Quantum Matter and Space

INSPYRE 2017
"The Space Frontier"

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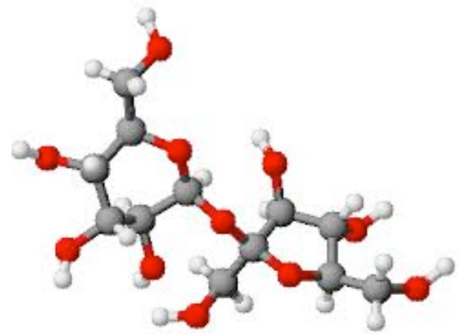
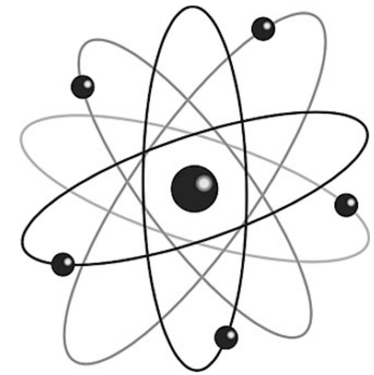
Quantum Mechanics

It is the theory we use to describe **atoms**, **molecules** and their **interactions**



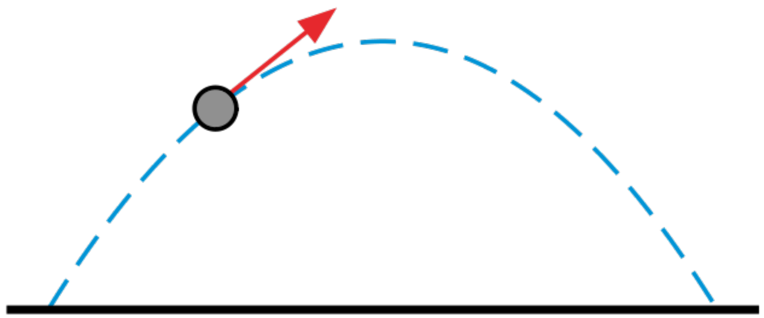


It mainly refers to microscopic systems, while **macroscopic objects** are typically described by **classical mechanics**

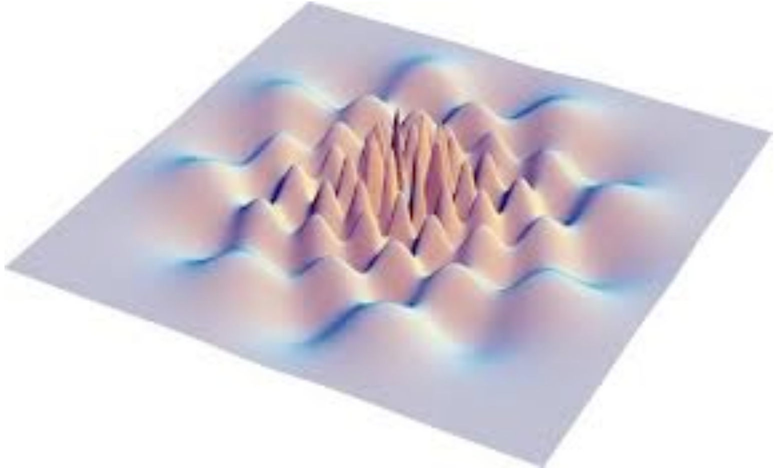
However **macroscopic objects are made of atoms**, which are quantum, therefore they should also be describable by quantum mechanics. And here the problems start…

The structure of the theory

Classical Mechanics: points, which move in space according to Newton's laws.



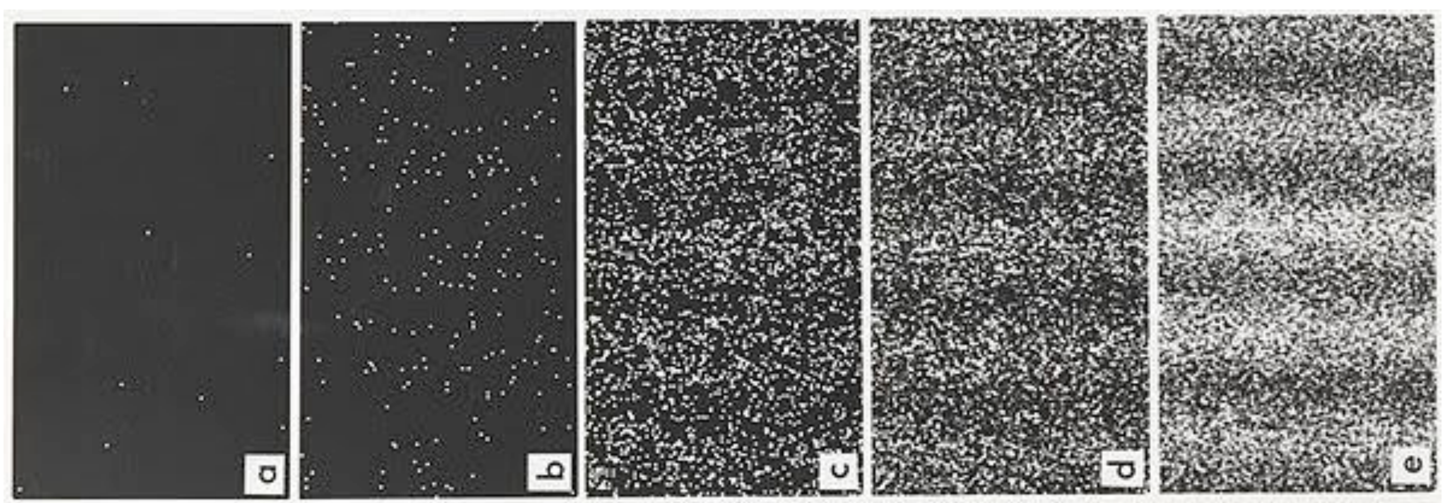
Quantum Mechanics: systems are described by a wave function, which moves – not in space - according to the Schrödinger's equation



First comment

Why do we need a wave function? Why can't we keep using points, as we do in classical mechanics?

