Local Realism & The EPR-Paradox

Neils Bohr and Werner Heisenberg

"The problems of language here are really serious. We wish to speak in some way about the structure of the atoms. But we cannot speak about atoms in ordinary language."

- Werner Heisenberg

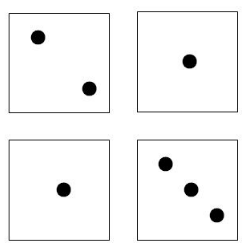
Day 38:
Hidden Variables
Local Realism
EPR Thought Experiments

Up Next:
Testing Local Realism
Single-Photon Experiments
And see Readings and reading questions for HW

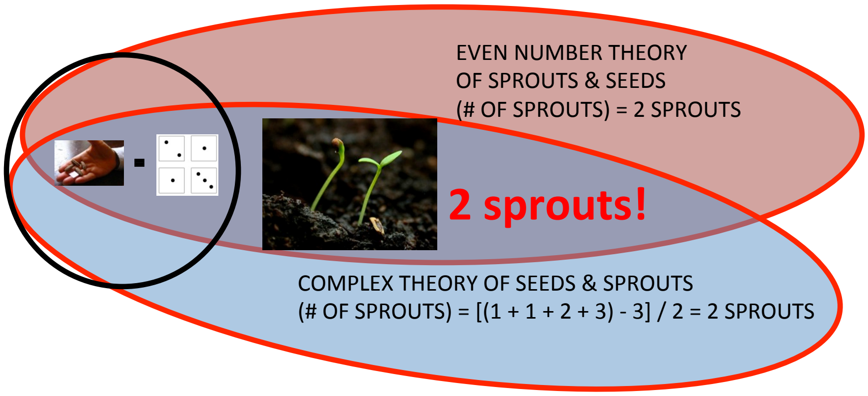
1

A MODEL

=

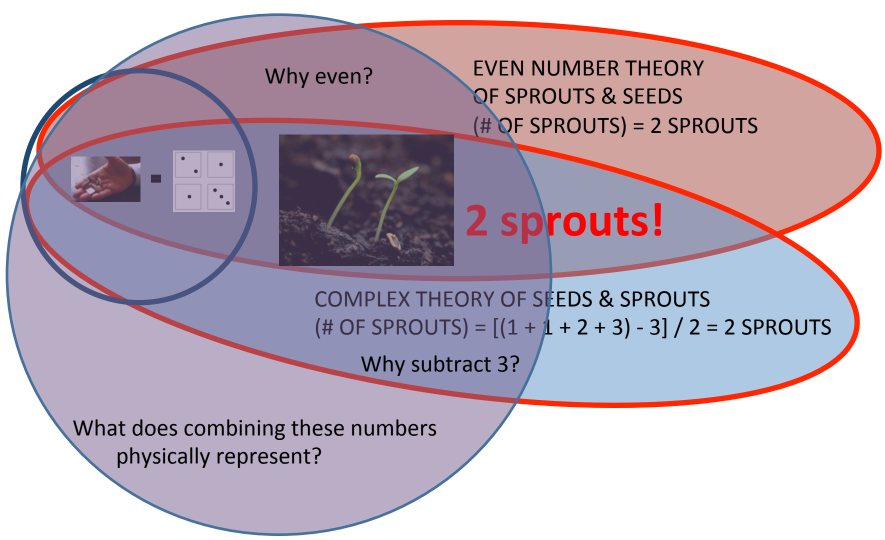


COMPETING THEORIES



…constrained by observation

INTERPRETATION



Summary

- Scientists "make up" theories to explain the evidence they see.
- These theories are constrained by experiment.
- We can't always open up the seed and look inside. Have to make inferences from indirect evidence.
- A theory with a plausible mechanism is more convincing than a rote algorithm.
- The more different cases our theory works on, the more we believe it.
- But it could always be wrong…

This Week:

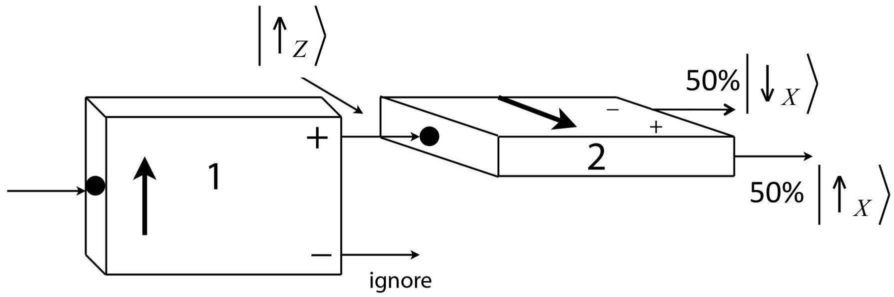
1. Longer readings (on D2L), different approach to homework.
2. Less calculations, more words.
3. Respond to reading questions (posted on the hoemwork).

Today:

1. Reminders of probability and Stern-Gerlach
2. Interpretations of repeated spin measurements (hidden variables).

2. Local Realism (an intuitive view of the universe).
3. Distant correlated measurements and what they imply about the nature of reality.

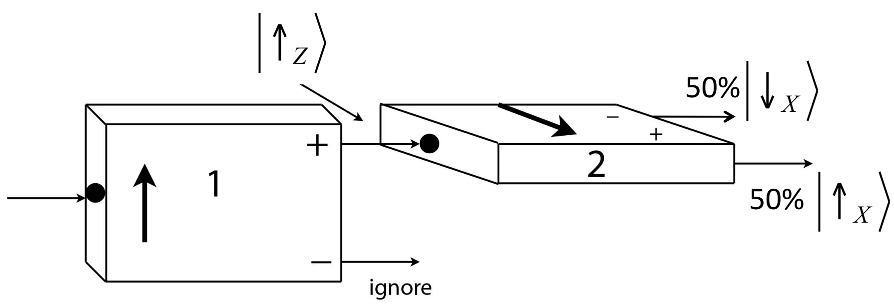
6



We always get one of two possible results: $|\uparrow_X\rangle$ or $|\downarrow_X\rangle$

With **Analyzer 2** oriented at 90^0 to **Analyzer 1**, either result $|\uparrow_X\rangle$ or $|\downarrow_X\rangle$ is equally likely.

We can't predict ahead of time whether an atom will exit through the plus-channel or the minus-channel of **Analyzer 2**, only that there is a 50/50 chance for either to occur.



What would be the expectation (average) value for m_X? $\langle m_X \rangle = ?$

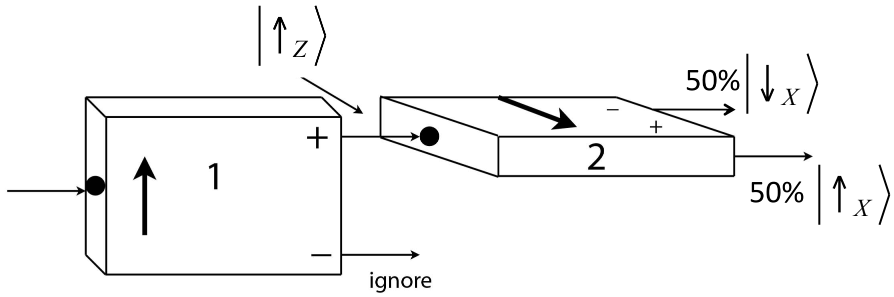
A) $-m_B$
B) $-1/2\ m_B$
C) 0
D) $+1/2\ m_B$
E) $+ m_B$

For continuous x

$$\langle x \rangle = \int_{-\infty}^{+\infty} x\ \rho(x)\ dx$$

For Discrete x

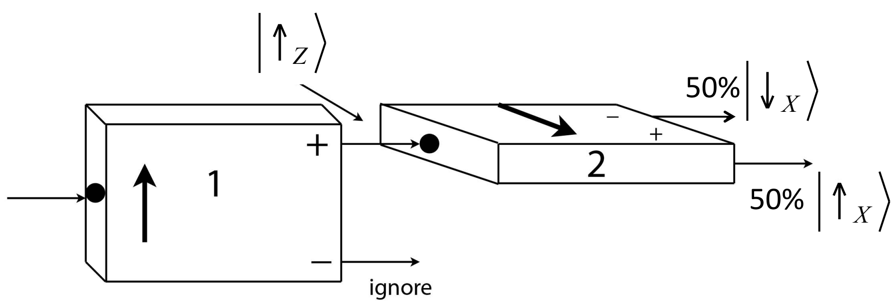
$$\langle x \rangle = \sum_{i=1}^{n} x_i P(x_i)$$



Interpretation One

An atom with a definite value of m_Z also has a definite value of m_X but that value changes so rapidly that we can't predict it ahead of time.

