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

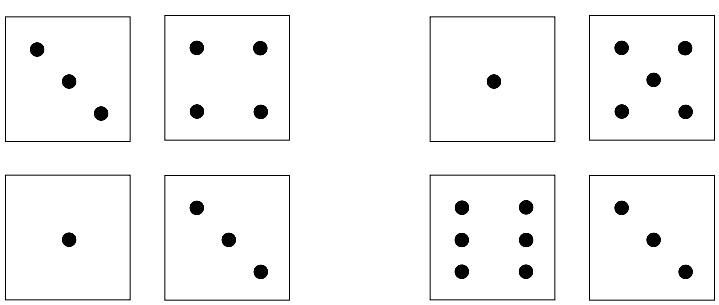
Up Next:
Testing Local Realism
Single-Photon Experiments
And see Readings and reading questions for HW

The Farmer and the Seeds

(a parable of scientific reasoning)

- A seed is a square with some dots on it.
- The farmer always plants 4 seeds in a group.

First Group: Second Group:



- Farmer observes # of sprouts each group produces.

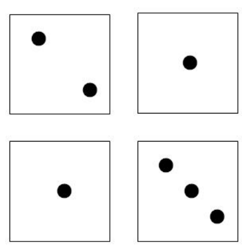
Questions from this story:

Possible Schemes
1. Totally Random (???)
2. (Number that is even) = 2 Sprouts
3. [(Sum of all Numbers) – 3] / 2 = 2 Sprouts

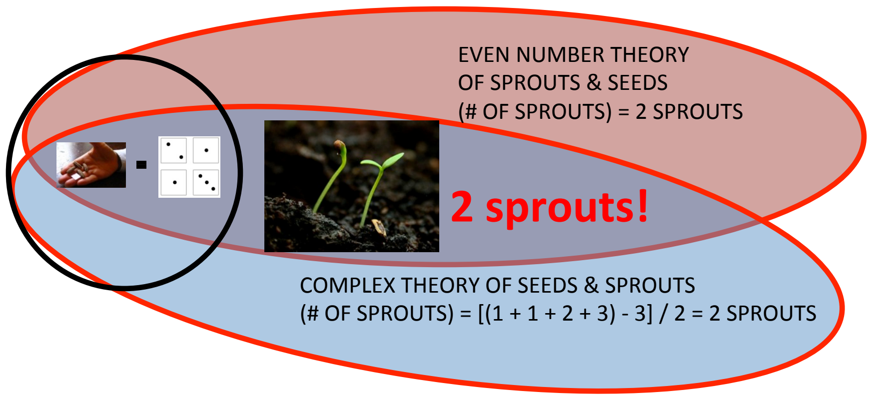
1. How could we decide if any of these three schemes is the correct one?
2. If the farmer had to wait to plant more seeds, are there reasons we might in the meantime favor one scheme over another?
3. How do we know if we've figured out all the possible schemes?
4. Where did these schemes we've been discussing come from? (Note: This question is not about the elements of the schemes, but the decisions as to what elements to use and how to use them.)

