

# Popper's experiment

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**Popper's experiment** is an experiment proposed by the 20th century philosopher of science Karl Popper, to test the standard interpretation (the Copenhagen interpretation) of Quantum mechanics.<sup>[1]</sup> <sup>[2]</sup> Popper's experiment is similar in spirit to the thought experiment of Einstein, Podolsky and Rosen (EPR). For some reasons, it did not become as well known. Currently, the consensus is that the experiment was based on a flawed premise, and thus its result doesn't constitute a test of quantum mechanics. Nevertheless, the experiment is important from a historical point of view and also exemplifies the pitfalls that one comes across in trying to make sense out of quantum mechanics.

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## Background

Quantum theory is an astoundingly successful theory when it comes to explaining or predicting physical phenomena. There are various interpretations of quantum mechanics that do not agree with each other. Despite their differences, they are nearly experimentally indistinguishable from each other. The most widely accepted interpretation of quantum mechanics is the Copenhagen interpretation put forward by Niels Bohr. The spirit of the Copenhagen interpretation is that the wavefunction of a system is treated as a composite whole, so disturbing any part of it disturbs the whole wavefunction. This leads to the counter-intuitive result that two well separated, non-interacting systems show a mysterious dependence on each other. Einstein called this spooky action at a distance. Einstein's discomfort with this kind of spooky action is summarized in the famous EPR argument.<sup>[3]</sup> Karl Popper shared Einstein's discomfort with quantum theory. While the EPR argument involved a thought experiment, Popper proposed a physical experiment to test the Copenhagen interpretation of quantum mechanics.

## Popper's proposed experiment

Popper's proposed experiment consists of a source of particles that can generate pairs of particles traveling to the left and to the right along the x-axis. The momentum along the y-direction of the two particles is entangled in such a way so as to conserve the initial momentum at the source, which is zero. Quantum mechanics allows this kind of entanglement. There are two slits, one each in the paths of the two particles. Behind the slits are semicircular arrays of detectors which can detect the particles after they pass through the slits (see Fig. 1).

Popper argued that because the slits localize the particles to a narrow region along the y-axis, from the uncertainty principle they experience large uncertainties in the y-components of their momenta. This larger spread in the momentum will show up as particles being detected even at positions that lie outside the regions where particles would normally reach based on their initial momentum spread.

Popper suggests that we count the particles in coincidence, i.e., we count

### Quantum physics

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

### Quantum mechanics

Introduction to...  
Mathematical formulation of...

#### *Fundamental concepts*

Decoherence · Interference  
Uncertainty · Exclusion  
Transformation theory  
Ehrenfest theorem · Measurement  
Superposition · Entanglement

#### *Experiments*

Double-slit experiment  
Davisson-Germer experiment  
Stern–Gerlach experiment  
Bell's inequality experiment

### **Popper's experiment**

Schrödinger's cat

#### *Equations*

Schrödinger equation  
Pauli equation  
Klein-Gordon equation  
Dirac equation

#### *Advanced theories*

Quantum field theory  
Wightman axioms  
Quantum electrodynamics  
Quantum chromodynamics  
Quantum gravity  
Feynman diagram

#### *Interpretations*

Copenhagen · Ensemble  
Hidden variables · Transactional  
Many-worlds · Consistent histories  
Quantum logic  
Consciousness causes collapse

#### *Scientists*

Planck · Schrödinger  
Heisenberg · Bohr · Pauli  
Dirac · Bohm · Born  
de Broglie · von Neumann  
Einstein · Feynman  
Everett · Others

only those particles behind slit B, whose other member of the pair registers on a counter behind slit A. This would make sure that we count only those particles behind slit B, whose partner has gone through slit A. Particles which are not able to pass through slit A are ignored.

We first test the Heisenberg scatter for both the beams of particles going to the right and to the left, by making the two slits A and B wider or narrower. If the slits are narrower, then counters should come into play which are higher up and lower down, seen from the slits. The coming into play of these counters is indicative of the wider scattering angles which go with narrower slit, according to the Heisenberg relations.

Now we make the slit at A very small and the slit at B very wide. According to the EPR argument, we have measured position "y" for both particles (the one passing through A and the one passing through B) with the precision  $\Delta y$ , and not just for particle passing through slit A. This is because from the initial entangled EPR state we can calculate the position of the particle 2, once the position of particle 1 is known, with approximately the same precision. We can do this, argues Popper, even though slit B is wide open.

We thus obtain fairly precise "knowledge" about the y position of particle 2 - we have "measured" its y position indirectly. And since it is, according to the Copenhagen interpretation, our *knowledge* which is described by the theory - and especially by the Heisenberg relations - we should expect that the momentum  $p_y$  of particle 2 scatters as much as that of particle 1, even though the slit A is much narrower than the widely opened slit at B.