(Remember, magnetic moments precess in the presence of a magnetic field.)



Other Interpretations?

A. ?
B.
C.
D. …

Hidden Variables

By either of the first two interpretations, the ***value of m_X*** for an atom in the state $\left|\uparrow_Z\right\rangle$ would be called a ***hidden variable***.

If m_X has some ***real*** value at any given moment in time that is unknown to us, then that variable is ***hidden***:

- The value of m_X ***exists***, but we can't predict ahead of time what we'll measure ("up" or "down").

- The ***objectively real*** value of m_X is unknown to us until we make an observation.

Classical Ignorance vs. Quantum Uncertainty

- Classical Experiment:
  - Take a blue sock and a red sock
  - Seal them up in identical boxes
  - Mix up boxes
  - Take them to opposite ends of galaxy
  - Open just one box, and you know what color sock is in the other box.

12

Classical Ignorance vs. Quantum Uncertainty

- No one knew which color was in which box until the moment ***one*** of the boxes was opened.
- Opening the first box only revealed to us something that was ***real*** and already ***predetermined*** here on Earth.
- **Quantum mechanics** would say the "quantum socks" were in a ***superposition state*** of equal parts blue and red.

$$\langle m_X \rangle = P\left[\left|\uparrow_X\right\rangle\right](+m_B) + P\left[\left|\downarrow_X\right\rangle\right](-m_B)$$

- Opening ***just one*** box instantly forced ***both socks*** to assume definite (but always opposite) colors ***at random***, even though the boxes are very far apart.
- ***Local Realism*** says that superposition state is a reflection of classical ignorance.

MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.

Albert Einstein believed that the properties of a physical system are ***objectively real*** – they exist whether we measure them or not.

Einstein, ***P***odolsky and ***R***osen (***EPR***) believed in the ***reality*** of hidden variables not described by quantum mechanics.

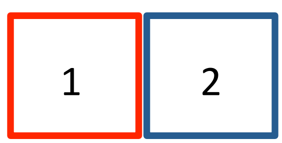
What do they mean by ***complete***?

Completeness

- Quantum mechanics doesn't predict what value of m_x will be measured, only the probability for a specific outcome.
- A theory that can't describe (predict) the value of a real (but unknown) physical quantity could be called ***incomplete.***
- A ***Realist*** (hidden variable) interpretation would say that quantum mechanics is incomplete (**Interpretations One** & **Two**).
- **Interpretation Three** says that m_x doesn't have a definite, real value - the value of ***m_x is indeterminate***.
- Quantum mechanics is ***not necessarily incomplete*** if it doesn't describe the value of a physical quantity that doesn't have a definite value to begin with.

Locality

EPR make one other ***assumption***, but is it really an assumption?



Suppose we have two physical systems, **1** & **2**.

If **1** & **2** are physically separated from one another, ***locality*** assumes that a measurement performed on **System 1** can't affect the outcome of a measurement performed on **System 2**, and vice-versa.

Local Realism

Put together a ***Realist perspective*** and the ***assumption of locality*** and we get an interpretation of quantum mechanics that we'll call ***Local Realism***.

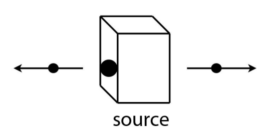
Local Realism says that hidden variables exist and that quantum mechanics is an incomplete description of reality.

Is this a question of science or philosophy?
How could we decide?

