Quantum Physics

Christian Wüthrich

http://www.wuthrich.net/

Introduction to the history and philosophy of science
Faculté des sciences, Université de Genève

Plan

The puzzle of quantum physics

John S Bell (2004, 173)

> *I think that conventional formulations of quantum theory, and of quantum field theory in particular, are unprofessionally vague and ambiguous. Professional theoretical physicists ought to be able to do better.*

John Stuart Bell ([2]2004). *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: University of Cambridge Press.

Experiment: The double slit

The quantum signature: interference and superposition

Richard Feynman *et al.* (1975, §37-1)

> *We choose to examine a phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. We cannot explain the mystery in the sense of 'explaining' how it works. We will tell you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics.*

Richard Feynman, Robert Leighton, and Matthew Sands (1975). *The Feynman Lectures of Physics*. Reading, MA: Addison-Wesley.

Experiment: The double slit

The quantum signature: crests and troughs

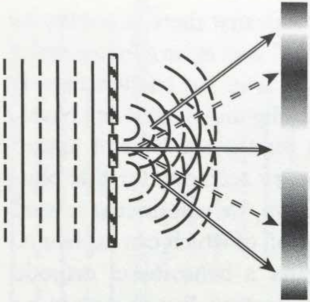


Figure 4

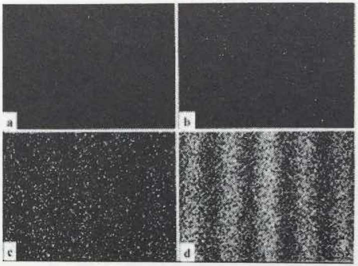


Figure 5. Credit: Reprinted courtesy of the Central Research Laboratory, Hitachi, Ltd., Japan.

Experiment: The double slit

How does an individual electron know to form an interference pattern?

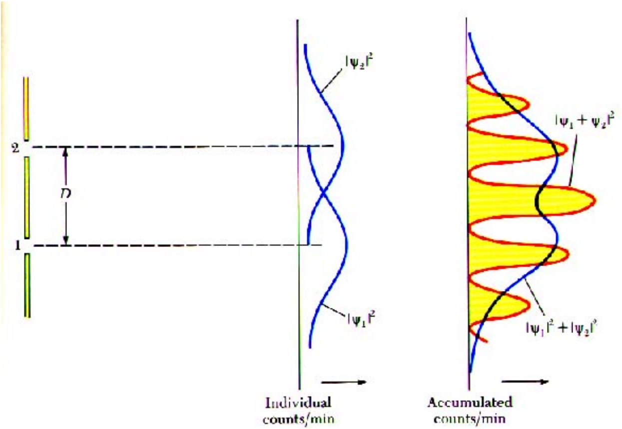


Figure: Interference pattern found in double-slit experiments.

Experiment: The double slit with monitoring

The monitoring proton destroys interference

Figure 6

Spin measurements

Wikipedia Commons

https://upload.wikimedia.org/wikipedia/commons/9/9e/Quantum_spin_and_the_Stern-Gerlach_experiment.ogv

- Elementary particles (such as electrons, photons, etc) and other atomic-scale systems have intrinsic properties called spin.
- Spin is genuinely quantum, i.e., there is no classical analogue.
- Its existence is inferred from experiments with an inhomogeneous magnetic field to deflect the particles (e.g. Stern-Gerlach).
- The magnetic field can be rotated 360 degrees, and the spin can be measured in any direction.
- Quantum spin assumes one of two values ('up', 'down'), classical angular momentum has continuous values.
- It usually suffices to measure spin in two orthogonal directions: up (U) - down (D) and left (L) - right (R)