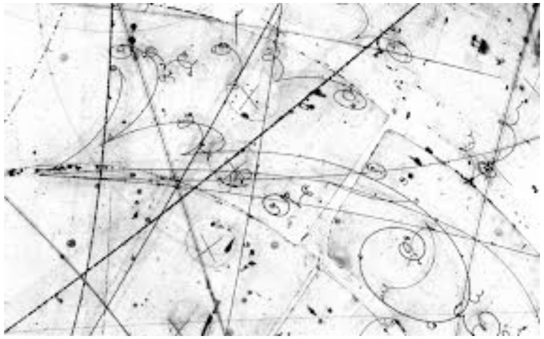
Answer: with purely point-like objects it is difficult to justify interference phenomena (see Newton vs Huygens)

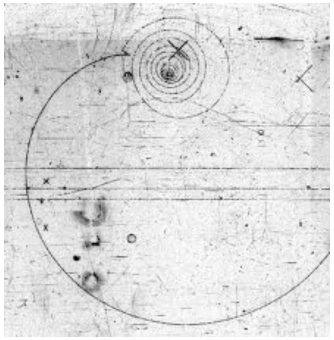


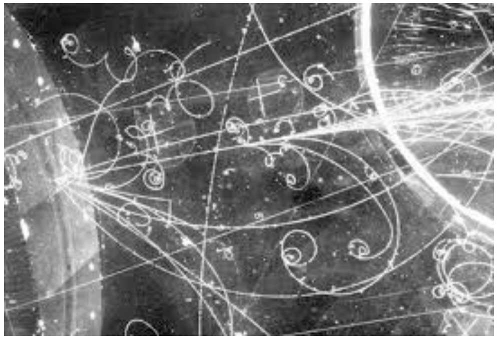
Second comment

What does the wave function represent? It does not represent the system; rather it represent (through the square modulus) the probability of finding the systems in a point in space if we perform a position measurement.

Reason: It is not possible to break a system in two parts, as it is usually doable with waves. Particles are always localized in space, when observed.







Third comment

Quantum superposition

$$\psi(x) = \frac{1}{\sqrt{2}}\left[\psi_{\mathrm{LEFT}}(x) + \psi_{\mathrm{RIGHT}}(x)\right]$$

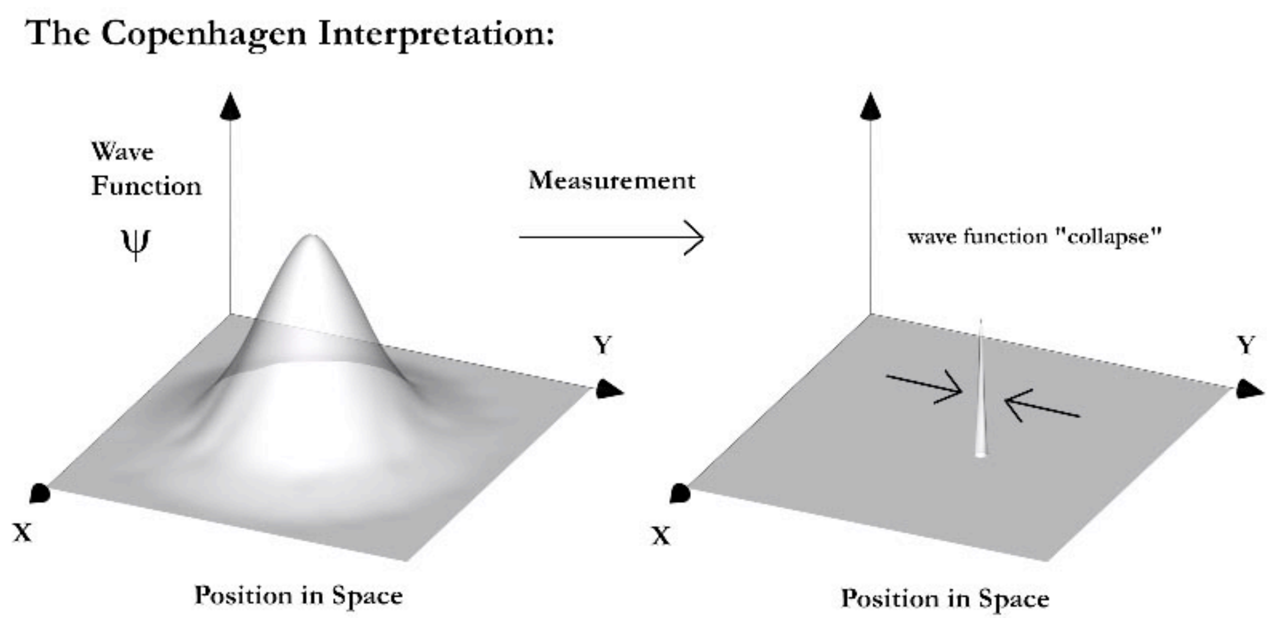
The particle can be found with probability ½ on the left, and with probability ½ on the right, if we measure its position.

Can we say that the particle was somewhere before the measurement? If we say so, then we are admitting that there is more information that that contained in the wave function, which does not tell us where the particle is, but only the probability of finding the particle somewhere. This means that the theory is **incomplete**. The **standard interpretation** does not accept the incompleteness of the theory, hence we have to admit that there is no fact about the position of the particle previous to the measurement.

