Bell's inequality.

The quantum world is stranger than we can imagine

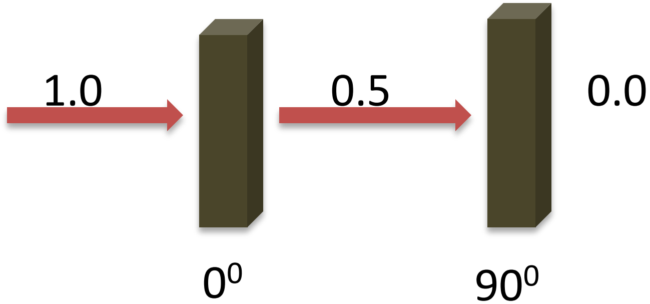
"Bell's theorem is the most profound discovery of science."
Henry Stapp

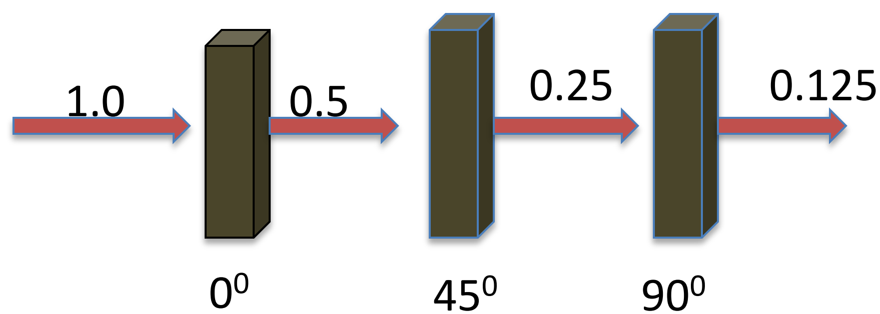
March 27 Quiz on Quantum Mechanics. Today
March 29 Term paper outline/ partial draft

Next time: Measurements

Polarization of light

- Light (E&M waves) come with 2 polarization states
- Vertical or horizontal, right or left.
- But light is made of photons (particles)
- A polarizer either stops a photon or lets it go through.
- Remember, relativity implies that photons don’t experience time so they cannot change or evolve.
- But we can do something to make them change their polarization

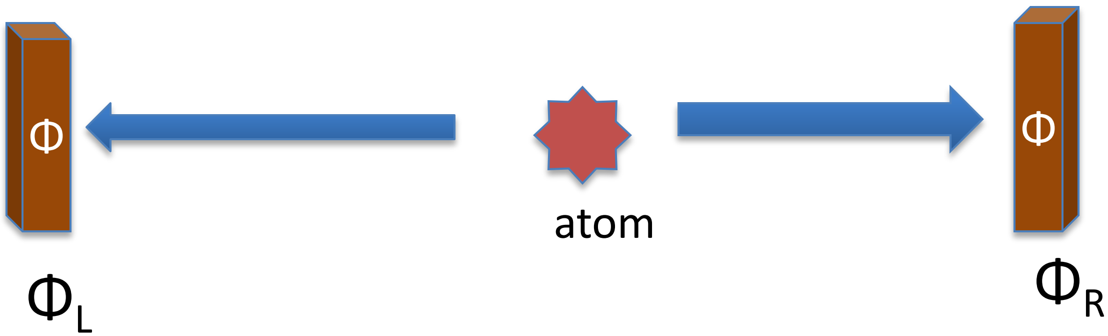




Quantum theory of light

- If a photon is known to be vertically polarized and it is passed thru a filter of angle Φ:
  - Probability of making through is $\cos^2(\Phi)$
  - Polarization state afterwards is Φ.
- The polarization description of 0^o and 45^o are complementary (like x and p). You cannot know both.
- If we measure the component in the vertical direction we destroy the component in the diagonal direction. (or any other direction)!
- Consistent with Maxwell's equation, except light is made of photons (quantized)

EPR experiment (Bohm's version)



- The source emits 2 photons are once, one to the left and one to the right.
- The photons always have the same polarizations
- If $\Phi_L = \Phi_R$ then left and right detectors either both detect a photon or neither do.
- If the detectors are at right angles then if the left detects the right does not and v.v.
- Random events are perfectly correlated.
- The distance of the polarizers from the source is irrelevant.
- Are they like identical twins? The attributes are unknown but if I know one, I can predict the other one.
  - <u>Classical ignorance</u>
  - <u>Quantum ignorance</u>: the polarization state is partially created by measurement.

Einstein-Podolsky-Rosen (1935)

"Can a quantum mechanical description of physical reality be considered complete?"