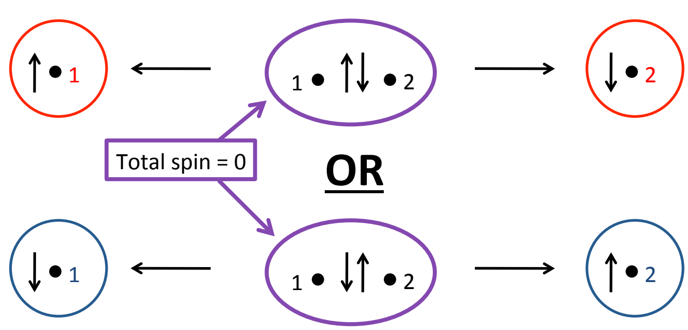
Can we devise an experiment to test whether the assumptions of ***Local Realism*** are correct?

Yes!! But first we have to learn about ***entanglement***…

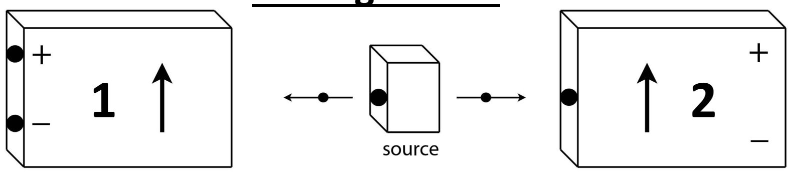
Entanglement



Suppose we have a source that produces ***pairs of atoms*** traveling in ***opposite directions***, and having ***opposite spins***:



Entanglement

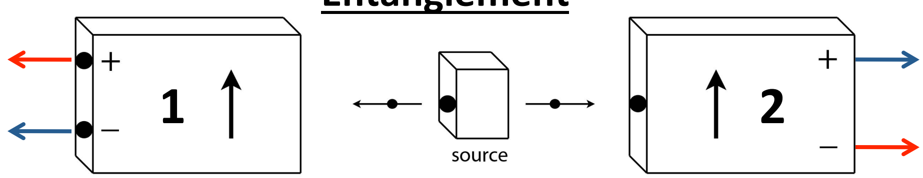


Place two Stern-Gerlach analyzers to the left and right of the source, and oriented at the same angle.

Let $|\Psi_{12}\rangle$ represent the quantum state of ***both*** atoms **1** & **2**.

How would we represent this?

Entanglement



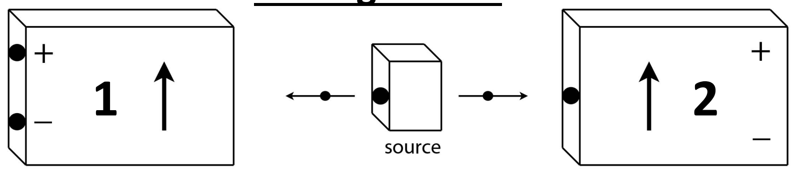
- We can't predict what the result for each individual atom pair will be.
- $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle$ and $|\Psi_{12}\rangle = |\downarrow_1\rangle|\uparrow_2\rangle$ are both equally likely.
- ***Quantum mechanics*** says to describe the quantum state of each atom pair as a ***superposition*** of the two possible states:

$$|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle \quad *$$

- When we perform the measurement, we only get one of the two possible outcomes, each with a probability of 1/2.

*NB: not normalized!

Entanglement



We measure at analyzer 1 $\left|\downarrow_1\right\rangle$

What is the wave function (state):

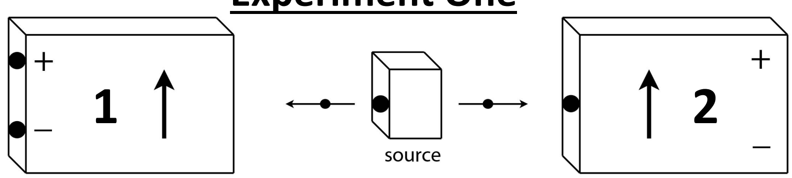
a) $\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle$

b) $\left|\Psi_{12}\right\rangle = \left|\downarrow_1\right\rangle\left|\uparrow_2\right\rangle$

c) $\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle + \left|\downarrow_1\right\rangle\left|\uparrow_2\right\rangle$

d) We can tell anythign

Experiment One



- Rotate the analyzers by any angle, as long as they're both pointing along the ***same direction***.
- If we measure along the x-axis, the result is either

