Gedanken and real experiments in modern physics

Jan Mostowski[1]

[1] *Institute of Physics*
Aleja Lotników 32/46
02-668 Warszawa, Poland

Abstract

In this talk I will give a short and concise description of some gedanken (thought) experiments and their role in modern physics. I will concentrate on these experiments that played a role in the development of modern physics and were later performed as real experiments. I will discuss the role of these experiments in teaching of modern physics.

1. Introduction

The term "modern physics" applies to the physics of 20th and 21st century. In this sense it is not really modern, a large part of it is over 100 years old. Also the standard understanding of the term "modern physics" applies to the theory of relativity, quantum physics, nuclear and particle physics, rather than to other areas of physics. All these modern branches of physics are based on experiments. There would have been no theory if it was not supported by a series of experiments. In the beginning of the 20th century, when the modern physics begun, experiments were rather crude and not precise. Nevertheless, on the basis of these experiments some most fundamental physics theories were built. I have in mind the theory of relativity and quantum mechanics.

In this talk I will not discuss relativity theory and the role of gedanken experiments there. This subject is well covered by many books. I will restrict myself to the quantum theory.

The quantum theory, formulated in the first 25 years of the 20th century was based on a couple of experimental findings. Let me mention the most important ones: the spectrum of the black body radiation does not follow the classical laws of thermodynamics, the photoelectric effect that contradicts the classical electrodynamics, atomic spectra that cannot be explained by classical electrodynamics. The founders of quantum physics used these experimental findings to formulate an adequate i.e. quantum theory. Quite often they added gedanken experiments to their reasoning to make the quantum physics look more natural.

Many years later, perhaps some 30 years ago it turned out that the gedanken experiments formulated in early years of quantum theory are within the reach of the existing experimental possibilities. In fact many of the gedanken experiments reported in textbooks on quantum mechanics are no longer gedanken, they are real experiments and can be used in classroom when discussing quantum physics.

Modern physics is usually difficult to teach. Such things as atoms, electrons, photons are not present in everyday life, it is therefore not easy to persuade students to be interested in their behaviour. Gedanken experiments, very helpful in professional research, do not help much to encourage the students to get interested in this subject. Real experiments, on the other hand, can. This is most evident in the case of counterintuitive results, when the results contradict the predictions based on the everyday life experience. I think that it is time to discuss real experiments in classrooms rather than to speak about gedanken experiments. Of course the experimental details are rather difficult to show and discuss. However the results are as easy to present as the results of the gedanken experiments.

In what follows I will present several gedanken experiments that were made real in recent years.

2. Diffraction and interference of matter waves

Diffraction and interference are often demonstrated in the double slit configuration. The double-slit experiment is well known in the case of light waves. It was used also as a gedanken experiment in the case of matter waves because it clearly shows the effect of quantum physics and the fundamental limitation of the ability to predict experimental results.

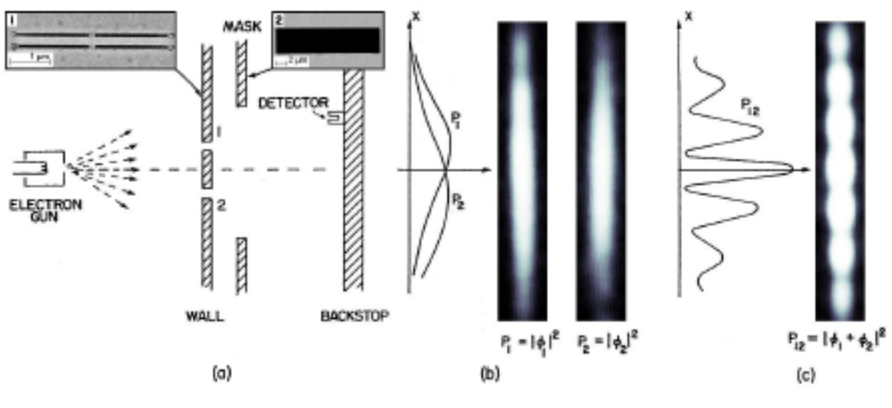

Fig. 1. The double slit experiment (from Ref. 2).

