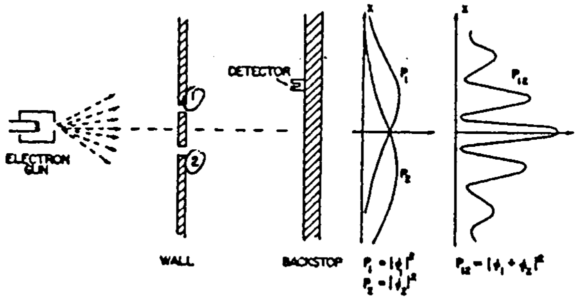
Experiments with electrons:



We chose a very weak electron source such that we register single, identical events in the detector, ie. we detect <u>single electrons</u>, similar to the particle experiment we discussed earlier.

Let's now measure the probabilities $P_1(x)$, $P_2(x)$ and $P_{12}(x)$

<u>Result</u>: $P_{12}(x)$ is <u>not</u> equal to the sum of $P_1(x)$ and $P_2(x)$!
We observe <u>interference!</u>

Let's analyze this result.
<u>Assumption</u>: since we register single events with the detector, let's assume that:
Each electron goes <u>either</u> through slits ① <u>or</u> through slit ②

If this is true, we can divide the registered electrons in two groups:

<u>Group 1:</u>electrons, which went through slit ①

<u>Group2:</u> electrons, which went through slit ②

Then our observed distribution would have to correspond to the <u>sum</u> of the individual effects.

However, this is in <u>contradiction</u> to our experience, since we observe interference.

This is somewhat mysterious, however the <u>mathematics</u> needed to get $P_{12}(x)$ from $P_1(x)$ and $P_2(x)$ is quite simple:
If we introduce the amplitudes ϕ_1 and ϕ_2, we get from experiment:

$$\underline{P_{12}(x) = |\phi_1(x) + \phi_2(x)|^2}$$

with
$$P_1(x) = |\phi_1(x)|^2$$
$$P_2(x) = |\phi_2(x)|^2$$

The electrons show particle-wave duality: we observe individual electrons (particle) but also interference (wave).

<u>Quantum Mechanical Point of View:</u>
Our assumption was, that an electron goes either through slit ① or ②. Quite a natural assumption in classical physics.

But apparently, this <u>assumption is wrong</u>!

It would require a precise knowledge of the <u>position</u> of the electron when going through the double slit apparatus! Quantum Mechanics does not allow this point of view and says, that the question or any statement about the position of a particle is only meaningful or allowed, if the experiment actually makes the measurement of the position! Even more, the measurement of the position of a particle will influence the experiment, and, under certain circumstances, change it drastically.

This means:

From a quantum mechanical point of view, the questions through which slit the electron went is meaningless since the experiment does not measure its position.

If we nevertheless make assumptions about the behavior of the electron at the two slits, we will get wrong results, as shown in the previous example, where we would not expect interference.

The solution of this problem is given by the

UNCERTAINTY PRINCIPLE
by Heisenberg (1927)

According to this principle, it is impossible to describe simultaneously and precisely the values of certain pairs of physical observables.

Examples are:

a) position and momentum (x p_x)

b) angle coordinate and angular momentum (ϕ L_z)

c) energy and time, at which energy is measured (E t)

We can describe the uncertainty principle in the following way:
The product of the uncertainties in the two variables has to be at least equal to h:

$$\Delta x \cdot \Delta p_x \geq h$$

and analogous for the other examples

The relation means that we cannot determine one component of the momentum precisely without sacrificing the accuracy of out knowledge of the corresponding position coordinate.

Bohr formulated in 1928 his so-called

which says	Complementary Principle Phenomena in micro-physics cannot be described with the same perfection as we expect it from classical dynamics

From an experimental point of view we can say that it is impossible to make more precise measurements as dictated by the uncertainty principle.

This is a law of nature!

If one tries to determine one variable of such a pair more and more precisely, one will influence, or change, the other variable in such a way that one can calculate the change only approximately.

This is a fundamental difference to the classical Situation:

There we also disturb a system with the measurement, however this disturbance can be computed and taken into account precisely.