- Einstein and collaborators (EPR) proposed that by using the conservation laws, one could show that QM was missing something.
- Either polarization might occur, but not a mixture, which would violate conservation of momentum.
- A conservation law says the particles have to have the same polarizations.

- Possible resolutions:
  - The conservation laws only hold on the average.
    Bohr thought this at one time, but it's completely wrong experimentally.
  - The particles always have the same polarization, because there is some hidden variable which allows them to know what to do when they are detected. QM is incomplete!
  - Even though it is predetermined that the photons are coupled, what those polarizations are is not determined until one is (randomly) detected. The other somehow knows its polarization, faster than the speed of light!
  - Einstein believed that this argument showed the incompleteness of QM.
  - But experiment finds such "*spooky correlations at a distance.*"

- Assume locality as demanded by the special theory of relativity.
- Implies that the left polarizer should not affect the right polarizer.
- If left polarizer were to be held at Φ, then the result for the right polarizer will be known if it is measured either at Φ or at right angles.
- We cannot use to send a signal because only after 2 observers have recorded their findings and brought than back together can we see that correlations exist. "quantum cryptography"
- Einstein: Each photon carries along "hidden variables" that say whether or not it will go through any possible filter.
- Bohr: How do you know? You can only do one measurement. After that the state has changed.
- "Counterfactual definiteness": a certain outcome would have led to a definite outcome.
- Bohr: "Unperformed experiments have no outcomes."

Einstein’s thesis:

- Reality Criteria “if without in any way disturbing a system we can predict with certainty the value of a physical quantity, then that quantity is physically real.”
- Completeness Criteria “ A theory is complete only if every element of physical reality has a counterpart in the theory.”
- “We are forced to conclude that the quantum mechanical description of physical reality is not complete.”
- Quantum mechanics has "spooky correlations at a distance."

Bohr's response:

- "The account must include all relevant features... Indeed the festure of wholeness ... Any attempt at a subdivision would demand a change in the experimental arrangement incompatible with the phenomena under investigation."
- "The apparent contradiction in fact discloses only an essential inadequacy of the customary viewpoint of natural philosophy for a rational account of physical phenomena....The interaction between object and measuring agencies entails- because of the impossibility of controlling the reaction of the object on the measuring instruments...the necessity of a final revision of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. The criterion of reality proposed contains an essential ambiguity... regarding the expression 'without in any way disturbing the system' The principal point is that such measurements demand mutually exclusive arrangements."
- "It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature."

Hidden Variables

- Nature follows the classical picture, with each event following directly from local causes:
  - Einstein, Schrödinger, DeBroglie thought it would work.
  - Bohr, Heisenberg, etc. assumed that it couldn't work.
  - We've seen that Bohr won the debate with Einstein as to whether there was some way around the uncertainty principle.
- Von Neumann had a purported proof that NO hidden variable theory could reproduce the results of QM. The proof was accepted for decades, until Bohm came up with a counter-example. Bohm showed that Von Neumann had snuck in a hidden assumption: that the measured property must depend only on the micro-system, and not also on the measurement apparatus.
- Bohm constructed an HV theory which could explicitly reproduce the results of QM for a single local variable, e.g. spin.
- But John Bell followed up on the original Einstein ideas for ways to show the incompleteness of QM by showing that for spatially extended systems, no LOCAL HV theory can reproduce the results of QM.
- Experiments agreed with QM, violating the predictions of all local realist theories.

Proof of Bell's theorem

- Assume there are 3 settings for the left and right detector.

  $\Phi=(0^o,30^o,60^o)$

- Quantum mechanics predicts:
  1. If R and L detectors are set the same, detectors always agree
  2. If we average over all 9 settings, we get equal number of agreements and disagreements.

These facts rule out a local hidden variable theory.

PROOF: assume each particle carries along information that tells what will happen for the 3 settings.

- There are 8 possible hidden variables (yyy,yyn,yny,….nnn)
- Call the unanimous variables (yyy or nnn) case A, and the mixed variables (yyn,yny,…) case B.
- For A particles, what is average over all 9 settings ?
- For B particles, what is average over all 9 settings?

How can we choose A or B to satisfy #2?

Case A

Hidden variable:
yyy

left/right	0	30	60
0	a	a	a
30	a	a	a
60	a	a	a

100% agreement

Case B

Hidden variable:
yyn

left/right	0	30	60
0	a	a	d
30	a	a	d
60	d	d	a

5/9 agreement=55.5%

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- For B particles, what is average over all 9 settings?