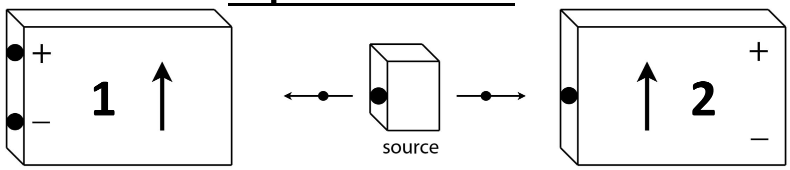
$$\left|\Psi_{12}\right\rangle = \left|\uparrow_{1,X}\right\rangle\left|\downarrow_{2,X}\right\rangle \quad \underline{\textbf{or}} \quad \left|\Psi_{12}\right\rangle = \left|\downarrow_{1,X}\right\rangle\left|\uparrow_{2,X}\right\rangle$$

- If we measure along the z-axis, the result is either

$$\left|\Psi_{12}\right\rangle = \left|\uparrow_{1,Z}\right\rangle\left|\downarrow_{2,Z}\right\rangle \quad \underline{\textbf{or}} \quad \left|\Psi_{12}\right\rangle = \left|\downarrow_{1,Z}\right\rangle\left|\uparrow_{2,Z}\right\rangle$$

- This is true no matter what angle we choose, as long as both analyzers point along the ***same direction***.

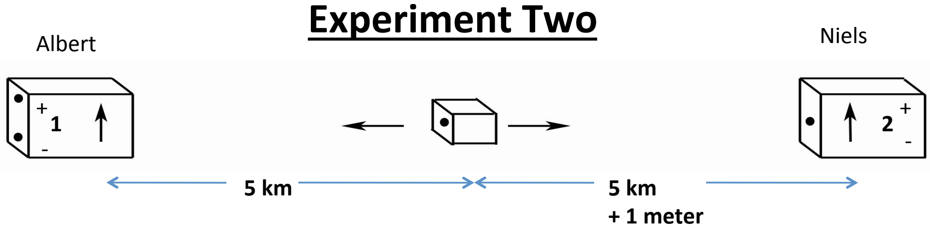
Experiment One



- The results of **Experiment One** show that the measurements performed on **Atom 1** and on **Atom 2** are ***anti-correlated***.
- ***Anti***-correlated means that, whatever answer we get for **Atom 1**, we'll get the ***opposite*** answer for **Atom 2**, as long as we're asking the ***same question***.
- Atom pairs in a correlated state $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle$ are said to be ***entangled***.

Note that $|\Psi_{12}\rangle \neq |\Psi_1\rangle|\Psi_2\rangle$!!

Experiment Two

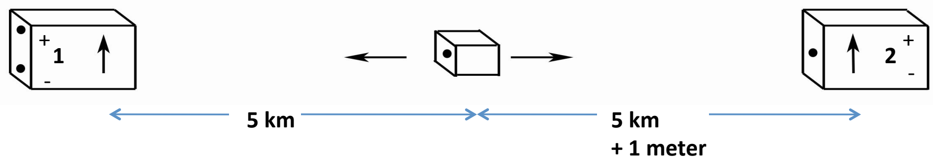


- **Analyzer 1** (watched by **Albert**) is placed 5 km to the left of the source.
- **Analyzer 2** (watched by **Niels**) is placed 5 km ***plus one meter*** to the right of the source.
- Perform **Experiment One**, exactly as before.
- How is this experiment different from the first?