Experiment: Spin

The Stern-Gerlach set-up

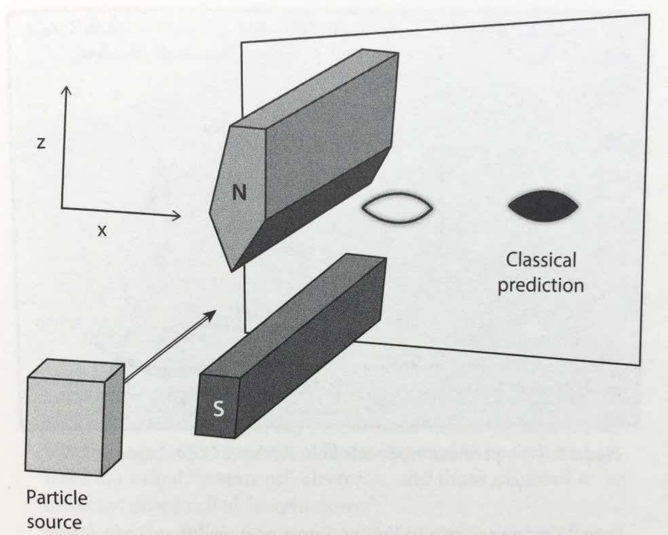


Figure 7

Experiment: Spin

Stern-Gerlach: confirmation of the quantization of spin

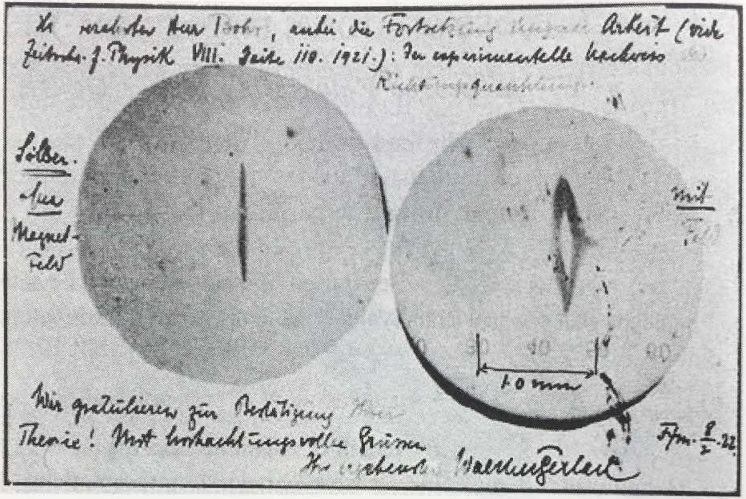
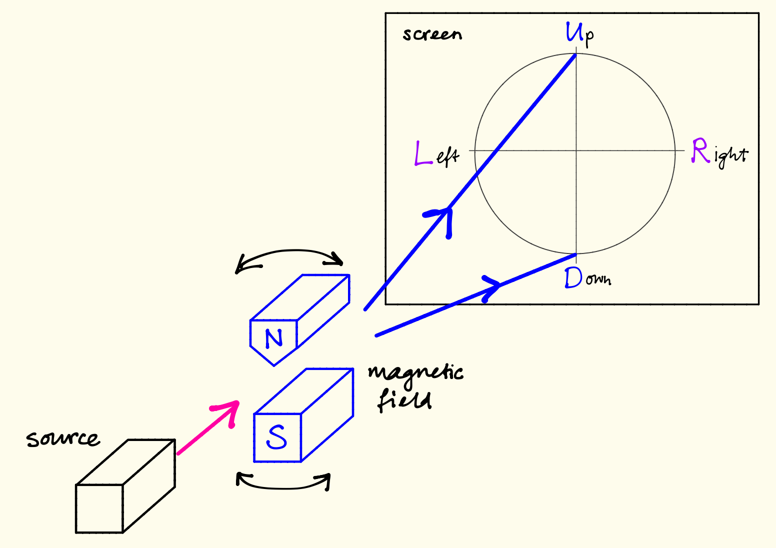
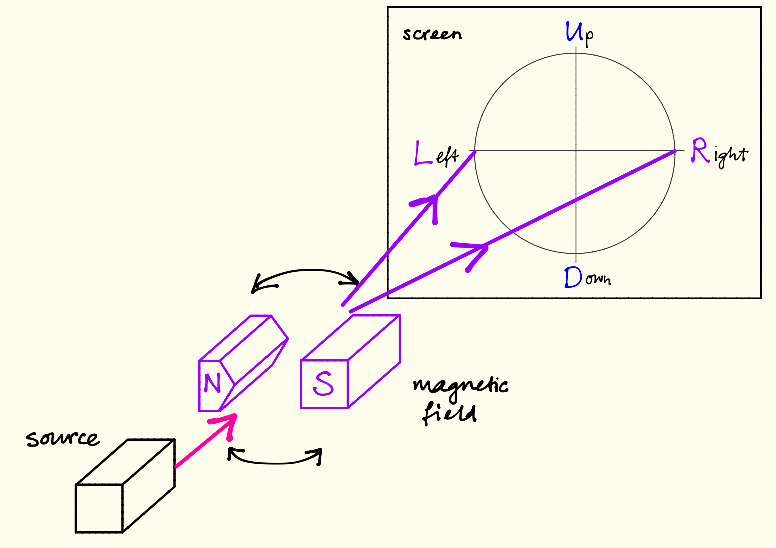


Figure 8. With permission of Niels Bohr Archive, Copenhagen.