Fourth comment

What happens after a measurement? The wave function collapses around the position where the particle has been found

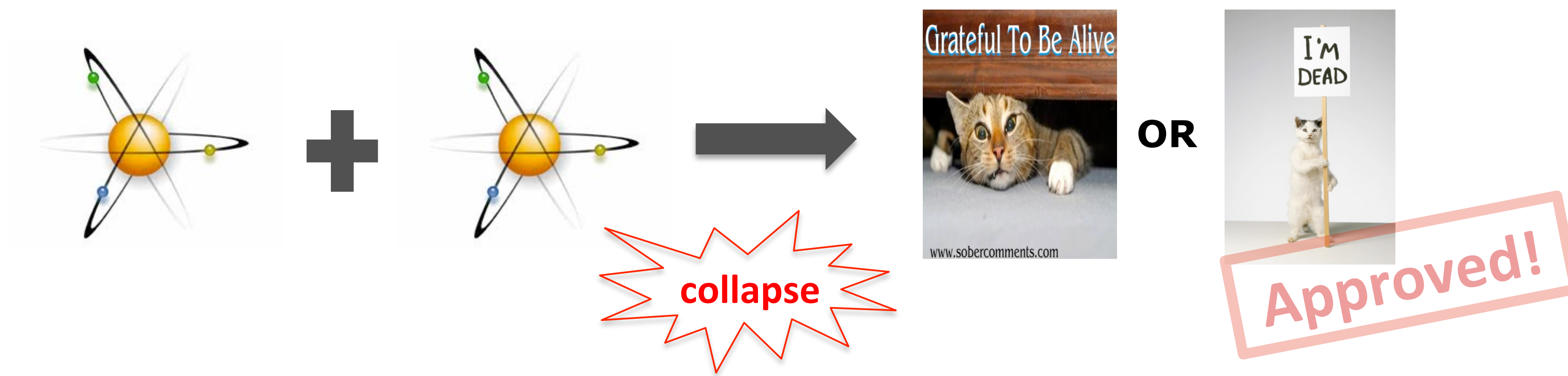
Motivation: If the wave function did not collapse, then if I repeat the same measurement immediately after the first one, there would be a non-null probability to find the particle elsewhere, which does not happen.



Collapse of the wave function

The Schrödinger equation is linear ➔ superposition principle ➔ Schrödinger's cat

Textbook solution: collapse of the wave function at the end of each measurement



Quantum Mechanics

1. Each physical system is described by a wave function $\psi(x)$

2. The wave function evolves according to Schrödinger's equation

3. $|\psi(x)|^2$ gives the probability (density) of finding the system at x, if we perform a position measurement

4. At the of the measurement, the wave function collapses around the region where the system has been found

Problem

Let us consider rules 2 and 4

2. The wave function evolves according to Schrödinger's equation

4. At the of the measurement, the wave function collapses around the region where the system has been found

They imply two completely different evolutions for the wave function. One when no measurement is performed (Schrödinger) and one when measurements are performed (collapse)

Problem: When does each one precisely apply? What is a measurement?

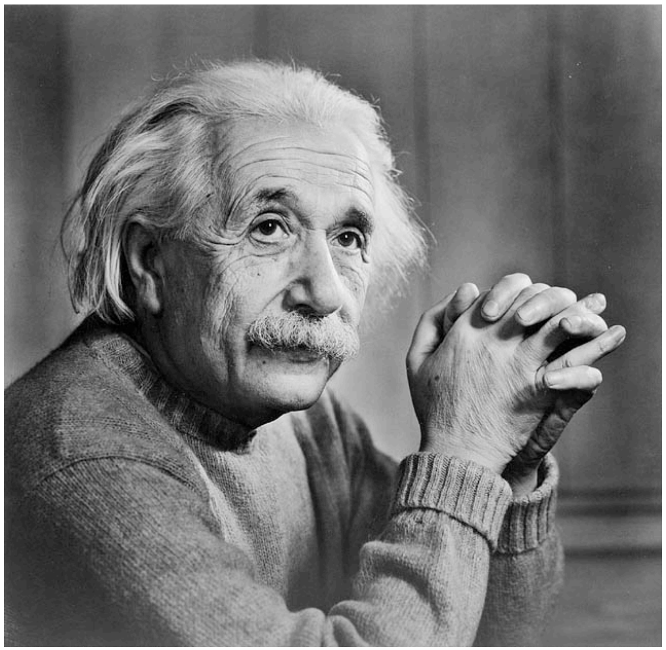
It would seem that the theory is exclusively concerned about ‘results of measurements’, and has nothing to say about anything else. **What exactly qualifies some physical systems to play the role of ‘measurer’?** Was the wave function of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system … with a Ph.D.?

J.S. Bell: “Against Measurement”, Physics Today – August issue, p. 33 (1990)

The Copenhagen interpretation assumes a **mysterious division** between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics. During measurement the state vector of the microscopic system collapses in a probabilistic way to one of a number of classical states, in a way that is unexplained, and cannot be described by the time-dependent Schrödinger equation […]

S. Weinberg, Phys. Rev. A 85, 062116 (2012)

The theory is incomplete



In, P. A. Schilpp, ed., *Albert Einstein-Philosopher Scientist*. 2nd ed. New York: Tudor Publishing, 1951

Within the framework of statistical quantum theory there is no such thing as a **complete description** of the individual system. More cautiously it might be put as follows: The attempt to conceive the quantum-theoretical description as the complete description of the individual systems leads to unnatural theoretical interpretations, which become immediately unnecessary if **one accepts the interpretation that the description refers to ensembles of systems and not to individual systems...**

Bohmian Mechanics

1927: Louis de Broglie

1952: David Bohm

Present: Dürr, Goldstein, Zanghì (and others)

Particles always have definite positions, and move along well defined trajectories.