Now the scatter can, in principle, be tested with the help of the counters. If the Copenhagen interpretation is correct, then such counters on the far side of slit B that are indicative of a wide scatter (and of a narrow slit) should now count coincidences: counters that did not count any particles before the slit A was narrowed.

To sum up: if the Copenhagen interpretation is correct, then any increase in the precision in the measurement of our *mere knowledge* of the particles going through slit B should increase their scatter.

Popper was inclined to believe that the test would decide against the Copenhagen interpretation, and this, he argued, would undermine Heisenberg's uncertainty principle. If the test decided in favour of the Copenhagen interpretation, Popper argued, it *could* be interpreted as indicative of **action at a distance**.

## The debate

Many viewed Popper's experiment as a crucial test of quantum mechanics, and there was a debate on what result an actual realization of the experiment would yield.

- In 1985, Sudbery pointed out that the EPR state, which could be written as  $\psi(y_1, y_2) = \int_{-\infty}^{\infty} e^{iky_1} e^{-iky_2} dk$ , already contained an infinite spread in momenta (tacit in the integral over k), so no further spread could be seen by localizing one particle. <sup>[4]</sup> <sup>[5]</sup> Although it pointed to a crucial flaw in Popper's argument, its full implication was not understood.
- Kripps theoretically analyzed Popper's experiment and predicted that narrowing slit A would lead to momentum spread increasing at slit B. Kripps also argued that his result was based just on the formalism of quantum mechanics, without any interpretational problem. Thus, if Popper was challenging anything, he was challenging the central formalism of quantum mechanics. <sup>[6]</sup>
- In 1987 there came a major objection to Popper's proposal from Collet and Loudon. <sup>[7]</sup> They pointed out that because the particle pairs originating from the source had a zero total momentum, the source could not have a sharply defined position. They showed that once the uncertainty in the position of the source is taken into account, the blurring introduced washes out the Popper effect. *However, it has been demonstrated that a point source is not crucial for Popper's experiment, and a broad spontaneous parametric down conversion (SPDC) source can be set up to give a strong correlation between two photon pairs.*
- Redhead analyzed Popper's experiment with a broad source and concluded that it could not yield the effect that Popper

Fig.1 Experiment with both slits equally wide. Both the particles should show equal scatter in their momenta.

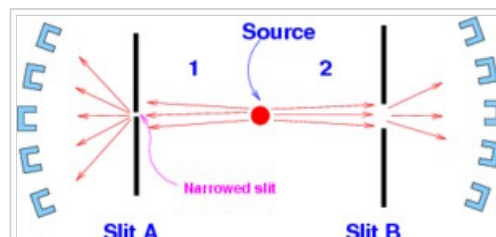


Fig.2 Experiment with slit A narrowed, and slit B wide open. Should the two particles show equal scatter in their momenta? If they do not, Popper says, the Copenhagen interpretation is wrong. If they do, it indicates *spooky action at a distance*, says Popper.

was seeking. [8] However, it has been demonstrated that if one uses a converging lens with a broad source, the kind of setup Popper was looking for, can be realized.

## Realization of Popper's experiment

Popper's experiment was realized in 1999 by Kim and Shih using a SPDC photon source. [9] Interestingly, they did not observe an extra spread in the momentum of particle 2 due to particle 1 passing through a narrow slit. Rather, the momentum spread of particle 2 (observed in coincidence with particle 1 passing through slit A) was narrower than its momentum spread in the initial state. This led to a renewed heated debate, with some even going to the extent of claiming that Kim and Shih's experiment had demonstrated that there is no non-locality in quantum mechanics. [10]

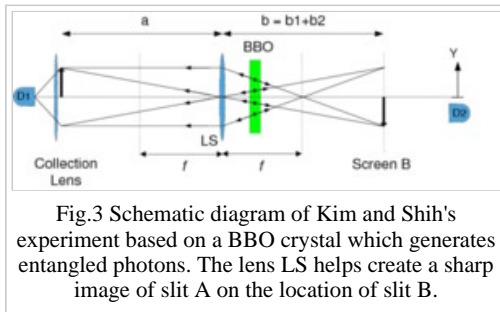


Fig.3 Schematic diagram of Kim and Shih's experiment based on a BBO crystal which generates entangled photons. The lens LS helps create a sharp image of slit A on the location of slit B.

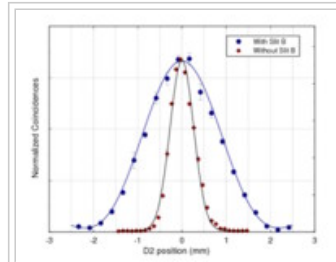


Fig.4 Results of the photon experiment by Kim and Shih, aimed at realizing Popper's proposal. The diffraction pattern in the absence of slit B (red symbols) is much narrower than that in the presence of a real slit (blue symbols).