Stern-Gerlach experiments: vertical



Stern-Gerlach experiments: horizontal



Combining Stern-Gerlach apparatuses

- The measurements are repeatable: if we let pass the same particle in two subsequent Stern-Gerlach apparatuses with the same orientation (and without tampering with the particle in the meantime), then the same measurement outcome will be observed (see Fig. 9(a)).

Question

Are the 'vertical' and the 'horizontal' spin properties related, i.e., are there correlations between the values for U-D and for L-R of the same particle?

- So let's combine Stern-Gerlach apparatuses (SG) with vertical (V) and horizontal orientation (H) (see Fig. 9(b)):

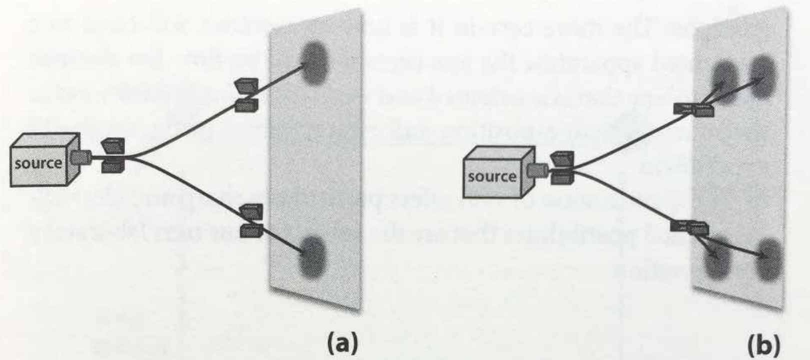


Figure 9

Spin measurements

- Exactly half of the particles coming out of the first SG will register with each outcome for the second SG.

⇒ So there appear to be no correlations, to have a spin in the vertical direction entails nothing about the spin in the horizontal direction and vice versa.

Three Stern-Gerlach experiments

- Suppose we have three SGs aligned for subsequent measurement, such that the first and third SG are oriented in the same direction as one another, but differently from the second: VHV or HVH
- No tampering with the particles between the measurements.
- Once the particles go into the third apparatus, they are presumably known to have a particular pair of spin properties (e.g. UL), so we should be able to predict the outcome of the third measurement.
- But it turns out that we cannot: precisely half the particles will register for either outcome...
- It seems as if the mere presence of the middle measurement constitutes some sort of tampering, as it randomizes the spin property of the particles in the other orientation.

Heisenberg's uncertainty principle

David Z Albert (1992). *Quantum Mechanics and Experience*. Harvard University Press.

- David Albert (1992, 7): it is impossible to assert that a particle has now such-and-such vertical spin and such-and-such horizontal spin
- This is an instance of Heisenberg's uncertainty principle, according to which some pairs of measurable properties ('observables') are incompatible in that the measurement of one of them disrupts the measurement of the other.

