Lecture 19

Fundamentals of Physics

Phys 120, Fall 2015

Quantum Physics II

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Fargo, October 29, 2015

Overview

- Review of Quantum Mechanics so far
- Probability
- Uncertainty principle
- The effect of detectors
- Quantum entanglement: spooky action at a distance

Pre-quantum deterministic universe:

“An intelligent being knowing, at a given instant of time, all forces acting in nature, as well as the momentary positions of all things of which the uni verseconsists,wouldbeabletocomprehendthe motions of the largest bodies of the world and th ose of the smallest atoms in one single formula, provided it were sufficiently powerful to subject all the data to analysis; to it, nothing would be uncertain, both future and past would be present before its eyes.”

Pierre Simon Laplace

Two slit experiment

Initially the electron (or photon) is a matter (or EM) wave as it passes through the slits. Then the matter field interacts with the atoms in the screen. The matter field (or EM field) then locally impacts one atom and an event occurs.

During the event the field changes character instantaneously, and this behavior is called **quantum nonlocality**.

The location of the event is unpredictable, a property called **quantum uncertainty**.

However, for many impacts the overall pattern (or statistics) is predictable.

Concept Check

How is an electron similar to a photon?

a) both contain electric charge

b) both move at lightspeed

c) both impact a tiny point on a viewing screen

d) both are quanta.

Concept Check

Why do subsequent electrons hit the screen at different locations?
a) they started out from the electron source at slightly different angles
b) even though they were identical until they arrived at the screen their quantum mechanical nature causes them to be deposited at different positions.
c) even though they were identical until they arrived at the screen, the atoms were in different positions and therefore interacted differently with the electrons.

Concept Check

Can the future be predicted?

a) No, because of the quantum mechanical effects that are inherently unpredictable.

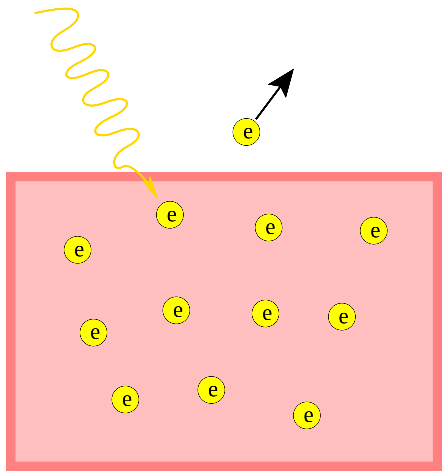
b) No, because we can never measure the position of all the atoms with sufficient accuracy.

c) Yes, as long as we know all there is to know about the system of interest.

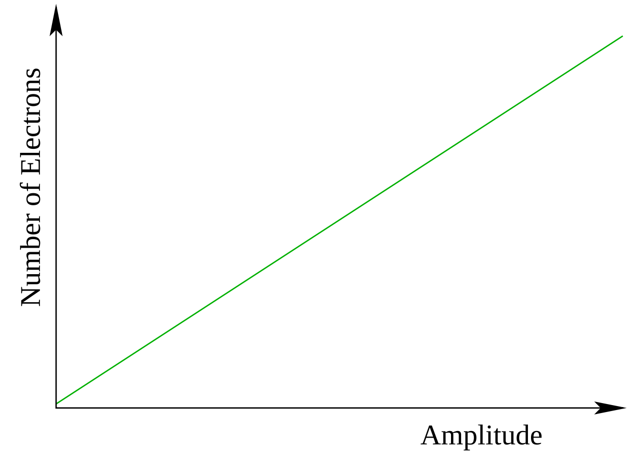
d) Yes, but only for large systems where the statistical uncertainty becomes irrelevant.

The photoelectric effect

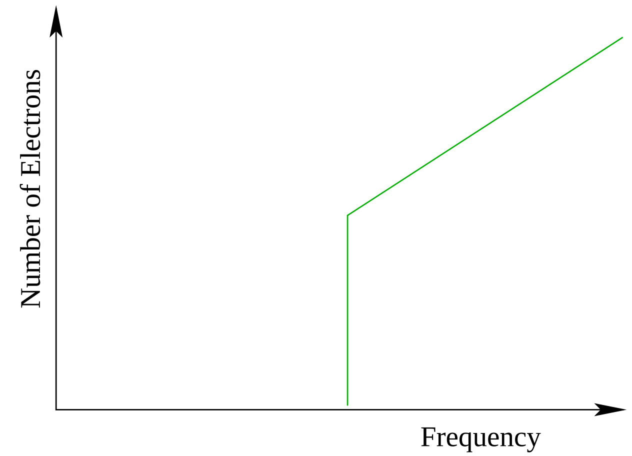
When light shines on a metal, this metal can release electrons. This is known as the photoelectric effect. From classical physics this can be understood as electrons interacting with the electromagnetic field absorbing energy.