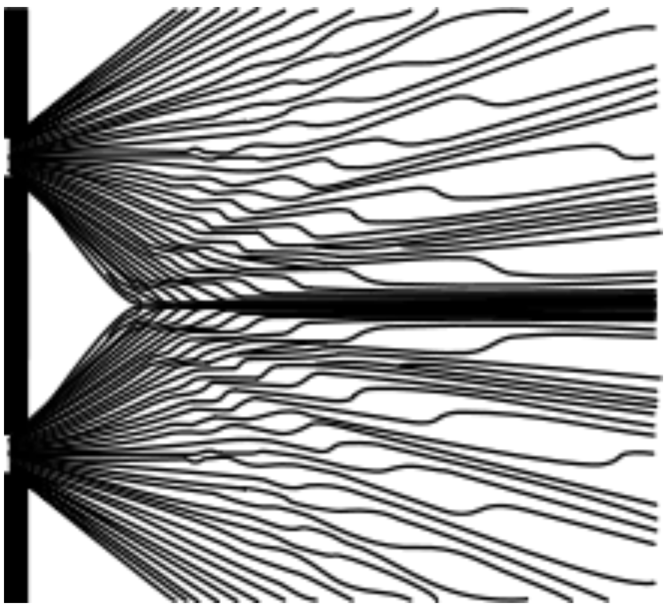
$$i\hbar \frac{d\psi(q,t)}{dt} = H\psi(q,t)$$

Schrödinger equation for the wave function. It guides te motion of particles

$$m_k \frac{dq_t^k}{dt} = \hbar \nabla_k \mathrm{Im} \ln \psi(q,t)$$

Guiding equation for the trajectories

Bohmian Mechanics



A very "natural" explanation of the double slit experiment. Particles – like all particles – move along definite trajectories and pass through one slit. Trajectories are such that the interference pattern is reproduced.

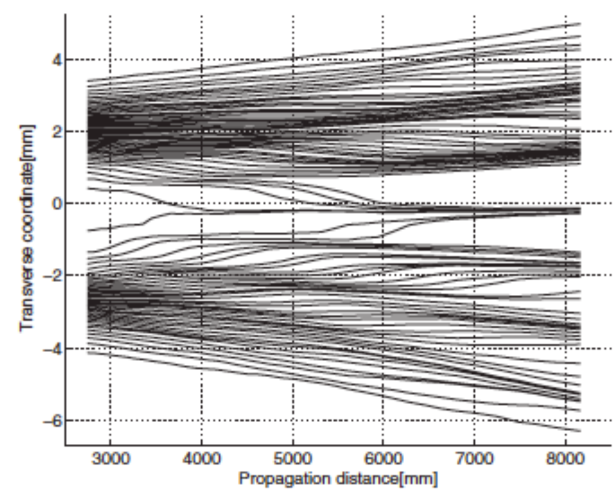


Fig. 3. The reconstructed average trajectories of an ensemble of single photons in the double-slit apparatus. The trajectories are reconstructed over the range 2.75 ± 0.05 to 8.2 ± 0.1 m by using the momentum data (black points in Fig. 2) from 41 imaging planes. Here, 80 trajectories are shown. To reconstruct a set of trajectories, we determined the weak momentum values for the transverse *x* positions at the initial plane. On the basis of this initial position and momentum information, the *x* position on the subsequent imaging plane that each trajectory lands is calculated, and the measured weak momentum value k_x at this point found. This process is repeated until the final imaging plane is reached and the trajectories are traced out. If a trajectory lands on a point that is not the center of a pixel, then a cubic spline interpolation between neighboring momentum values is used.

S. Kocsis e*t al*, Science **332**, 1170 (2011)

The theory is complete - Many Worlds

1957: Hugh Everett

1960s: Bruce DeWitt

All possible alternative histories represented by the different components of the wave function ("dead cat" and "alive cat", for example) are real, each representing an actual "world" (or "universe")

Criticism: "In such a deterministic theory it is hard to see how probabilities can arise. Also, the branching of the world into vast numbers of histories is disturbing, to say the least".

(S. Weinberg, Phys. Rev. A 85, 062116 (2012))

Modify the Schrödinger equation

What then must be done about the shortcomings of quantum mechanics? One reasonable response is contained in the legendary advice to inquiring students: “Shut up and calculate!” There is no argument about how to use quantum mechanics, only how to describe what it means, so perhaps the problem is merely one of words.
On the other hand, the problems of understanding measurement in the present form of quantum mechanics may be warning us that the theory needs modifications

Modify the Schrödinger equation

J.S.Bell
Speakable and Unspeakable in Quantum Mechanics

E.P. Wigner
in: Quantum Optics, Experimental gravity and Measurement theory, Plenum, NY (1983)

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Supplement Progr. Theor. Phys. 69, 80 (1980)

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In: Quantum Implications: Essay in Honor of David Bohm, Routledge & Kegan Paul, London (1987)

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Phys. Rev. Lett. 62, 486 (1989).

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In: Quantum Concepts of Space and Time, Oxford U.P. (1985)