I will briefly discuss the interference of matter waves in the case of a double-slit experiment. Such experiments are very nicely explained in ref. 1. I present here a simplified experimental setup for such an experiment for electron diffraction, as used in Ref. 2 (see Fig. 1a). An electron beam is sent towards a wall with two slits in it. A mask can block electrons allowing the ones traversing through slit 1 (P_1), slit 2 (P_2), or both (P_{12}) to reach detector. Figure 1 b,c shows probability distributions for electrons that pass through a single slit (b), or both slits. (c). It should be noticed that the probability distribution for electrons passing through both slits is not a sum of the probabilities passing through individual slits. This is one of the most remarkable effects of quantum physics, matter (electrons in this case) does not behave like classical balls but rather as waves that interfere.

The probabilistic interpretation of electron positions can be seen in fig. 2. When the electron beam has very low intensity, as in fig. 2a the position of the electron detection is totally unpredictable. Predictions of electron position detection can only be made in case of a large number of electrons. In fact in the latter case of many electrons (fig. 2b) the positions of electron detection form an interference pattern.

These predictions were nicely demonstrated in a paper titled "Controlled double-slit electron diffraction", by Roger Bach, Damian Pope, Sy-Hwang Liou, and Herman Batelaan (see fig. 2).

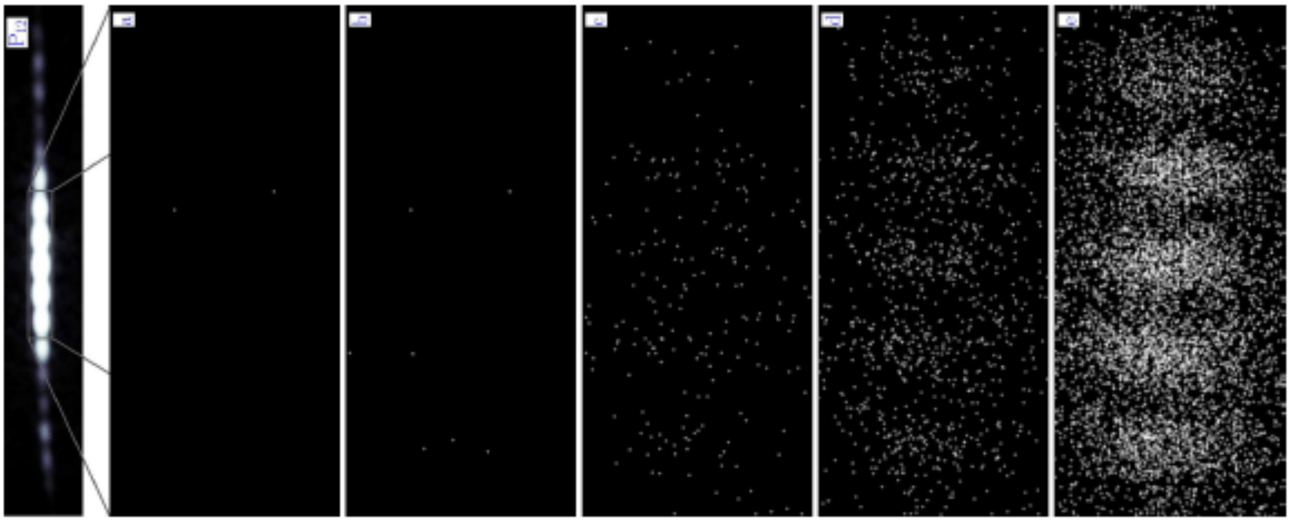

Fig. 2. Electron micrographs of the double slit and mask are shown. The individual slits are 50 nm wide x 4 mm tall with a 150 nm support structure midway along it's height, and separated by 280 nm. The mask is 5 mm wide x 20 mm tall. (from ref. 2)