Spin measurements: summary

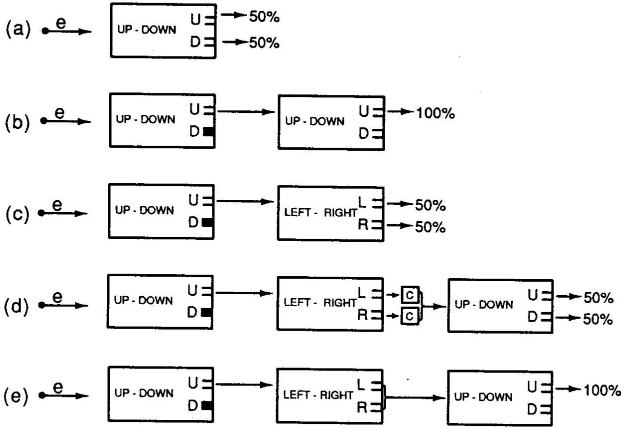
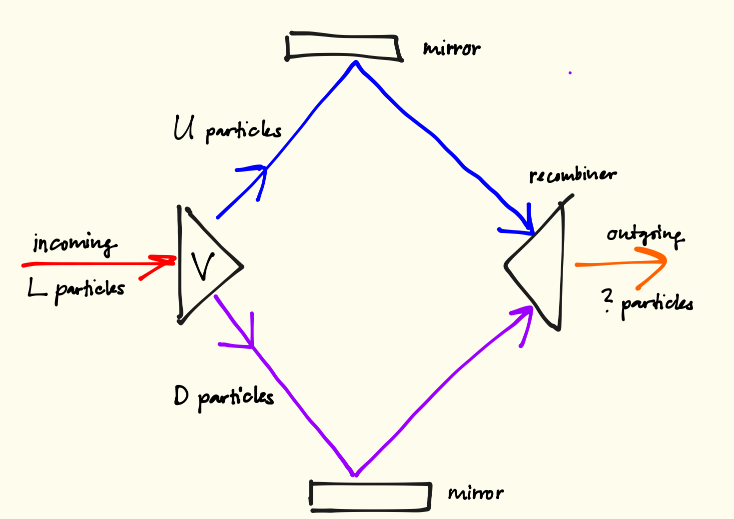


Figure: Stern-Gerlach experiment with 'mixture' (d) and 'superposition' (e) (Sklar, Fig. 4.4)

Experiment: The (Mach-Zehnder) interferometer

Entangling spin and position



- Suppose that L particles are fed into the device and we measure their V-spin after recombining. Expectation: we find half U and half D. And this is what we find.
- Suppose that U particles are fed into the device and we measure their H-spin after recombining. Expectation: we find half L and half R. And this is what we find.
- Suppose that L particles are fed into the device and we measure their H-spin after recombining. Expectation: we find half L and half R. But this is not at all what we find: all particles are found to be L!

- Add a sliding wall into the D-path. What happens if we slide the wall in?
- Expectation: overall output goes does down 50%; given that all particles were just found to be L, they should still be so, right?
- But they are not: only half of the particles are now L, the other half R.

Considering the paths of the particles: superposition

Which route does a particle take when the wall is out?

- Can it have taken the U-path? Apparently not, since these particles are known to randomize H-spin.
- Can it have taken the D-path? No, for the same reason.
- Can it somehow have taken both routes? Apparently not, since whenever we stop experiment and look to see where the particle is, we find it either on the U-path or on the D-path.
- Can it have taken neither route? No, since if we wall up both routes, nothing goes through.

Quantum mechanics: the five basic principles

Principle (A: Physical states)

Every physical system, composite or simple, is associated with some particular vector space. Every unit vector in this space (the 'state vectors') represents a possible physical state of the system. The states picked out by these vectors are taken to comprise all of the physically possible situations, although the correspondence is not one-to-one.

Principle (B: Observables)

Measurable properties of physical systems ('observables') are represented by (linear) operators on the vector spaces associated with those systems. The rule connecting the operators and the vectors states that if the vector happens to be an eigenvector (with eigenvalue, say, a) of an operator in question, then the state corresponding to the vector has the value a of that particular measurable property associated with the operator.

Incompatibility of V-spin and H-spin

The V-spin and H-spin operators are incompatible with one another, in the sense that states of definite V-spin have no assignable H-spin value, and vice versa.

Principle (C: Dynamics)

Given the state of any physical system at any 'initial' time, and given the forces and constraints to which the system is subject, the Schrödinger equation gives a prescription whereby the state of that system at any other time is uniquely determined. This dynamics of the state vector is thus deterministic.

The dynamical laws are linear: if any state $|A\rangle$ at t_1 is evolved into another state $|A'\rangle$ at t_2 and any $|B\rangle$ at t_1 is evolved into $|B'\rangle$ at t_2, then $\alpha|A\rangle + \beta|B\rangle$ at t_1 is evolved into $\alpha|A'\rangle + \beta|B'\rangle$ at t_2.

We know what happens if we measure a state with respect to a particular property when that state is in an eigenstate of the operator corresponding to the measurable property in question (what?). But what happens if it isn't?