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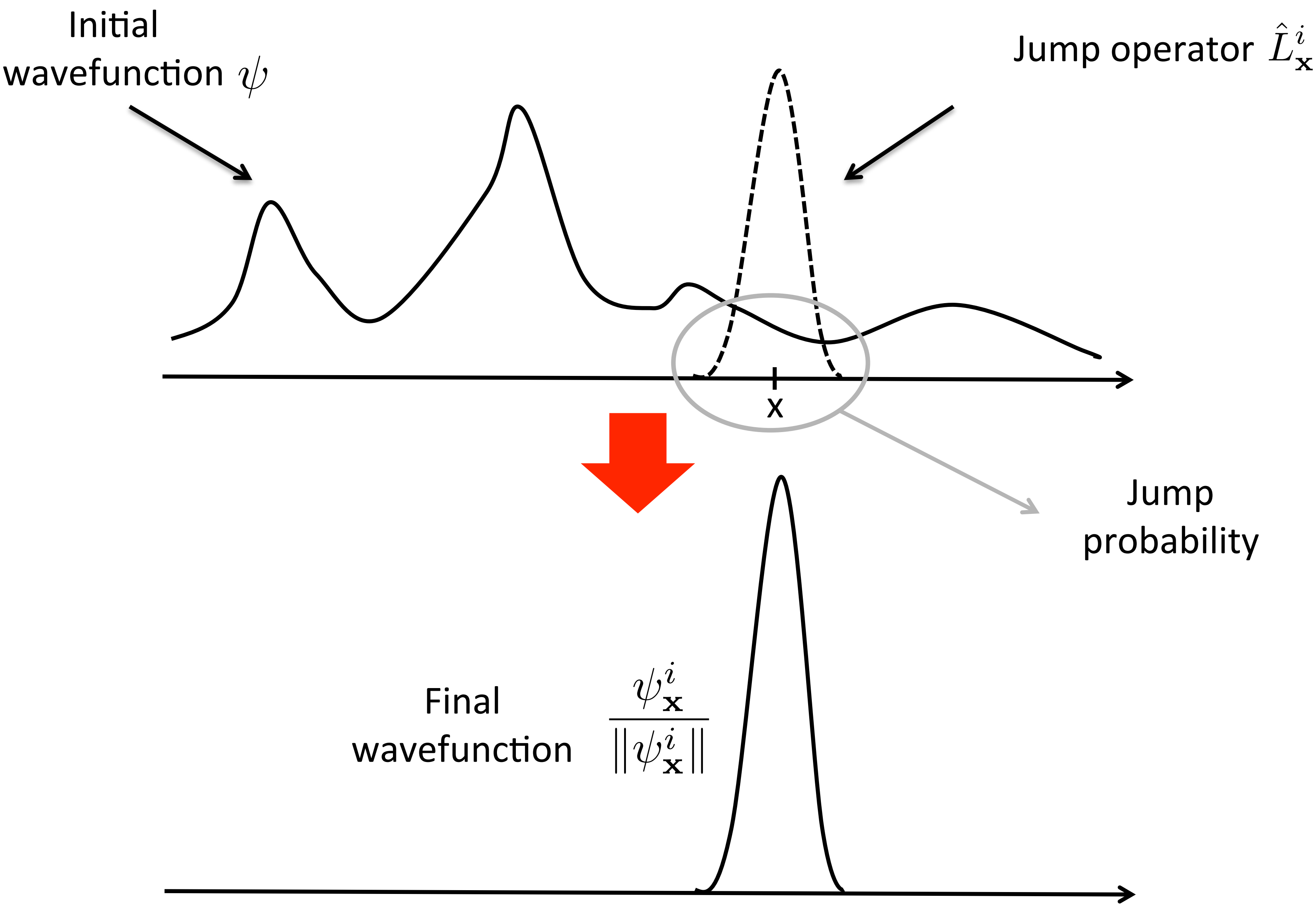
Phys. Rev. D 34, 470 (1986)

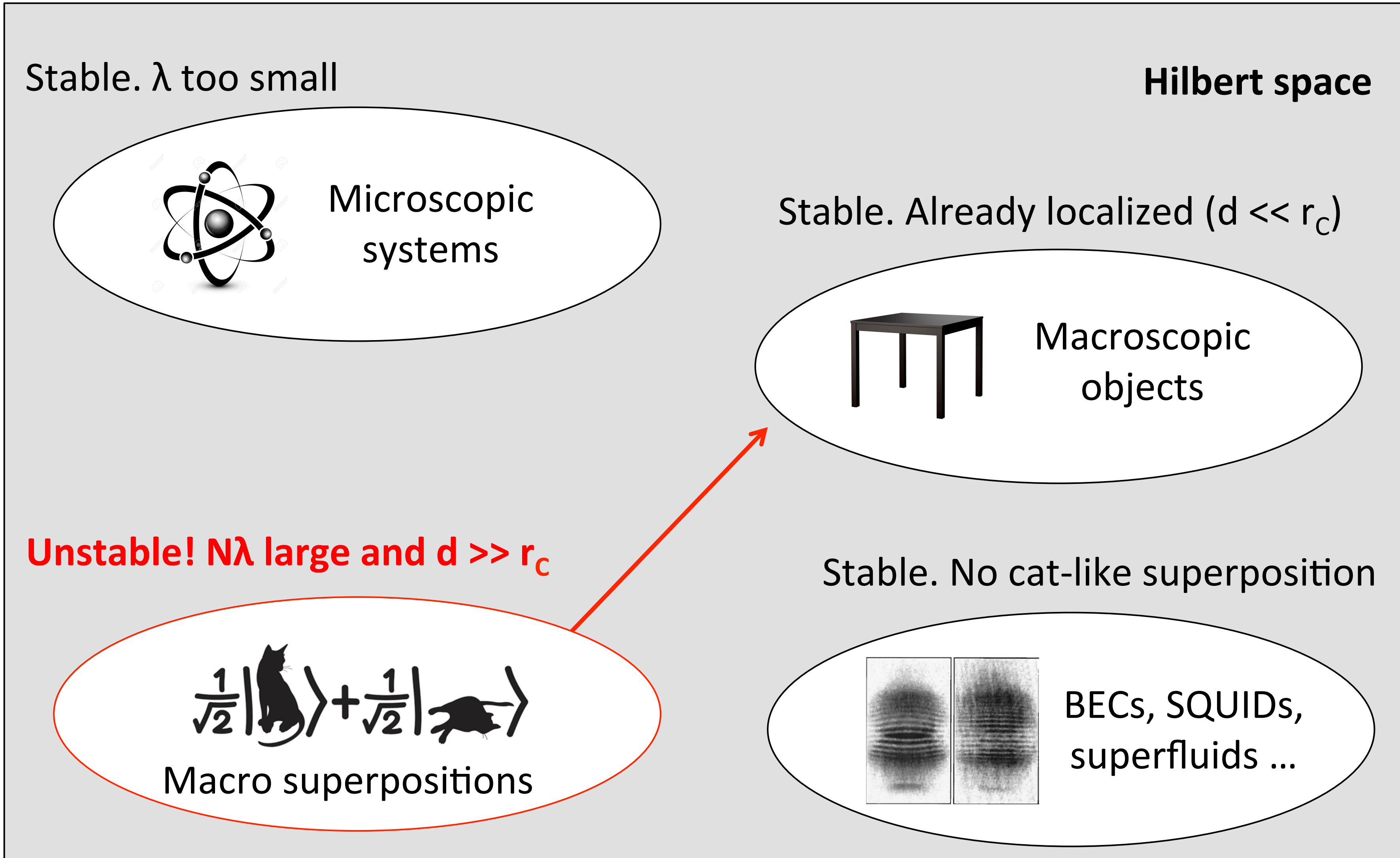
P. Pearle
Phys. Rev. A 39, 2277 (1989)