3. Which way?

The second case of a gedanken/real experiment is to determine „which way" an electron (or other particle) has gone. These questions were discussed in great detail some 30 years ago in the case of atoms and photons. The main problem is illustrated in fig. 3. A particle (e.g. an atom) emitted from the source S can reach the screen (a set of detectors like a photographic plate) taking one of two ways: through cavity C_1 or cavity C_2. This is just a variation of the two slit experiment discussed before, the particle distribution on the screen D exhibits an interference pattern. But, because of the cavities, there is possibility of determining which way the atom has gone. The atom can absorb a laser photon before entering a cavity and deposit it on its way in

C_1 or C_2. Detection of a photon in the C_1 cavity proves that the atom took the way through this cavity, not through C_2. This information should destroy the interference patter.

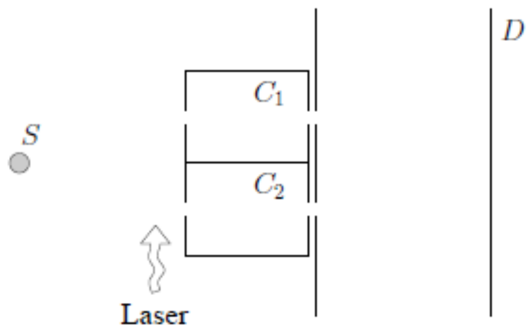

Fig. 3. Schematic representation of a which way experiment

Such experiments were performed for the first time in the ’90, I will quote here the pioneering work of Dürr et al. (S.Dürr, T.Noon, and G.Rempe, Origin of quantum-mechanical complementarity probed by a ‘which-way’ experiment in an atom interferometer”, Nature 1998). This experiment is illustrated in fig. 4.

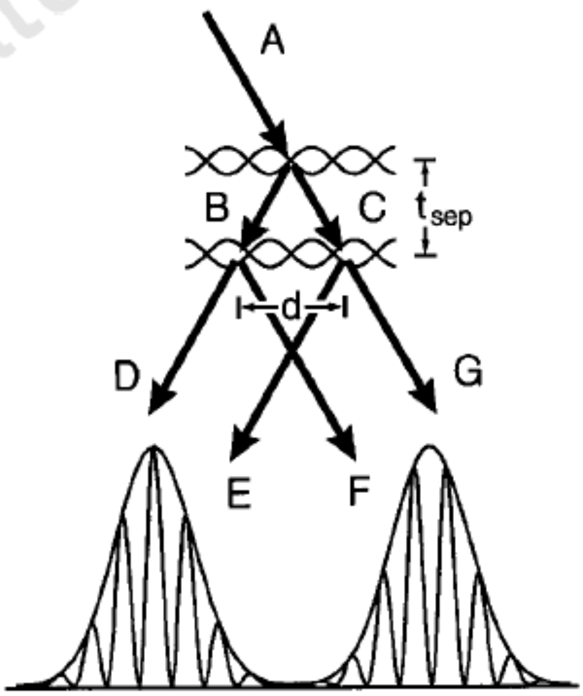

Fig. 4. Idea of a which way experiment (ref. 3)

In this case atoms were used as quantum particles. The idea is to use the internal degrees of freedom (electronic levels) to influence the atom motion. In the experiment the incoming atomic beam A is split into two beams: beam C is transmitted and beam B is Bragg-reflected from a standing light wave. The beams are not exactly vertical, because a Brag condition must be fulfilled. After free propagation for a time

t_{sep} the beams are displaced by a distance *d*. Then the beams are split again with a second standing light wave. In the far field, a spatial interference pattern is observed. The results are shown in figs. 5 and 6.