Principle (D: Connection with experiment, 'Born's rule')

A measurement of the observable $\hat{A}$ is performed on a system in state $|b\rangle$, where the eigenvectors of $\hat{A}$ are $|a_i\rangle$ with eigenvalues a_i, i.e. $\hat{A}|a_i\rangle = a_i|a_i\rangle$ for all i. The probability that the outcome of such a measurement will be a_i is equal to

$$|\langle b|a_i\rangle|^2.$$

Remarks:

- The number $|\langle b|a_i\rangle|^2$ is in the interval $[0, 1]$.
- In the special case when the system is in an eigenstate of the operator corresponding to the measurement, we get with probability 1 that the outcome is the eigenvalue associated with the eigenstate.
- Probability that L-particle is found to be U is 1/2, as it should be.

Principle (E: Collapse)

Whatever the state vector of a system S was just prior to a measurement of an observable O, the state vector of S just after the measurement must be an eigenvector of O with an eigenvalue corresponding to the outcome of that measurement.

Remarks:

- Which eigenvector the system jump into is determined by the outcome of the measurement; and this outcome, by Principle D, is a matter of probability.

$\Rightarrow$ element of chance, indeterminism, enters into the evolution of the state vector

Notice that Principle C was supposed to be a completely general account of how the state vector evolves under any circumstances, while Principle E seems to be a special case of C, but can't obviously be deduced it...

- Measurement in QM is (according to the standard view) a very active process that in general changes the measured system.

Albert (1992,38)

That's what's at the heart of the standard view. The rest... is details.

The puzzle of measurement

Feynman, R. P., 'Simulating physics with computers', *International Journal of Theoretical Physics* 21 (1982): 467-88.

Feynman (1982, 471)

> *[We] always have had (secret, secret, close the doors!) we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it... you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there is no real problem. It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem.*

The problem with the standard view of QM

In a nutshell

Principle C asserts that the dynamics of any quantum system is described by the Schrödinger equation, which is a linear and deterministic equation. Principle E asserts that whenever a measurement is made upon a quantum system, its state collapses into an eigenstate of the measured observable. This collapse is non-linear and indeterministic. As stated, the two Principles are thus incompatible. They could be made compatible if we gave a precise and complete dynamical prescription for all quantum systems in all circumstance, e.g., by giving necessary and sufficient conditions for what is a 'measurement' and what the precise collapse dynamics is.

Schrödinger's cat

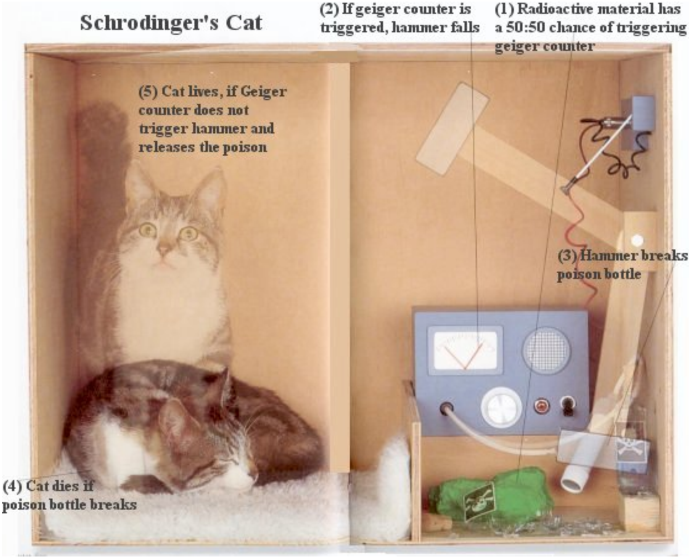
Schrödinger, E., 'Die gegenwärtige Situation in der Quantenmechanik' ('The present situation in quantum mechanics'), *Naturwissenschaften* 23 (1935): 807-812; 823-828; 844-849.

Schrödinger (1935)

One can even set up quite ridiculous cases. A cat is penned up in a steel chamber, along with the following device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny bit of radioactive substance, so small, that perhaps in the course of the hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The psi-function of the entire system would express this by having in it the living and dead cat (pardon the expression) mixed or smeared out in equal parts.

Schrödinger (1935)

It is typical of these cases that an indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be resolved by direct observation. That prevents us from so naively accepting as valid a 'blurred model' for representing reality. In itself it would not embody anything unclear or contradictory. There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks.


