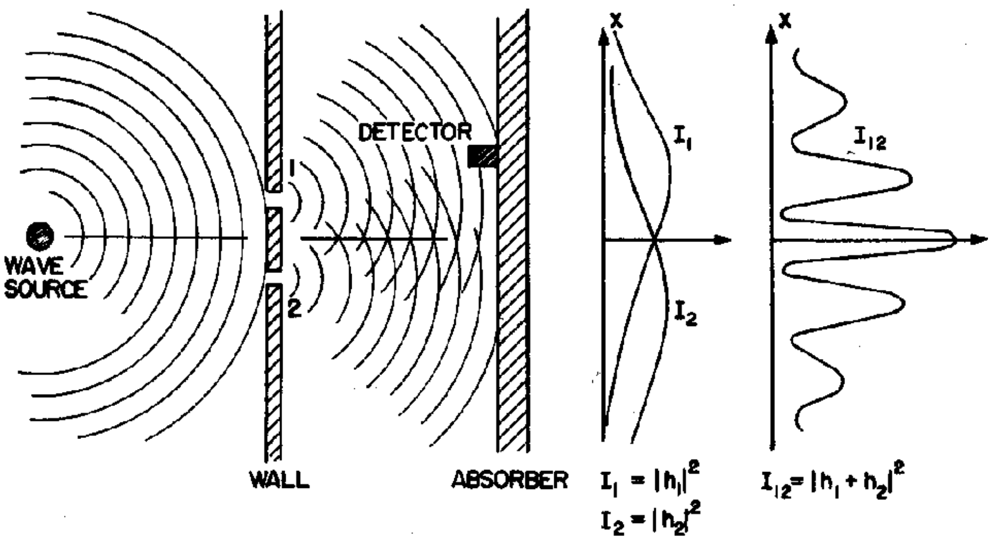
How far can we push it?



$$\frac{F^2}{L\lambda} = \frac{(100nm)^2}{1,25m \times 2,49pm}$$

$$= 3,21 \times 10^{-3} \ll 1$$

But particles fall while traveling

$$t = \frac{L}{v} = \frac{1,25m}{220m/s} = 5,68 \times 10^{-3}s$$

$$d = \frac{1}{2}gt^2 = \frac{1}{2} \times 9,81m/s^2 \times (5,86 \times 10^{-3}s)^2 = 0,16mm$$

How far can we push it?

The Fraunhofer condition constraints the product

The size of slits cannot be significantly decreased, due to technological limitations and because molecules would get stuck.

The size of the experiment cannot be enlarged too much.

Therefore the de Broglie wave length cannot change too much.

So if we want to increase the mass, we need to decrease the velocity.

But then the **time of flight increases.**

And the molecule **falls more in gravity.**

By **increasing the mass by 3 orders of magnitude**, the distance of free fall also increases by 6 order of magnitude, from 0,1mm to 100m. This is too much!

$$\frac{F^2}{L\lambda} \ll 1$$

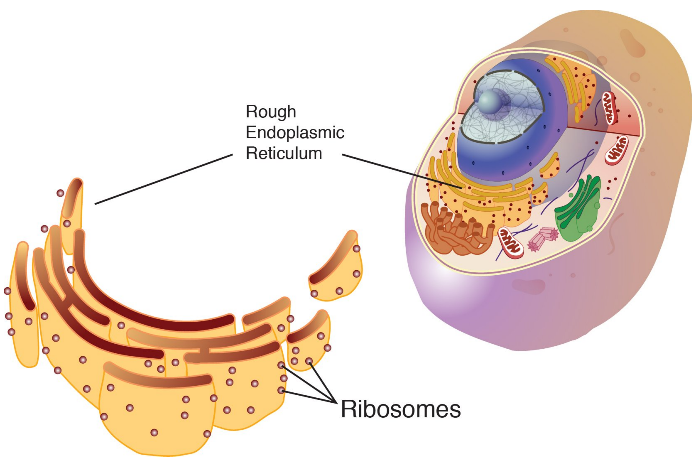
$$\lambda = \frac{h}{mv}$$

$$t = \frac{L}{v}$$

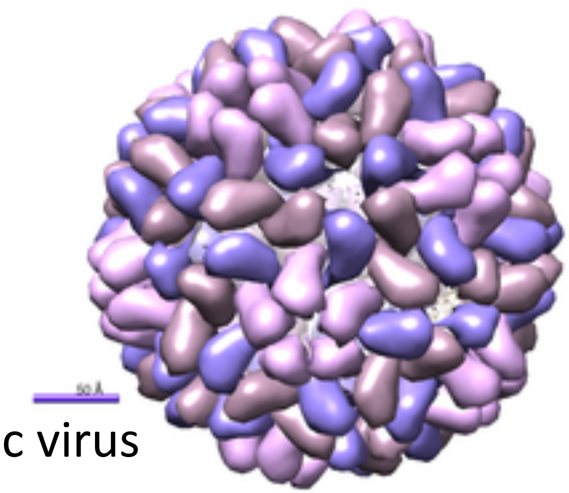
$$d = \frac{1}{2}gt^2$$

How far can we push it?