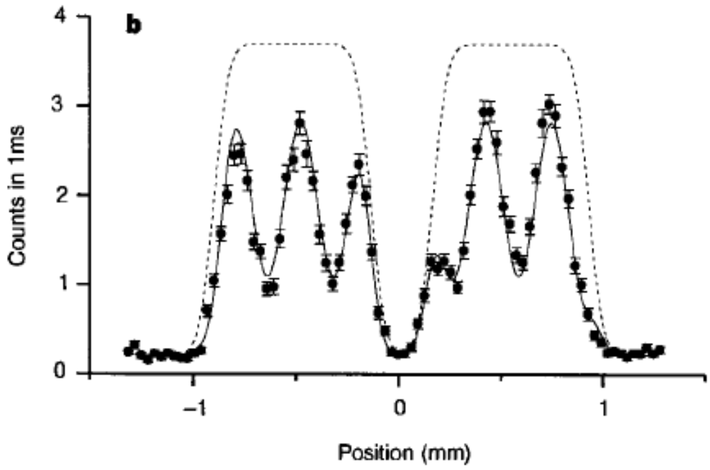

Fig. 5 Spatial fringe pattern in the far field of the interferometer.

In fig. 5 the dashed lines represent the independently measured beam envelope, which consists of two broad peaks. The right peak is due to beams F and G (fig. 4), with a shape determined by the momentum distribution of the initial beam A. The left peak is a combination of beams D and E. Interference between the two beams is clearly seen.

Interference is seen only when there is no way to determine the trajectory. One may say that the interference takes place between the possible trajectories rather than between particles.

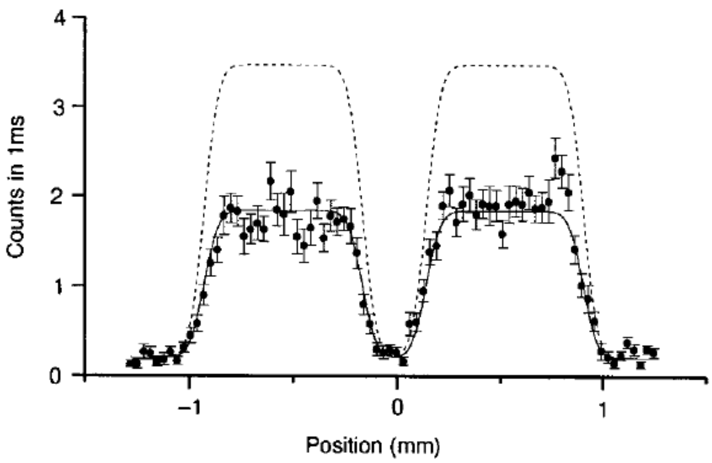

Fig. 6. Interference is lost!

Fig. 6 shows the result of a different experiment. Atoms passing through the cavities can be in one of the two internal state, due to possible absorption of a laser photon. The atom internal state is determined by the interaction of the atom with the laser beam and cavities. The atomic state depends upon the cavity, atoms that passed through cavity C_1 are in a different state from atoms that passed through cavity C_2.Thus the state of the atom depends upon the path it took. Interference is lost in this case. Which way information is stored in the internal atomic state. The interference fringes are lost due to the storage of the which way information.

I should add that there were more experiments on the which way problem, not only with atoms as quantum particles but also with photons. The conclusion of these experiments is that the interference pattern is lost whenever the information of the particle trajectory is available.

4. Schrödinger's cat

The Schrödinger cat is one of the best known paradoxes in quantum physics. A paradoxical situation occurs if one considers a particle in a quantum superposition of two states. If the particle is macroscopic (e.g. a cat) and the states of the particle are properly chosen (cat alive and cat dead) one reaches a situation that the cat can be in a superposition of being alive and dead.

There are at least two things that should be said here. The first one pertains to the application of quantum laws to a classical macroscopic object. Can a macroscopic particle, like a cat, be described by a wavefunction? The obvious answer is that there is no wavefunction of a cat, such big objects should be described by classical physics. But a more serious question is about the limits of quantum physics applicability. For sure cat is a classical object and electron is a quantum object. But where is the border line? Are large molecules, like proteins, more quantum or more classical? We are not going to explore this question here. We will concentrate on states of microscopic (quantum) objects that are in a non-trivial superposition of states.