L. Diosi
L. Diosi, *Phys. Rev. A* 40, 1165 (1989)

Spontaneous collapse models



The overall picture of collapse models



What is matter?

- **Bohmian Mechanics:** It is made of particles moving in space. Somehow like classical particles.

- **Many Worlds:** An abstract entity in Hilbert space. One has to justify our 3D experience of Nature

- **Collapse models:** A mass distribution evolving in space. Somehow like a jelly

Conclusion: there is no consensus so far on what matter really is

Entanglement

$$\psi(x,y) = \frac{1}{\sqrt{2}}\left[\psi^{(1)}_{\text{LEFT}}(x)\psi^{(2)}_{\text{RIGHT}}(y) + \psi^{(1)}_{\text{RIGHT}}(x)\psi^{(2)}_{\text{LEFT}}(y)\right]$$

1. With probability ½ particle 1 will be found on the left, and with probability ½ it will be found on the right, upon a position measurement. Same thing for particle 2.

2. Suppose we measure the position of particle 1 and we find it on the left. Then, because of the collapse, the wave function changes into

$$\psi_{\text{COLL}}(x,y) = \psi^{(1)}_{\text{LEFT}}(x)\psi^{(2)}_{\text{RIGHT}}(y)$$

If now I measure the position of particle 2, I will certainly find it on the right.

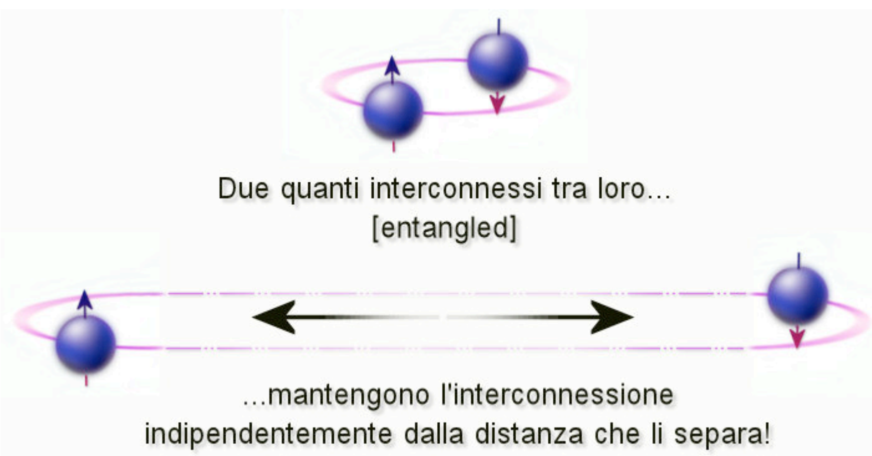
There is a perfect correlation between the position of the two particles.

Entanglement

$$\psi(x,y) = \frac{1}{\sqrt{2}}\left[\psi^{(1)}_{\mathrm{LEFT}}(x)\psi^{(2)}_{\mathrm{RIGHT}}(y) + \psi^{(1)}_{\mathrm{RIGHT}}(x)\psi^{(2)}_{\mathrm{LEFT}}(y)\right]$$

Before the measurement, none of the two particles has a definite position in space.

If the position of one of the two particle is determined upon measurement, then also the position of the other particle is automatically determined, independently from their mutual distance.



Entanglement: quantum systems correlated at a distance. Not interacting. The correlation is independent of the distance. Nonlocal element.

Bell inequalities

Bell was extremely impressed by Bohm's theory: among the other things, it contradicted the von Neumann impossibility theorem for hidden variable theories.

Bell Spent two sabbatical years in the US.

There, he **first** proved that von Neumann's theorem is irrelevant.

Secondly, he discovered that Bohm's theory is fundamentally non local. He then tried, without any success, to work out a similar – but local – theory. He did not succeed.

At that point, he entertained the idea that **perhaps one could prove that it is impossible to work out a local hidden variable theory compatible with Quantum Mechanics**. So he came up with his famous inequalities.

A music-hall interlude

The performance:

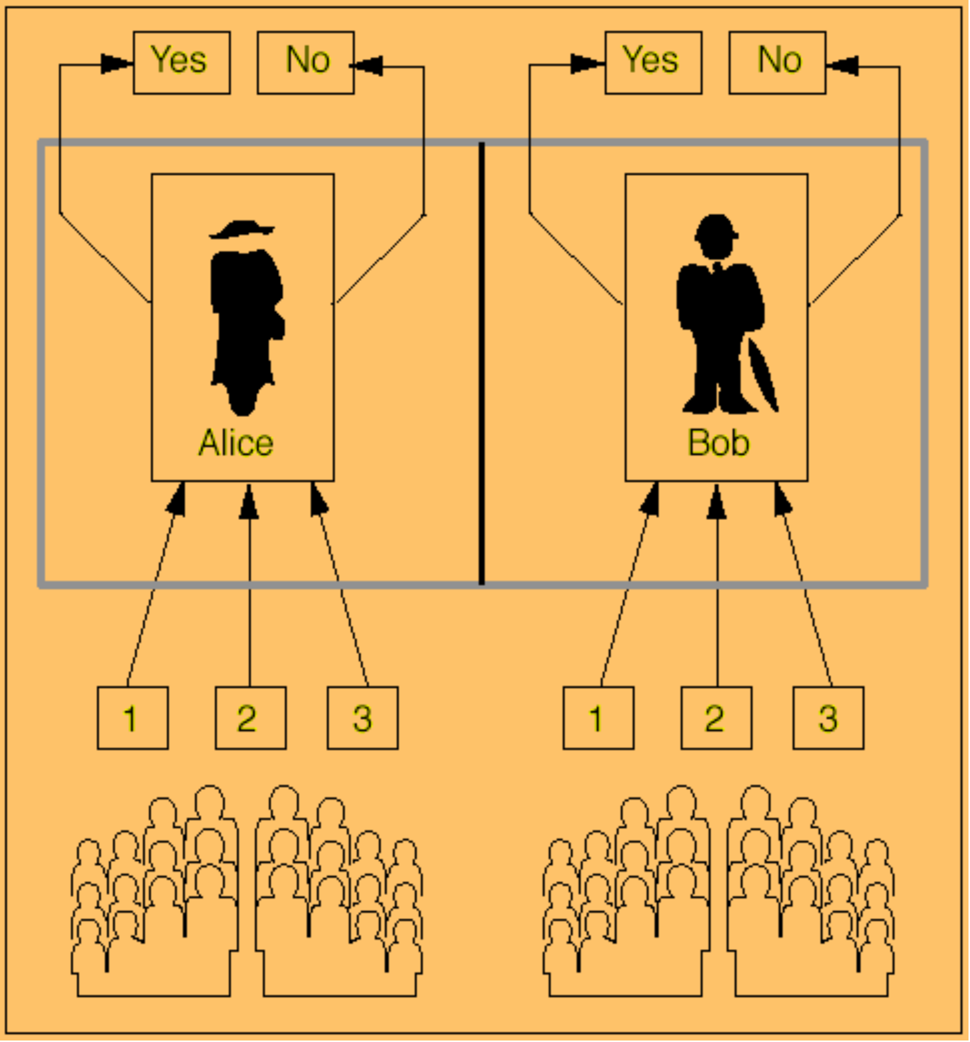
There are two characters: Alice and Bob.

There are two groups of people: one group gives a piece of paper to Alice, the other a piece of paper to Bob.

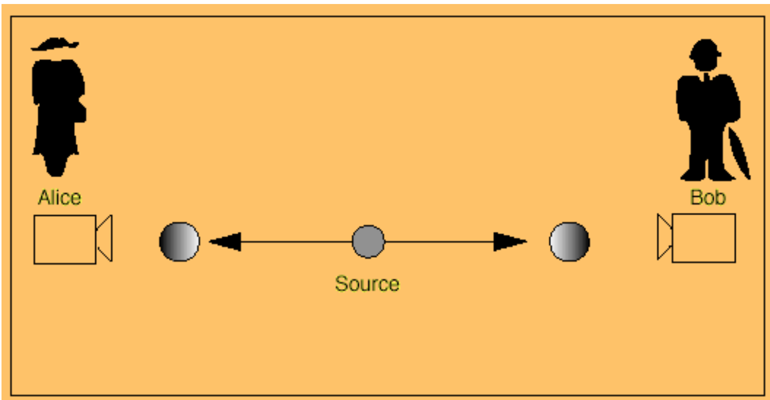
Each piece of paper carries a number: 1, 2 or 3.

Alice and Bob have to write either “Yes” or “No” on the piece of paper they receive.

Alice and Bob **cannot** communicate!



How they paly the (quantum) game



N. 1: Measurement of vertical polarization

N. 2: Measurement of polarization at a 60°

N. 2: Measurement of polarization at 120°

Alice and Bob have their standard source of photon pairs: one photon arriving immediately after they have got the paper.

According to the number which is written on their piece of paper, they decide which polarization measurement they will perform.