Experiment Two

Albert

Niels



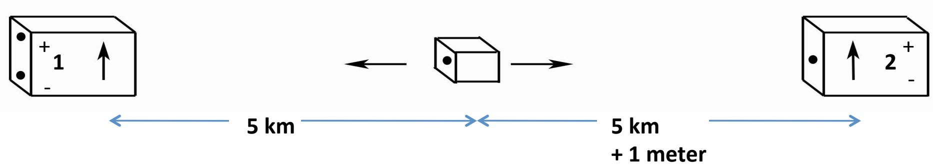
- **Albert** can tilt **Analyzer 1** any way he wants, and **Niels** can do the same with **Analyzer 2**.
- When **Analyzers 1** & **2** are tilted at different angles, they sometimes get the same answer, sometimes different answers.
- But when they compare their data, whenever the analyzers were tilted at the same angle they got ***opposite*** answers.
- The measurements are still 100% ***anti-correlated***.

$$\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle + \left|\downarrow_1\right\rangle\left|\uparrow_2\right\rangle$$

The EPR Argument

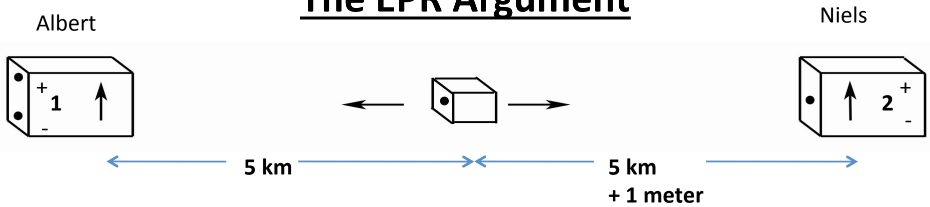
Albert

Niels



- **Analyzers 1** & **2** are set at the same angle and **Albert** measures the spin of **Atom 1** ***first.*** He observes $\left|\uparrow_1\right\rangle$.
- **Albert** ***knows*** what the result of **Niels'** measurement will be ***before*** **Atom 2** reaches **Analyzer 2**. [And **Niels** knows he knows it.]
- If we ***assume locality***, then **Albert's** measurement can't change the outcome of **Niels'** measurement! **Niels** observes $\left|\downarrow_2\right\rangle$, and that must have been the state of **Atom 2** all along.

The EPR Argument



- In other words, if **Albert** can predict with 100% certainty that **Niels** will observe $\left|\downarrow_2\right\rangle$ ***before*** he performs the measurement, then $\left|\downarrow_2\right\rangle$ must have been the ***real***, ***definite*** state of **Atom 2** ***at the moment the atom pair was produced***.

- ***Local Realism*** says the atom pair was produced in the state

$$\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle$$

and the measurements revealed this ***unknown reality*** to us.

OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. Bohr, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

- ***The Copenhagen Interpretation*** says the atom pair was produced in the ***superposition*** state $\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle + \left|\downarrow_1\right\rangle\left|\uparrow_2\right\rangle$

- Albert's measurement of $\left|\uparrow_1\right\rangle$ ***instantly collapses*** $\left|\Psi_{12}\right\rangle$ into the ***definite*** state $\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle\left|\downarrow_2\right\rangle$

- This ***collapse*** must be ***instantaneous***, because there is no time for a signal to travel from **1** to **2**.

Albert Einstein: God does not play dice with the universe.

Niels Bohr: Who are we to tell God how to act?

Niels Bohr and Albert Einstein together at the 1930 Solvay Conference.

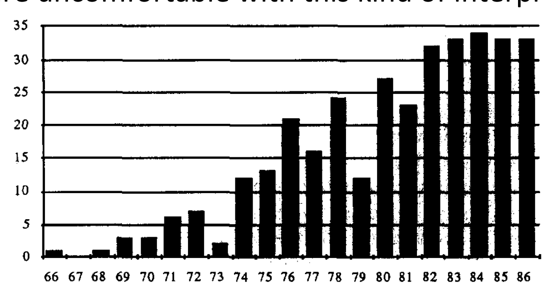
Philosophy or Science?

Bell's Theorem

There is a powerful general theorem by J. S. Bell that proves:

No local interpretation of quantum phenomena can reproduce all of the predictions of quantum mechanics.

[We can devise a realistic scheme that is non-local, but most scientists are uncomfortable with this kind of interpretation.]