So we can go up to masses of 10^{-21}Kg = attogram



Ribosome



Brome mosaic virus

Although technologically very challenging, these object are still very small.

Performing diffraction experiments with small **viruses** would represent the first type of experiment with a **living object.**

It’s time for Space

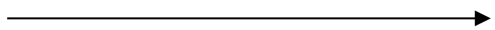
In outer space one can create conditions of almost **0 gravity**.

Experiments can be run for longer times (**< 100s** technological limit).

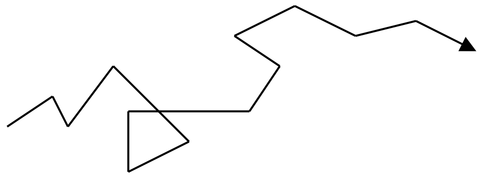
Masses **larger by 2-3 orders of magnitude** (femtogram) can be used

Indirect tests

If the superposition principle fails, atoms and molecules behave in a different way



Particle (Schrödinger)



Particle (Schrödinger + modifications)

More specifically, it can be proven that their motion is not “free”

A European project

TEQ

Testing the large-scale limit of Quantum Mechanics

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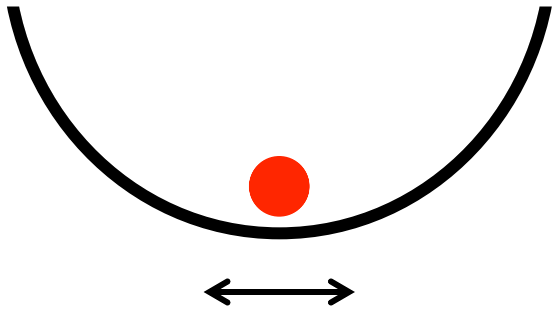
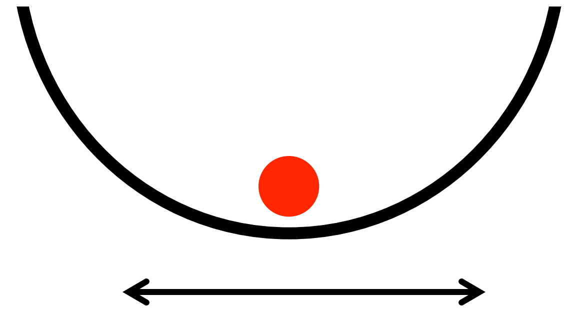
Quantum mechanics provides, to date, the most accurate understanding of the microscopic world of atoms, molecules and photons allowing them to be in the superposition of two different, perfectly distinguishable configurations at the same time.
However, the macroscopic world that is before our very own eyes doesn't seem to respect quantum rules. Why is that so?

TEQ addresses such a fundamental quest from an innovative standpoint, supported by a € 4.4M grant awarded by the European Commission.
The TEQ partners will develop new theoretical models and implement a test of the quantum superposition principle on macroscopic objects to establish the ultimate bounds to the validity of the quantum framework, if any.