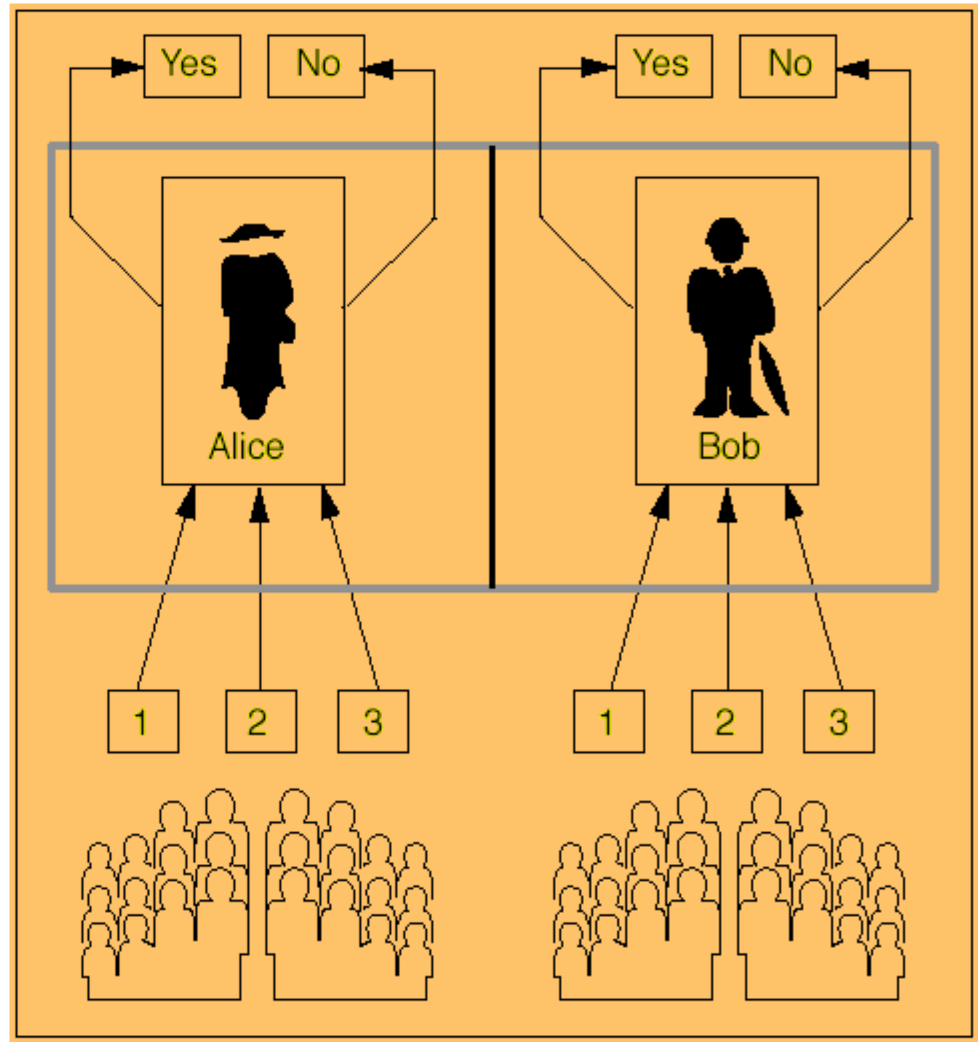
If their photon passes the polarization test they write Yes, if it fails, they write No on the paper.

Outcome of the game

Alice and Bob answer in the following way:

1. The sequence of "Yes" and "No" each of them gives, is **completely random**, with an **equal** number of "Yes" and "No".

2. However, when they receive a piece of paper carrying the same number, their answer **always** agrees: either they **both** say "Yes" or they both say "No". In such cases, half times they answer "Yes", and half times "No".



Conclusion (provisional…)

- They cannot communicate
- In some cases, they give the same answer

⬇

THEY ARE TELEPATHIC

⬇

In physical terms, it means that Quantum Mechanics is a non-local theory

Simple explanation (Einstein – 1935)

One from the audience disagrees with the conclusion. “Alice and Bob use a simple trick: they agree in advance on the answers they will give to all questions, changing the agreement from run to run.”

An example:

First run:

1	2	3
Yes	No	No

Second run:

1	2	3
No	No	Yes

and so on changing all times the answers in such a way to simulate the randomness.

This smart guy can be identified with Einstein, according to which Quantum Mechanics is not complete. The extra missing variables, when found, will explain why Alice and Bob give the same answers.

Not so easy (Bell – 1964)

In the audience there is another pedantic but deep guy. He has registered all answers (also when Alice and Bob have received pieces of paper with different numbers) and he has discovered that such answers agree or disagree in (about) 50% of the cases. On the basis of this fact he screams:

Alice and Bob are actually telepathic!

This spectator can be identified with John S. Bell, who discovered the famous inequality (Bell-inequalities), which were as used as a test to prove that Quantum Mechanics is non-local.

Explanation

First run:

1	2	3
Yes	No	No

Second run:

1	2	3
No	No	Yes

1/1	1/2	1/3	2/1	2/2	2/3	3/1	3/2	3/3
Y/Y	Y/N	Y/N	N/Y	N/N	N/N	N/Y	N/N	N/N
A	D	D	D	A	A	D	A	A

1/1	1/2	1/3	2/1	2/2	2/3	3/1	3/2	3/3
N/N	N/N	N/Y	N/N	N/N	N/Y	Y/N	Y/N	Y/Y
A	A	D	A	A	D	D	D	A

If they agreed in advance on the answer to give, there would be on the average 5 Agreements versus 4 Disagreements.

Since, for an extremely large sample, the A and D occur in 50% of the cases, they cannot have agreed in advance: **telepathy!**

5/4 versus 5/5 is a form of Bell's inequality

Quantum Mechanics and space

Quantum nonlocality is different from classical nonlocality

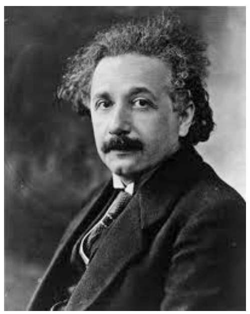
- It does not lead to superluminal signaling, so there is some consistency with relativity
- It does not depend on the distance, contrary e.g. to Coulomb force.

This creates a problem with our notion of space. How can particles be correlated, no matter how distant they are? This suggests that perhaps space – as we know it – is not fundamental.

From foundations to technologies

Electromagnetism ➔ Radio, TV
General Relativity ➔ GPS
Quantum Mechanics ➔ Semiconductor devices (computer), laser, STM, …

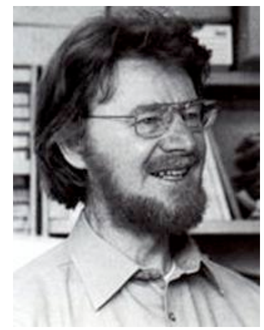
1935



EPR: on the meaning of Quantum Mechanics

Entanglement

1964



Study of Bohmian Mechanics

Bell's inequalities

1981

Nonlocality experiment

2018

Quantum Technologies Flagship

1 billion Eur

Quantum technologies: Quantum communication, information, computing, sensing, …
COST Action QTSpace "Quantum Technologies in Space" – www.qtspace.eu

Anthony Leggett

New Scientist, 2010

"I am inclined to put my money on the idea that if you push quantum mechanics hard enough it will break down and something else will take over – something we can't envisage at the moment."

Acknowledgments

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