- Short criticized Kim and Shih's experiment, arguing that because of the finite size of the source, the localization of particle 2 is imperfect, which leads to a smaller momentum spread than expected. [11] However, Short's argument implies that if the source were improved, we should see a spread in the momentum of particle 2.
- Sancho carried out a theoretical analysis of Popper's experiment, using the path-integral approach, and found a similar kind of narrowing in the momentum spread of particle 2, as was observed by Kim and Shih. [12] Although this calculation did not give them any deep insight, it indicated that the experimental result of Kim-Shih agreed with quantum mechanics. It did not say anything about what bearing it has on the Copenhagen interpretation, if any.

## What is wrong with Popper's proposal?

The fundamental flaw in Popper's argument can be seen from the following simple analysis. [13] [14]

The ideal EPR state is written as  $|\psi\rangle = \int_{-\infty}^{\infty} |y, y\rangle dy = \int_{-\infty}^{\infty} |p, -p\rangle dp$ , where the two labels in the "ket" state represent the positions or momenta of the two particle. This implies perfect correlation, meaning, detecting particle 1 at position  $x_0$  will also lead to particle 2 being detected at  $x_0$ . If particle 1 is measured to have a momentum  $p_0$ , particle 2 will be detected to have a momentum  $-p_0$ . The particles in this state have infinite momentum spread, and are infinitely delocalized. However, in real world, correlations are always imperfect. Consider the following entangled state

$$\psi(y_1, y_2) = A \int_{-\infty}^{\infty} dp e^{-p^2/4\sigma^2} e^{-ipy_2/\hbar} e^{ipy_1/\hbar} \exp\left[-\frac{(y_1 + y_2)^2}{16\Omega^2}\right]$$

where  $\sigma$  represents a finite momentum spread, and  $\Omega$  is a measure of the position spread of the particles. The uncertainties in position and momentum, for the two particles can be written as

$$\Delta p_2 = \Delta p_1 = \sqrt{\sigma^2 + \frac{\hbar^2}{16\Omega^2}}, \quad \Delta y_1 = \Delta y_2 = \sqrt{\Omega^2 + \hbar^2/16\sigma^2}$$

The action of a narrow slit on particle 1 can be thought of as reducing it to a narrow Gaussian state:

$\phi_1(y_1) = \frac{1}{(\epsilon^2 2\pi)^{1/4}} e^{-y_1^2/4\epsilon^2}$ . This will reduce the state of particle 2 to  $\phi_2(y_2) = \int_{-\infty}^{\infty} \psi(y_1, y_2) \phi_1^*(y_1) dy_1$ . The momentum uncertainty of particle 2 can now be calculated, and is given by

$$\Delta p_2 = \sqrt{\frac{\sigma^2(1 + \epsilon^2/\Omega^2) + \hbar^2/16\Omega^2}{1 + 4\epsilon^2(\sigma^2/\hbar^2 + 1/16\Omega^2)}}$$

If we go to the extreme limit of slit A being infinitesimally narrow ( $\epsilon \rightarrow 0$ ), the momentum uncertainty of particle 2 is

$\lim_{\epsilon \rightarrow 0} \Delta p_2 = \sqrt{\sigma^2 + \hbar^2/16\Omega^2}$ , which is exactly what the momentum spread was to begin with. In fact, one can show that the momentum spread of particle 2, conditioned on particle 1 going through slit A, is always less than or equal to  $\sqrt{\sigma^2 + \hbar^2/16\Omega^2}$  (the initial spread), for any value of  $\epsilon, \sigma$ , and  $\Omega$ . **Thus, particle 2 does not acquire any extra momentum spread than what it already had.** This is the prediction of standard quantum mechanics.

**Thus, the basic premise of Popper's experiment, that the Copenhagen interpretation implies that particle 2 will show an additional momentum spread, is incorrect.**

On the other hand, if slit A is gradually narrowed, the momentum spread of particle 2 (conditioned on the detection of particle 1 behind slit A) will show a gradual increase (never beyond the initial spread, of course). This is what quantum mechanics predicts. Popper had said

...if the Copenhagen interpretation is correct, then any increase in the precision in the measurement of our mere knowledge of the particles going through slit B should increase their scatter.

This clearly follows from quantum mechanics, without invoking the Copenhagen interpretation.

## Popper's experiment and faster-than-light signalling

The expected additional momentum scatter which Popper wrongly attributed to the Copenhagen interpretation can be interpreted as allowing faster-than-light communication, which is known to be impossible, even in quantum mechanics. Indeed some authors have criticized Popper's experiment based on this impossibility of superluminal communication in quantum mechanics [15] [16]. Every attempt to use quantum correlations for faster-than-light communication is known to be flawed because of the no cloning theorem in quantum mechanics. One will putatively try to signal 0 and 1 by narrowing the slit, or not narrowing it. However in order to investigate the scattering of each single qubit, one needs to have many identical copies of it. Due to unitarity in quantum mechanics, if one tries to copy a qubit they will produce an entangled "pseudo-copy" that will collapse at the very moment the original qubit is measured. So the result of Popper's experiment cannot be used for faster-than-light communication.

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