Schrodinger's Cat
(2) If geiger counter is triggered, hammer falls
(1) Radioactive material has a 50:50 chance of triggering geiger counter
(5) Cat lives, if Geiger counter does not trigger hammer and releases the poison
(3) Hammer breaks poison bottle
(4) Cat dies if poison bottle breaks

Jeff Barrett (1999). *The Quantum Mechanics of Minds and Worlds*. OUP. §2.5, pp. 43f.

- After exactly one hour, the cat is in the superposition state

$$\frac{1}{\sqrt{2}}|\text{alive}\rangle + \frac{1}{\sqrt{2}}|\text{dead}\rangle, \tag{1}$$

  but to have a macroscopic object like a cat in a superposition state like this seems bizarre...
- So, we could insist on definite measurement outcomes (and linear dynamics), but that would mean that the quantum state (the wave function) of the cat is not complete (there is a fact of the matter whether the cat is dead or alive).
- Copenhagen orthodoxy: Our act of observation collapses the superposition to one of its terms, making the cat definitely dead or alive.
- It is somehow our lifting of the lid of the box that causes the collapse.

Maudlin's version of the measurement problem

Tim Maudlin. Three measurement problems. *Topoi* 14 (1995): 7-15.

Theorem (Measurement Problem (MP))

"The following three claims are mutually inconsistent.

1.A *"The wave-function of a system is complete, i.e. the wave-function specifies (directly or indirectly) all of the physical properties of a system.*

1.B *"The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).*

1.C *"Measurements of, e.g., the spin of an electron always (or at least usually) have determinate outcomes, i.e., at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up)." (7)*

'Proof.' Essentially along the lines of Albert's chapter 4, e.g. if 1.A is true, and thus the wave function must specify every physical fact about the measuring device, and 1.B is true, then 1.C must be false, etc. □

Taxonomize the solutions to MP

1. Hidden-variables theories deny 1.A, since they postulate more reality than is represented in $|\psi\rangle$
   - Examples: Bohmian mechanics, modal interpretations such as van Fraassen's (1991)
2. Collapse theories abandon 1.B, since they assert that dynamics is, at least sometimes, non-linear
   - Examples: Copenhagen, Spontaneous Localization theory of Ghirardi, Rimini, Weber (1986) (GRW); Continuous Spontaneous Localization theory of Perle (1990)
3. Multiverse theories reject 1.C, since they maintain that measuring devices indicate both (or all) outcomes
   - Examples: many-world theories, Everett's Relative State interpretation (1957)

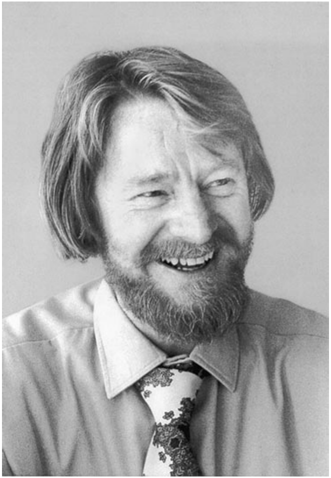
New physics

- A solution to MP must thus by necessity either be a hidden-variables theory, a collapse theory, or a multiverse theory (or some combination thereof).

⇒ each option involves the postulation of new physics, according to Maudlin:

1. Hidden-variables theories must specify what additional variables there are and what dynamical laws govern them.
2. Collapse theories must provide the non-linear dynamical equations and specify when exactly they apply (something the Copenhagen interpretation did not do).
3. Multiverse theories must explain why it seems as if there are definite outcomes; in other words, they must answer why Schrödinger's cat seems either definitely alive or definitely dead.

John Stewart Bell (1928-1990)



- studied physics at Queen's University Belfast, PhD U Birmingham, CERN
- 'On the Einstein-Podolsky-Rosen paradox' (1964): derivation of Bell's inequality
- Bell's theorem: this inequality, derived from basic assumptions about locality and separability, conflicts with the predictions of QM

Bell's relevance

N. David Mermin, 'Is the moon there when nobody looks? Reality and the quantum theory', *Physics Today*, April 1985, 38-47.

- By the mid-60s, almost all physicists just moved on and worked with QM, but didn't reflect its foundations.