The term Schrödinger's cat used in recent research papers refers to states of quantum systems that are superpositions of two states that differ in positions or momenta. Thus the two states are "very different", in other words a particle the "cat state" is simultaneously in two regions of space. There is large probability of finding the particle around one or another point in space but zero, or almost zero, probability of finding this particle between the two points.

It is possible to prepare a quantum particle in such a state. A very elegant experiment on "cat states" was performed by Monroe et.al, ref 4. The particle studied was beryllium ion.

Ion traps capable of trapping a single ion were developed in the late '70. They consists of electrodes providing static and oscillating electromagnetic field. In addition a laser beam, resonant with the electronic transition illuminates the ion. The electrodes are placed in a vacuum chamber, ions are created in the space between electrodes by ionization of atoms from an atomic beam. Under special conditions one can trap exactly one, two or mode ions. A laser beam or beams can be used to manipulate the motional state of the ion. In particular one can slow down its motion so that it remains in the ground state, the quantum equivalent of "no motion at all".

In fig. 7 we show a picture of two ions illuminated by laser light, in an ion trap. The separation is larger than the laser wavelength, so in a microscope the two ions can be seen as two objects. Colours are artificial, there is a little puzzle, what is the actual colour of the ions?

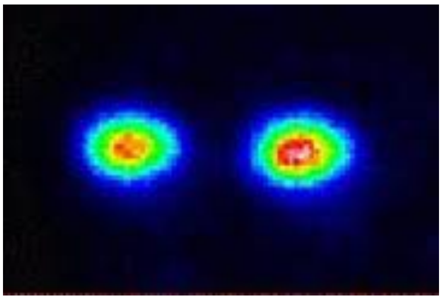

Fig. 7. Two trapped ions.

Ion can be then excited by illuminating them with a series of laser pulses to a state shown in fig. 8. The ion is then in a superposition of being in the left hand side of the trap and right hand side of the trap. Thus it is a superposition of two states (being in the left and being at the right), probability of finding the ion in the centre of the trap is zero.