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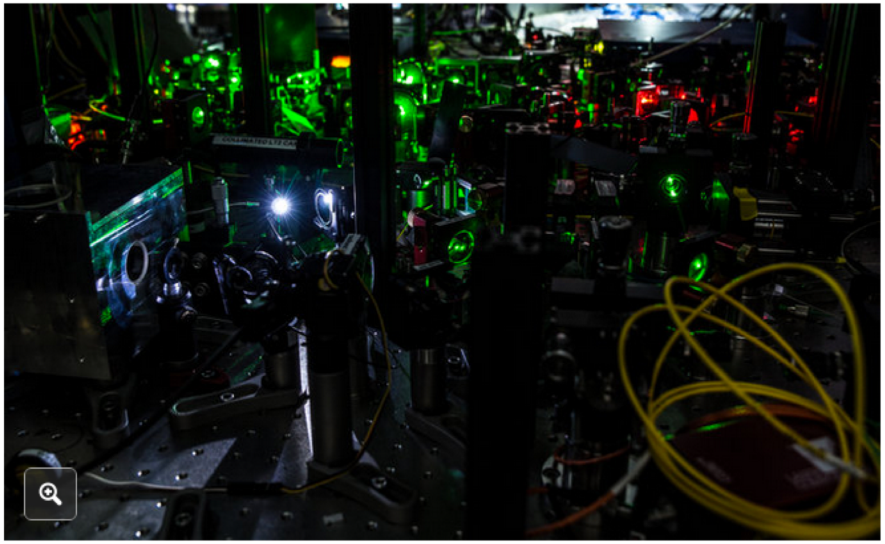
- Call the unanimous variables (yyy or nnn) case A, and the mixed variables (yyn,yny,…) case B.
- For A particles, what is average over all 9 settings ? 100%
- For B particles, what is average over all 9 settings? 56%

How can we choose A or B to satisfy #2? Impossible

SCIENCE

Sorry, Einstein. Quantum Study Suggests 'Spooky Action' Is Real.

By JOHN MARKOFF OCT. 21, 2015



Part of the laboratory setup for an experiment at Delft University of Technology, in which two diamonds were set 1.3 kilometers apart, entangled and then shared information.
Frank Auperle/Delft University of Technology

In a landmark study, scientists at Delft University of Technology in the Netherlands reported that they had conducted an experiment that they say proved one of the most fundamental claims of quantum theory — that objects separated by great distance can instantaneously affect each other's behavior.

The finding is another blow to one of the bedrock principles of standard physics known as "locality," which states that an object is directly influenced only by its immediate surroundings. The Delft study, published Wednesday in the journal Nature, lends further credence to an idea that Einstein famously rejected. He said quantum theory necessitated "spooky action at a distance," and he refused to accept the notion that the universe could behave in such a strange and apparently random fashion.

But since the 1970s, a series of precise experiments by physicists are increasingly erasing doubt — alternative explanations that are referred to as loopholes — that two previously entangled particles, even if separated by the width of the universe, could instantly interact.

The new experiment, conducted by a group led by Ronald Hanson, a physicist at the Dutch university's Kavli Institute of Nanoscience, and joined by scientists from Spain and England, is the strongest evidence yet to support the most fundamental claims of the theory of quantum mechanics about the existence of an odd world formed by a fabric of subatomic particles, where matter does not take form until it is observed and time runs backward as well as forward.

The researchers describe their experiment as a "loophole-free Bell test" in a reference to an experiment proposed in 1964 by the physicist John Stewart Bell as a way of proving that "spooky action at a distance" is real.

"These tests have been done since the late '70s but always in the way that additional assumptions were needed," Dr. Hanson said. "Now we have confirmed that there is spooky action at distance."

According to the scientists, they have now ruled out all possible so-called hidden variables that would offer explanations of long-distance entanglement based on the laws of classical physics.

The Delft researchers were able to entangle two electrons separated by a distance of 1.3 kilometers, slightly less than a mile, and then share information between them. Physicists use the term "entanglement" to refer to pairs of particles that are generated in such a way that they cannot be described independently. The scientists placed two diamonds

Researchers like Dr. Hanson envision a quantum communications network formed from a chain of entangled particles girdling the entire globe. Such a network would make it possible to securely share encryption keys, and know of eavesdropping attempts with absolute certainty.

Loopholes?

1. The initial passage of the particles through the angular momentum selectors are space-like separated. In the first generation of experiments, the conversion of those micro-events to some large-scale device setting was slow enough for it to be conceivable that a time-like signal could propagate between the detectors before "measurement" is complete. This loophole is now closed in some experiments, e.g. with satellites many km apart.