Electrons are held inside the metal by a potential energy ΔE. Classically the electron absorbs some energy from the field. The available energy would depend on the amplitude and the frequency of the electromagnetic field.



Number of electrons increases with amplitude of electromagnetic wave.



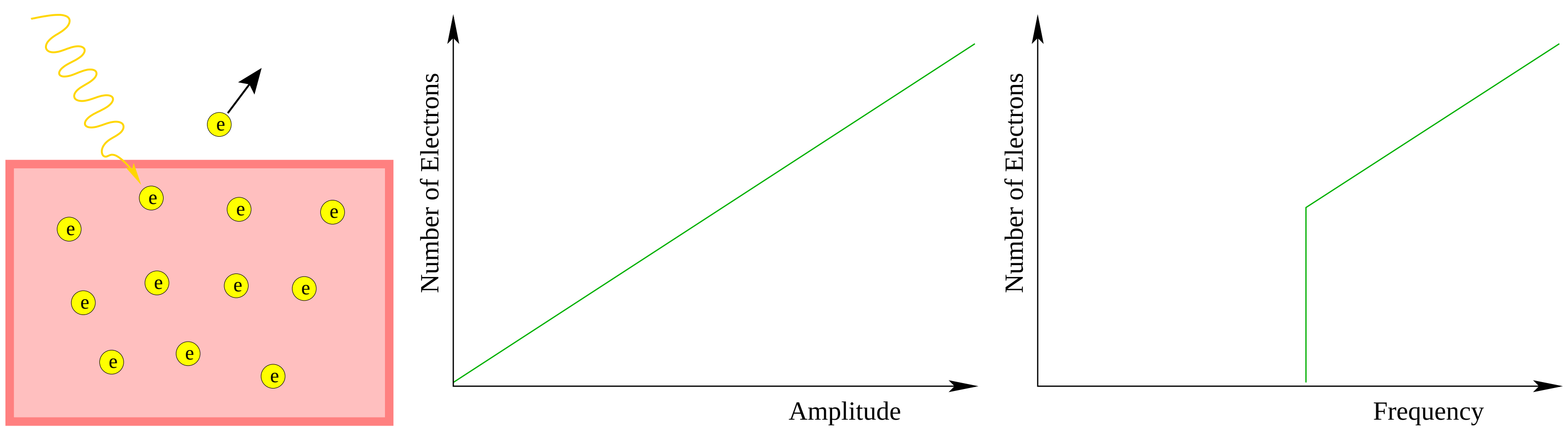
Number of electrons increases with frequency of electromagnetic wave, but below a threshold, the emission stops.

Photoelectric effect, cont.

In another landmark paper of 1905 Einstein explained this strange phenomena by insisting that electrons can only absorb discrete quanta of electromagnetic radiation, called photons. These photons have an energy of

$$E = hf$$

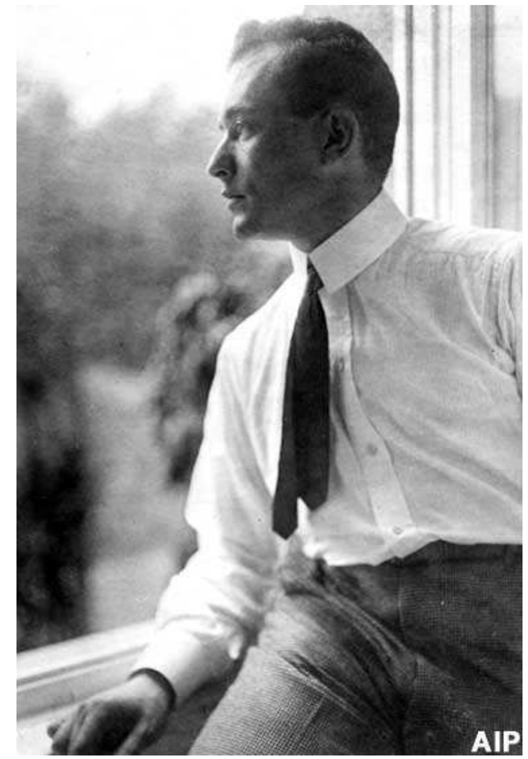
i.e. the energy is given by Plank's constant times the frequency of the electromagnetic wave. (remember $h = 6.6 \times 10^{-34} m^2 kg/s$)



It was this work for which Einstein received the Nobel Price in Physics in 1921.