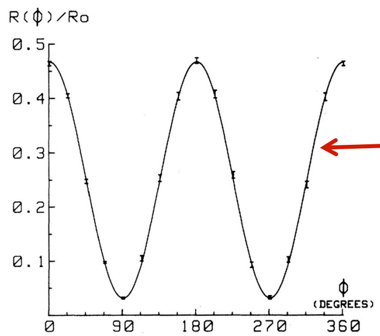


Number of annual citations of "On the Einstein-Podolsky-Rosen Paradox"
J. S. Bell, *Physics* **1**, 195 (1964)

Bell's Theorem

There is a more general theorem by J. S. Bell that proves:

No local interpretation of quantum phenomena can reproduce all of the predictions of quantum mechanics.

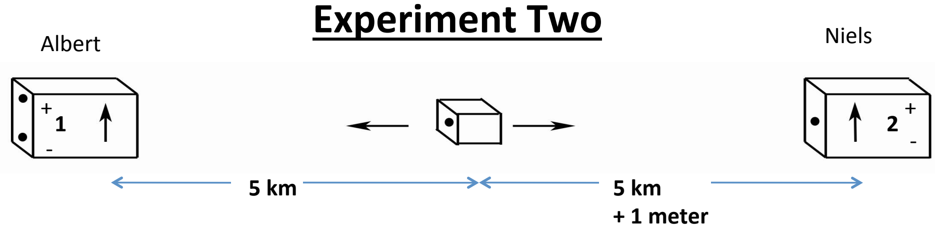


Error bars represent one standard deviation

Not a "best-fit" curve !!

A test of Bell's Theorem performed by A. Aspect (1981)

Experiment Two



- **Albert** can tilt **Analyzer 1** any way he wants, and **Niels** can do the same with **Analyzer 2**.
- When **Analyzers 1** & **2** are tilted at different angles, they sometimes get the same answer, sometimes different answers.
- But when they compare their data, whenever the analyzers were tilted at the same angle they got ***opposite*** answers.
- The measurements are still 100% ***anti-correlated***.

$$|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle + |\downarrow_1\rangle|\uparrow_2\rangle$$

Interpretations One & **Two** involved ***hidden variables***.

Interpretation Three said:

In general, the state of a quantum system is indeterminate until measured.

We can restate this as:

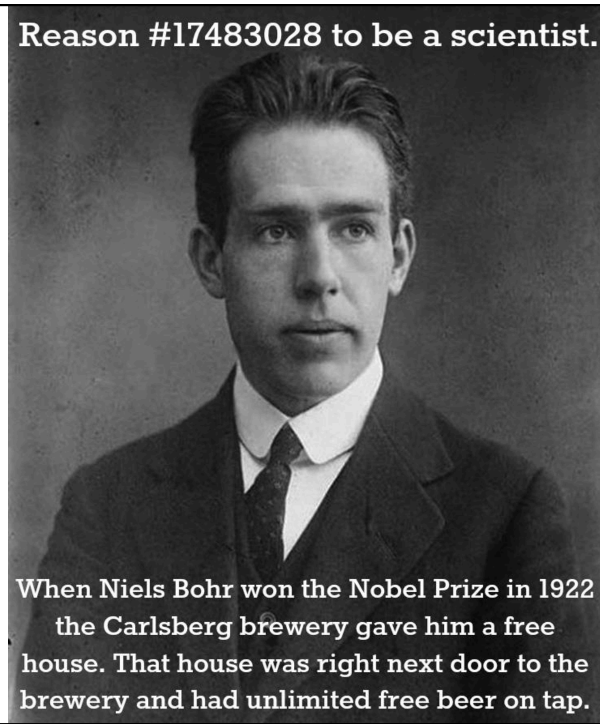
THE OUTCOME OF A QUANTUM EXPERIMENT CANNOT, ***IN GENERAL****, BE PREDICTED EXACTLY; ONLY THE PROBABILITIES OF THE VARIOUS OUTCOMES CAN BE FOUND.

****IN GENERAL*** – What would be a counter-example to this statement?

Single Photon Experiments

"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.

– **Niels Bohr**


Reason #17483028 to be a scientist.
When Niels Bohr won the Nobel Prize in 1922 the Carlsberg brewery gave him a free house. That house was right next door to the brewery and had unlimited free beer on tap.