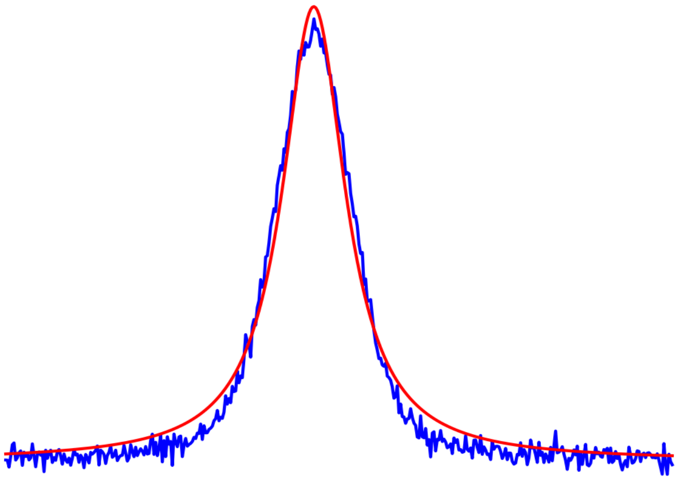
The experiment

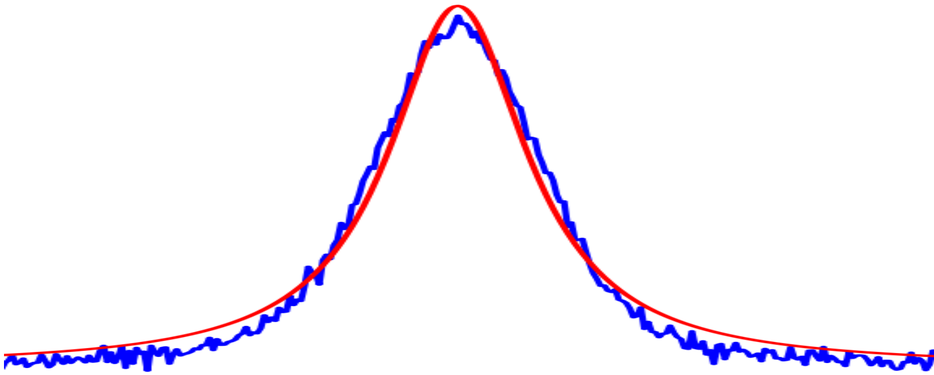




Schrödinger equation

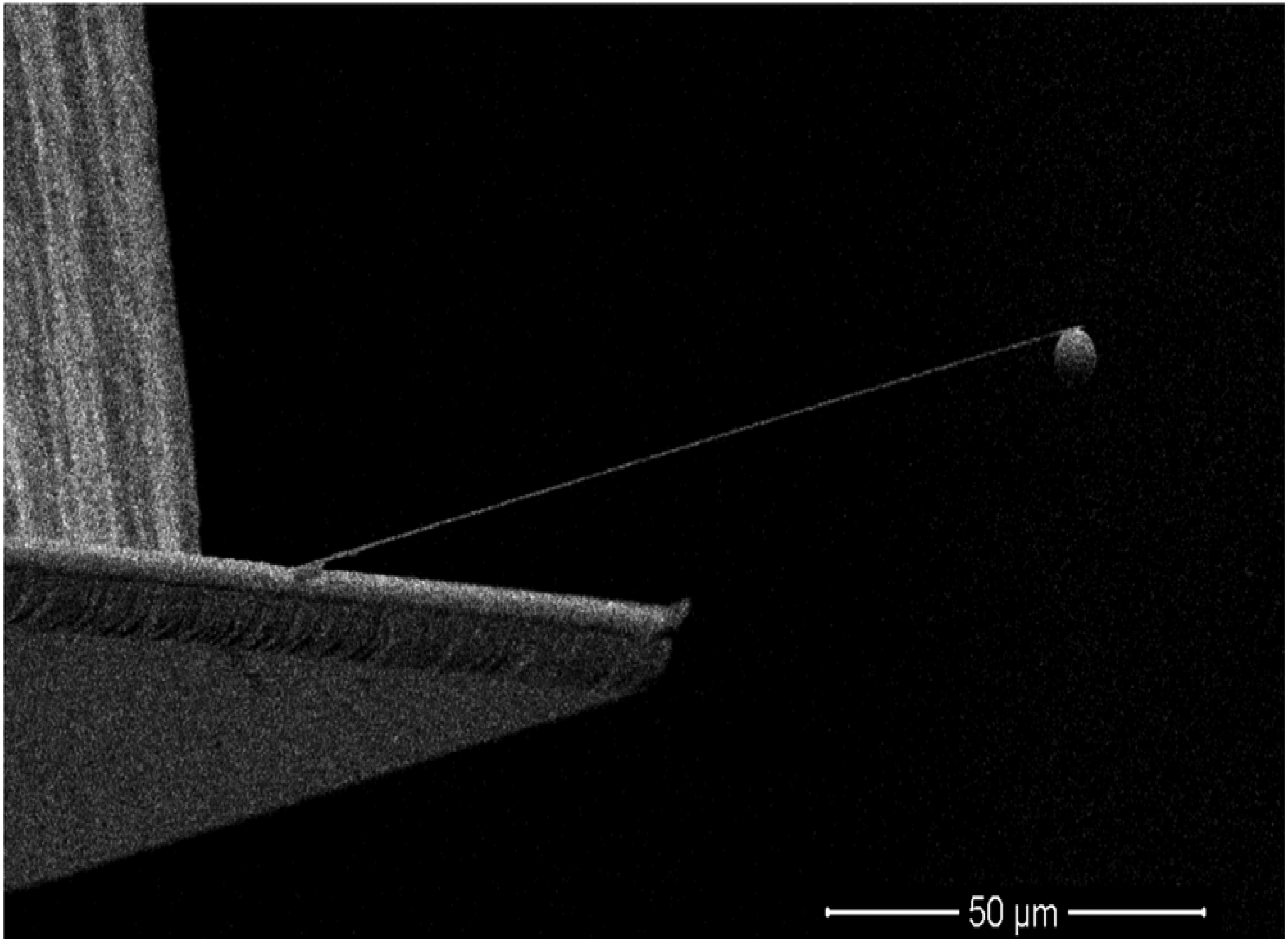
Modified Schrödinger eq.





Output signal – from a laser monitoring the particle's motion

The experiment



A. Vinante *et al.*, *Physical Review Letters 119, 110401 (2017)*

La caccia al gatto di Schrödinger continua…