Matter field and probability

In 1929 German physicist Max Born was the first to connect the intensity of the matter wave gave the *probability* for a single electron to hit a certain point on the screen.



The intensity[a] of the matter field at any particular point represents the probability that an electron impact will occur at that point if a viewing screen or some other detecting device happens to be at that point.

[a]Quantitatively, intensity means the square of the matter field's amplitude.

Probabilities

The Theory of probability is much older than quantum mechanics. You may know about it from examples like a coin toss or the throw of a dice. For a coin toss you would say there is a probability of 50%, or 0.5 for the coin to land heads up.

These examples are examples for which Newtonian physics is an excellent approximation. Here our uncertainty really stems only from our lack of control over the starting position of the coin. If we knew exactly how the coin lies on the index finger and how the thumb accelerates the coin we could predict the outcome of the coin toss*.

Quantum phenomena, however are different. For quantum phenomena the outcome is truly random, not due to a lack of our knowledge about the system. This was hard to swallow for many physicists, including Albert Einstein who complained: "*God does not play dice!*"

*There is an interesting connection to Chaos theory here, which we unfortunately don't cover in this class.

Schrödinger's equation

How do matter waves move? In 1926 the Austrian physicist Erwin Schrödinger developed the quantum analog to Newton's equations by using de Broglie's relation $\lambda = h/mv$ and a good bit of intuition to develop the **Schrödinger Equation**. This equation correctly describes the motion of the matter waver for electrons or any other material particle in a wide variety of situations.

Historically most important: understanding atoms!

This equation is a continuous equation for the matter field.

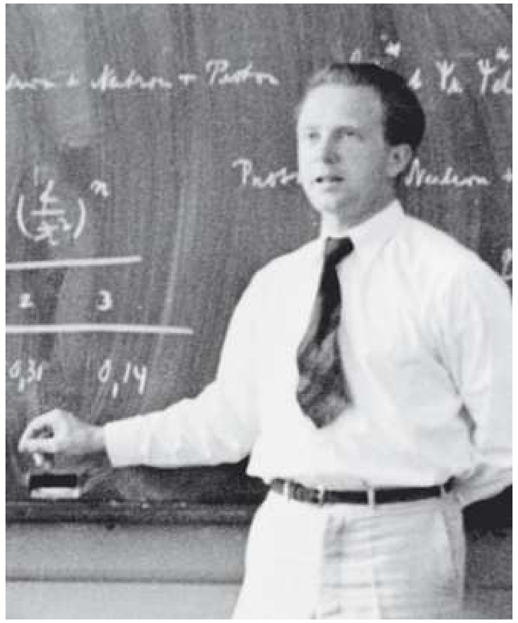
The uncertainty arises in the **measurement process**, when the wave function is suddenly supposed to collapse (as in when a photon is absorbed at a photo plate in the two-slit experiment).

The uncertainty principle

In the two slit experiment we noticed that there is an inherent uncertainty in quantum events. We saw that it was not possible to know where the impact of the electron was going to be. In 1927 the German physicist Werner Heisenberg found out that the uncertainty can be quantified!

The uncertainty principle quantified

He noticed that there are two pairs of measurable quantities and that knowing one precludes knowing the other. He noticed that if you know the position in the x-direction you cannot know the momentum in the x-direction and vice versa. He quantitatively determined:



The uncertainty principle

The position and velocity of every material particle are uncertain. Although either uncertainty can take on any value, its product can at best approximately equal Planck's constant divided by the particle's mass. In symbols,