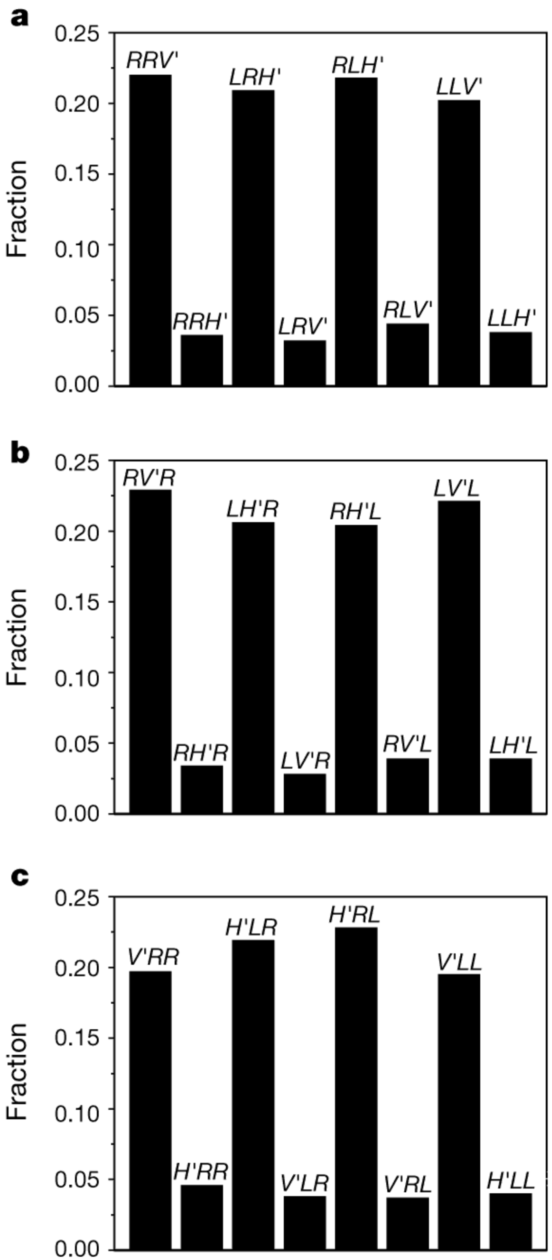
2. Detection efficiency. There's a complication in that many particles are missed, requiring some extrapolation. This is now closed in some experiments using atoms rather than photons.

The loopholes have mostly been closed with better experiments.

Does the problem lie with probabilities?

- We concentrated on probabilities and correlations. This may give the incorrect impression that the fundamental issue is the probabilities. It is possible to devise a 3-particle spin measurement in which the distinction between QM and local reality can be seen in every single measurement.
- Prepare a 3-particle (each spin 1/2) state with the z-components of the spins described by (uuu - ddd)/$2^{1/2}$. Measure the x-components of the spins.
  - QM predicts $s_1 s_2 s_3 = -1$, always,
  - LR predicts $s_1 s_2 s_3 = +1$, always.
- A single measurement of the 3 spins could do the job. (See article by N. D. Mermin in *Physics Today* , June 1990.)

Three-particle results



Nature **403**, 515-519 (3 February 2000) | doi:10.1038/35000514

Experimental test of quantum nonlocality in three-photon Greenberger–Horne–Zeilinger entanglement

Jian-Wei Pan[1], Dik Bouwmeester[2], Matthew Daniell[1], Harald Weinfurter[3] & Anton Zeilinger[1]

More than 85% of the time $X_1X_2X_3 = -1$ was found, which is impossible classically. The remaining 15% or so is attributed to imperfections in the analyzers, etc.

We assumed

- Realism. Not that the world must be deterministic, but only that those aspects of it which can be predicted perfectly are determined by some element of reality. You can predict the result on any particle by making the corresponding measurement on its partner.
  - "If, without in any way disturbing a system, we can predict with certainty (*i.e.*, probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity." (Einstein, Podolsky, Rosen, 1935)
- Local causality. The value of a property possessed by an isolated system cannot be affected by any operations carried out at a sufficient (*i.e.*, spacelike) separation from it.
- Induction. (no conspiracies) The unmeasured values (chosen by random quantum processes) are not statistically different from the measured values. The properties of an ensemble are defined completely by the preparation conditions. In particular, the distribution of "possessed values" of a variable for the subensemble which we actually measure is identical to the distribution for the complete ensemble. (random sampling)

Which one are you willing to give up?