⇒ many of them didn't notice, and still fail to appreciate the relevance of Bell's theorem

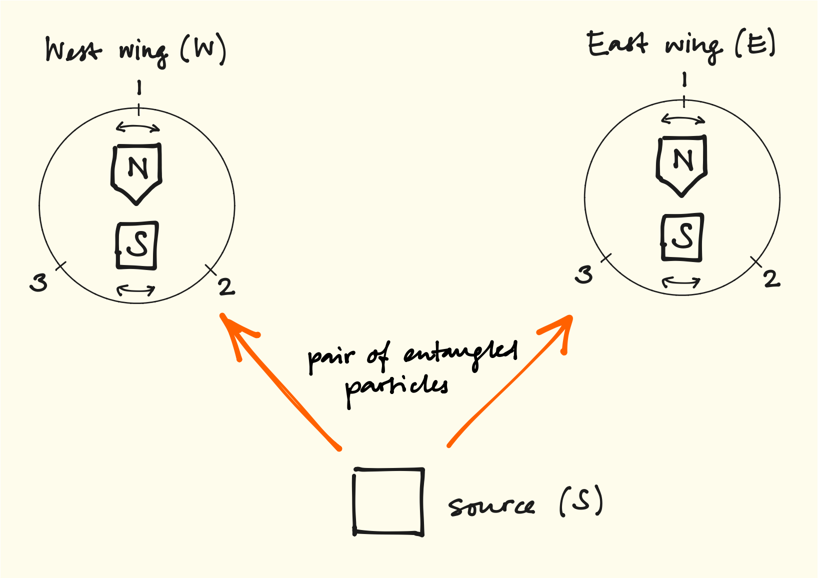
- But not all: "Bell's theorem is the most profound discovery of science" (Henry Stapp)
- A bit more nuanced (but only a bit): "Anybody who's not bothered by Bell's theorem has to have rocks in his head" ("a distinguished Princeton physicist")
- Mermin's classification of physicists:
  - Type 1 bothered by EPR and Bell's theorem, type 2 (the majority) not bothered
  - Type 2a explain why not, but either miss the point entirely or make assertions that are demonstrably false
  - Type 2b refuse to explain why they are not bothered

A simple version of the EPR-Bohm thought experiment

N. David Mermin, 'Is the moon there when nobody looks? Reality and the quantum theory', *Physics Today*, April 1985, 38-47.

- based on Mermin (1985)
- Three pieces: two detectors (W and E), and a source (S)
- Each detector has a switch with three settings (1, 2, 3), and responds to an event by flashing a red (R) or green light (G).
- There are no connections or signals between the pieces other than the two particles sent from S to W and E (this can be tested by sliding walls, etc).
- The switch of each detector is independently and randomly set to one of its settings, and a button is pushed at S to initiate the process of creating a pair of entangled particles and sending them to the opposite wings.
- Many runs of the experiments are made, and lots of data of form (11GG, 23GR, etc) is collected.

A simple version of the EPR-Bohm thought experiment



A simple version of the EPR-Bohm thought experiment

The data has two features:

1. For those runs when settings were the same in W and E, we find that the light always flashed in same colour. (PERFECT CORRELATION)
2. For all runs regardless of the settings in W and E, the pattern of flashing is completely random. In particular, half of the time the same colour flashes, half of the time a different one does. (NO CORRELATION)

Challenge:

Find an account which explains both of these features.

How can this data be explained?

- The perfect correlation cries out for explanation.
- Traditional possibilities: (i) the events are really parts of one larger event, or (ii) W causes E or vice versa, or (iii) they have common cause
- If the detectors could communicate, this would be easy. But they don't. And can't.
- Neither can the detectors have been preprogrammed always to flash the same colour, since they also need to account for data point 2, and their settings are random and independent.

Born offers an explanation (in a letter of May 1948 to Einstein):

> *[O]bjects far apart in space which have a common origin need not be independent... Dirac has based his whole book on this.*

Mermin: could we have a common cause explanation?

That is, a "local hidden variable" explanation?

- A common cause explanation: both particles are imparted the same ordered triple of labels as they leave the source (three bits of information, e.g. RRG, GRG, etc; 2^3 possibilities), each telling the detector which colour to flash, depending on its setting.
- These instructions must cover each of the possible detector settings because there is no communication between the source and the detectors other than the particles.
- This also means that instructions must be carried in every run, since one can never know at the source whether the settings are the same:

⇒ This can easily account for data 1.