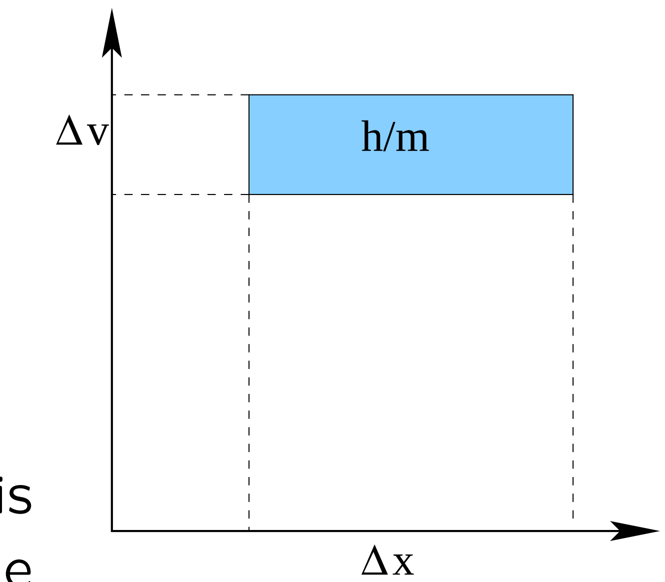
$$(\Delta x)\dot{(}\Delta v) \approx \frac{h}{m}$$

where h is Planck's constant and m is the particle's mass[a].

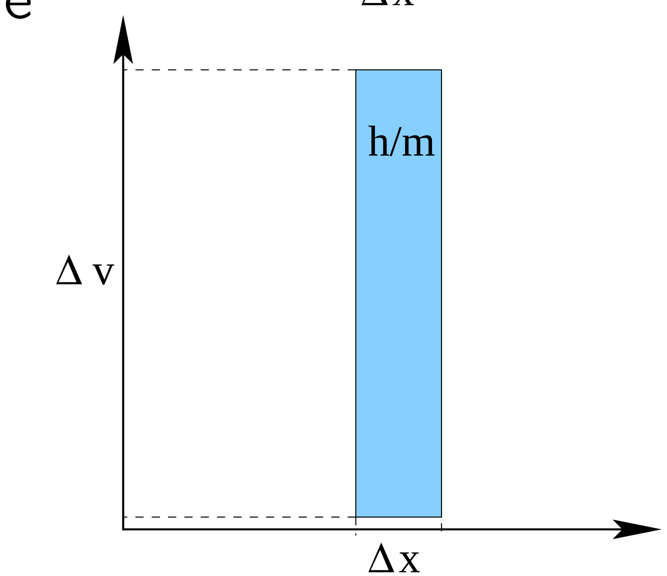
[a]More precisely: $\Delta x \Delta v \geq h/4\pi m$.

Examples

Let us look at some situations and see if we can see what this means.



Let us a assume that we know that the diameter is about $1\mathring{A} = 10^{-10}m$. What does this imply about the uncertainty in the velocity of the electron?



Solution

We see that $\Delta x = 10^{-10} m$.

$$\Delta x \; \Delta v > \frac{h}{m} \tag{1}$$

The mass of an electron is $m_e \approx 10^{-30} kg$.

$$\Delta v = \frac{h}{m \; \Delta v} = \frac{6.6 \; 10^{-34}}{10^{-30} 10^{-10}} = 6.6 \; 10^{6} m/s \tag{2}$$

so electrons inside an atom have to be very fast!

Do we need to take relativistic effects into account?

Solution 2

Relativistic effects all go with

$$\frac{v}{c} = \frac{6.6\ 10^6}{3\ 10^8} = 2.2\ 10^{-2}$$

So this is only about two hundredth of the speed of light and relativistic effects are not yet important.

Quantum entanglement: Spooky action at a distance

Quantum non-locality was the strange phenomenon that a field collapsed instantaneously when a macroscopic detection event occurred (like leaving a mark on a film, causing a detector signal etc.)

We have only discussed this in the case of a single particle, but these quantum states can be many particle states. Multiple quanta that are described by one field are called **entangled**. Such particles can move away from each other while they still form a *single two-particle wave packet*.

Now if one of the particles impacts a screen, or gets detected, *this immediately alters the second particle*, even if this second particle is by now lightyears away. The first experiment to show this was done in 1972 at a distance of 144 km.