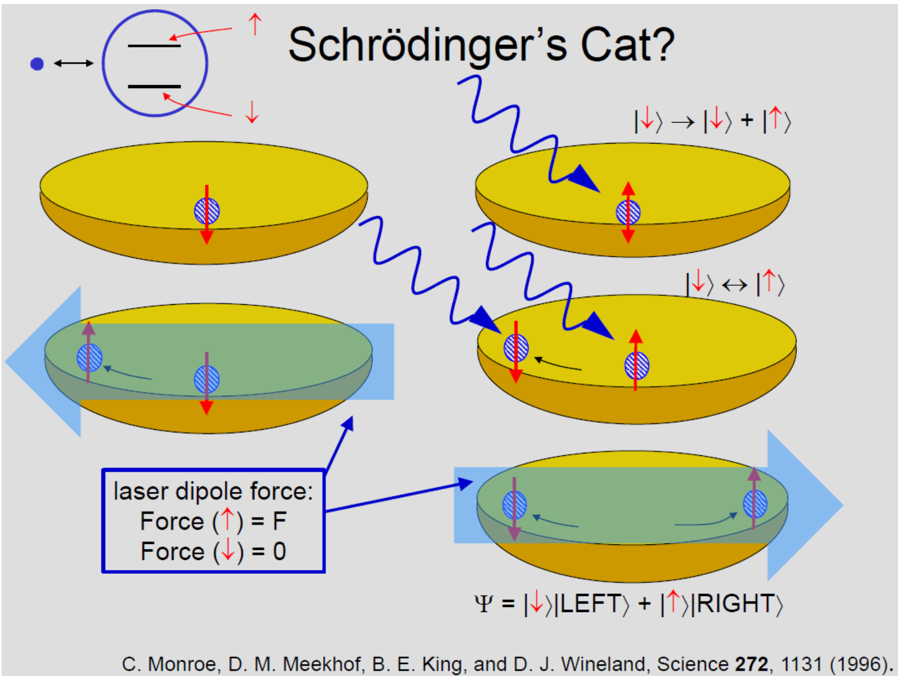

Fig. 8 Experimental realization of a cat state

One more thing has to be said. Namely one has to have a way of measuring the state the ion is. Such measuring scheme has been developed, it is called quantum tomography. The technique allows to measure not only the ion position but the whole wavefunction. We will not go into details of this technique, it suffices o say that it is based on the same principles as the tomography used in medicine.

5. EPR paradox

One of the paradoxical quantum gedanken experiments was formulated by A. Einstein, B. Podolsky and N. Rosen, ref. 5 and is known as the EPR paradox. It was used by Einstein as an argument proving that quantum physics is an incomplete theory. Modern version of this paradox was formulated by J. Bell ref. 6, the first experimental verification of the EPR effect was given by A. Aspect (ref. 7). There are numerous recent research, as well as review and popular articles on the subject.

In a recent version the EPR effect is formulated for spin one half particles (see fig. 9). A source emits two spin ½ particles in opposite directions. The spins are such that one of them points up and the other one points down, but it is not known which spin is up and which is down. Of course the “up” or “down” direction has no real meaning, both observers can choose to project the spin onto any directions. It is certain that whenever one of the spins is up with respect to an axis, the other spin must be down with respect to the same axis. The spins are measured by two observers, called Alice and Bob, separated by a large distance. If Alice measures that her particle has value +1/2 (up), she is sure that Bob will find that the spin of his particle is -1/2 (down). This is nothing else but a classical correlation and has nothing to do with quantum mechanics. The point is that Bob can choose to measure the spin component along some other axis, different by angle *a* from the one chosen by Alice. Suppose that Alice has measured that her spin has a value ½ along some axis (up). This information is unavailable to Bob since he is separated from Alice by a large distance. Does Alice’s measurement result influence the Bob result? In order to answer this question we should define the meaning of the word “influence”. This is defined through correlations. Suppose that Bob’s axis is rotated by an angle *a* from Alice’s axis. Joined probability that Alice finds her spin “up” and Bob finds his spin “up” (relative to his axis) is the measure of “influence”. Quantum mechanics predicts that this correlation should be equal to $-\cos^2 a$. Thus if $a=0$ there is perfect anti-correlation, no two parallel spins to be detected. If $a=180^0$, both measurements are perfectly correlated. If $a=90^0$ the measurements are not correlated. If, however, the axis form some other angle the measurements exhibits some non-trivial correlations.

The existence of such correlation worried Einstein, it seemed to him that information about the outcome of Alice’s measurement must be somehow transferred to Bob’s particle, otherwise he could not explain the correlations. These arguments were put into a theorem by J. Bell. He proved that the correlation predicted by quantum mechanics cannot be explained in the framework of any classical local probability theory.

Experiments on the correlations were performed for the first time by A. Apect in the ’80 (ref. 7) and later repeated in various version by many other groups. All these experiment proved that the EPR correlations exist in nature, as predicted by quantum mechanics, and cannot be explained by any probabilistic local classical theory. A whole class of theories alternative to the standard quantum mechanics was eliminated.

6. Conclusions

I have reviewed some of well - known experiments in quantum physics. They were first gedanken experiments, but played a big role in the development of quantum physics. The real experiments, inspired by their gedanken ones, provide a strong verification of quantum mechanics.

Elementary expositions of quantum physics should in my opinion include at least some of these new results. The real experiments are conceptually not harder than the gedanken experiments. From the pedagogical point of view it is much better to show the students real experiments than to talk about the gedanken ones. Modern physics should be easier to understand if it is presented from the experimental point of view (if we measure this we get that, and this is one). As teachers we should bear in mind that quantum physics will remain a counterintuitive part of science.

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