- But despite the naturalness of this type of explanation (arguably the only natural explanation), it cannot be true: it's inconsistent with data 2!
- Note that "we are about to show that 'something one cannot know anything about'—the third entry in an instruction set—cannot exist." (Mermin 1985, 43) (one can never learn more than two of the entries in the instruction sets imparted on the particles)
- Here's the argument for the inconsistency with data 2. Consider a possible instruction set, e.g. RRG.

⇒ The detectors will flash the same colour for settings 11, 22, 33, 12, 21, and different colours for settings 13, 31, 23, 32 (3^2 settings).

- Since the settings are random and independent, each of the nine possibilities are equally probable.

⇒ The instruction set RRG will result in the same colour flashing in 5/9 of the time.

- Evidently, the same holds for instruction sets RGR, GRR, GGR, GRG, and RGG (because the argument uses only the fact that one colour appears twice, and the other once).
- Two more instruction sets are left: RRR and GGG, but these both result in the same colours flashing all the time (with probability 1). But this gives us the famous:

Theorem (Bell's theorem (baby version))

If instruction sets exist, the same colours will flash in at least 5/9 of all the runs, regardless of how the instruction sets are distributed among the runs.

- This is (the baby version of) Bell's inequality: the probability that the same colours flash is larger or equal to 5/9.
- It's now obvious that data 2 cannot be accounted for: data 2 violates Bell's inequality!

Thus, there cannot be a common cause explanation.

Comments

- The simplified thought experiment captures the relevant features of the EPR-Bohm experiment.
- The Baby Bell theorem shows why there cannot be a common cause, contra Einstein, Podolsky, and Rosen (1935, 'EPR') who argued that QM was incomplete (because it didn't contain such a common cause).
- Bell was the one who added the runs with different settings in order to extract from QM the prediction about data 2.
- It was exactly data 2 that showed that a common cause story is incompatible with the predictions of QM.
- Alain Aspect, Paris 1982; Nicolas Gisin, Geneva 1997: detectors are 10 km apart, settings chosen after photons left source

$\Rightarrow$ experimental falsification of common cause theory

Bell's assessment of his result

J.S. Bell, 'Bertlmann's socks and the nature of reality', in *Speakable and Unspeakable in QM*, 139-158.

Bell sees at least four different positions that one might:

1. QM is wrong in sufficiently critical situations. But that's unconvincing in the light of empirical evidence.
2. The detector settings are not independent variables. But this would imply strange conspiracies between spatially distant apparatuses, or our free will is conspiratorially entangled with them or both.
3. Causal influences can go faster than light, perhaps by reintroducing an aether. But this would create formidable challenges...
4. Perhaps there is no reality beyond some 'classical' 'macroscopic' level.

Bell's assessment of his result

There are actually more options:

5. The measurement events in the two wings are not separate, i.e., they are like different aspects of the same event.
6. There is backward causation such that the settings in either or both of the wings (which can be set after the particles departed the source) causally influence the common cause at the source event.

Note:

One of these options must be true.

Additional considerations on nonlocality

David Z Albert (1992). *Quantum Mechanics and Experience*. Harvard University Press, Ch. 3.

- EPR thought that the nonlocal character of measurements on non-separable states is a merely disposable artifact of the particular formalism of standard QM.
- The upshot of Bell's theorem is that this is demonstrably wrong:

Albert (1992, 70)

> *What Bell has given us is a proof that there is as a matter of fact a genuine nonlocality in the actual workings of nature, however we attempt to describe it, period. That nonlocality is... necessarily... a feature of every possible manner of calculating... which produces the same statistical predictions as quantum mechanics does; and those predictions are now experimentally known to be correct.*

Important

This result in independent of quantum mechanics—it is nature itself that is non-local.

Three final comments

Tim Maudlin, *Quantum Non-Locality and Relativity*, Ch. 1.

Three results concerning the 'quantum connection':

1. It is unattenuated: in contrast to classical (instantaneous) action, the quantum connection is unaffected by distance.
2. It is discriminating: while gravitational forces affect similarly situated objects in the same way, the quantum connection is a private arrangement between entangled particles.
3. It is instantaneous: while Newton's theory of gravity has gravity propagate instantaneously, it need not do so, and GR certainly involves no instantaneous gravitational action; but the quantum connection appears to act essentially instantaneously.