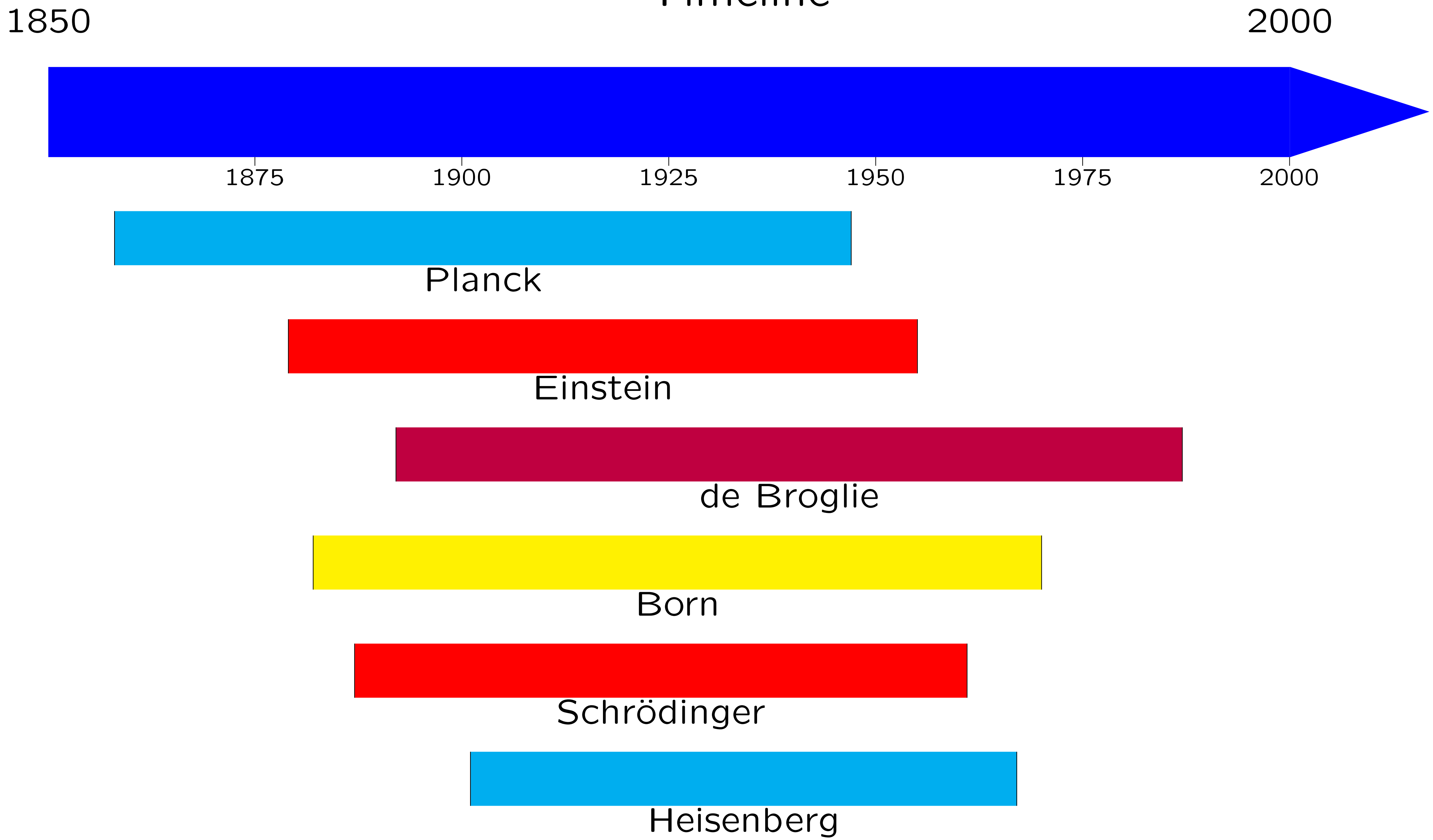
Is it really spooky?

You could imagine a simpler kind of classical correlation: If I put one silver and one gold coin in an envelope each and send one to Research two and the second one to South Engineering, you would not know which coin is where. But if you open the envelope in South Engineering and find the silver coin you suddenly know that the envelope in Research two contains a gold coin.

In 1964 John Bell analyzed the problem in detail and found that it was of a fundamentally different kind. In this analogy it is as if the coin in the envelope was not either a gold or a silver coin before you opened the envelope, it just turned into one as you looked.

This is related to what we learned about the uncertainty principle. You can measure a particles position, but that does not mean that it had a position before you did the measurement!

Timeline


1850
2000
1875
1900
1925
1950
1975
2000
Planck
Einstein
de Broglie
Born
Schrödinger
Heisenberg

Summary

- Photoelectric effect
- Schroedinger's equation
- Heisenberg's uncertainty relation
- Quantum entanglement