A MODEL

=

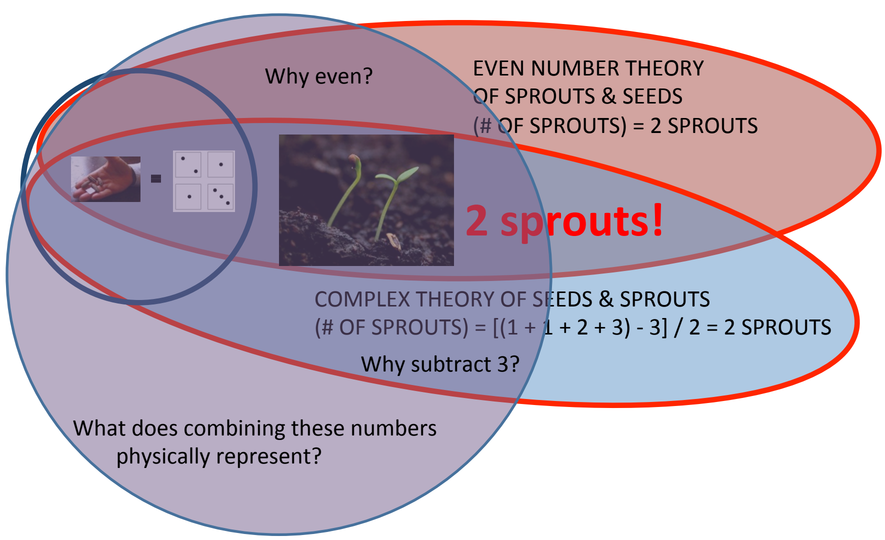


COMPETING THEORIES



…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…

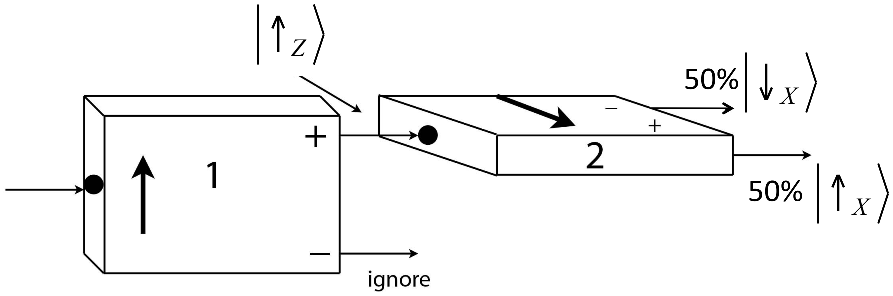
This Week:

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.

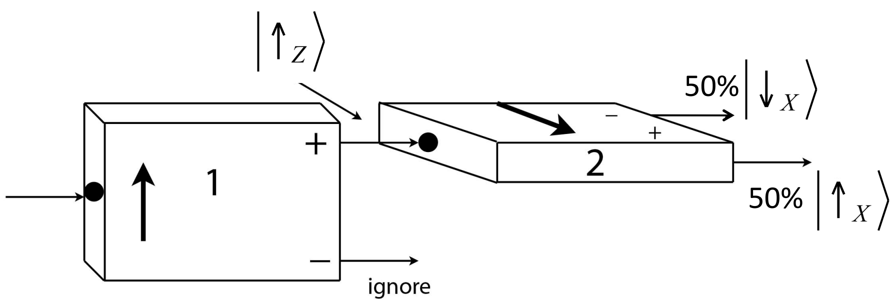
8



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? $\langle m_X \rangle = ?$

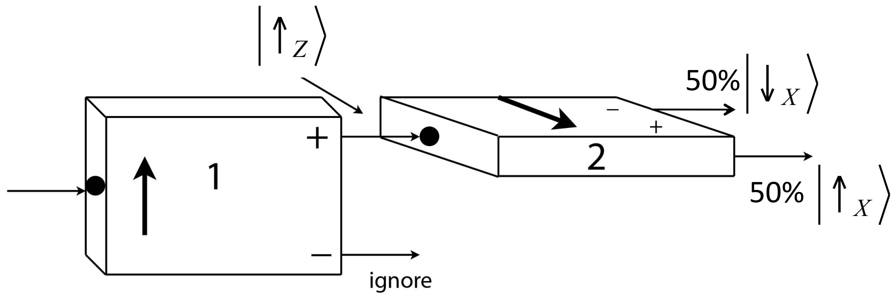
A) $-m_B$
B) $-1/2\ m_B$
C) 0
D) $+1/2\ m_B$
E) $+\ m_B$

For continuous x

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

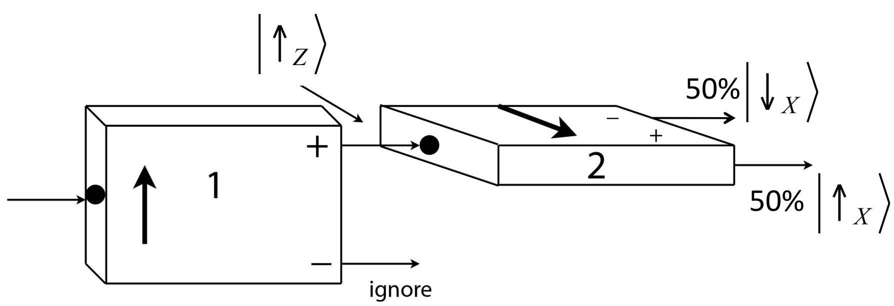
For Discrete x

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



What would be the expectation (average) value for m_X?

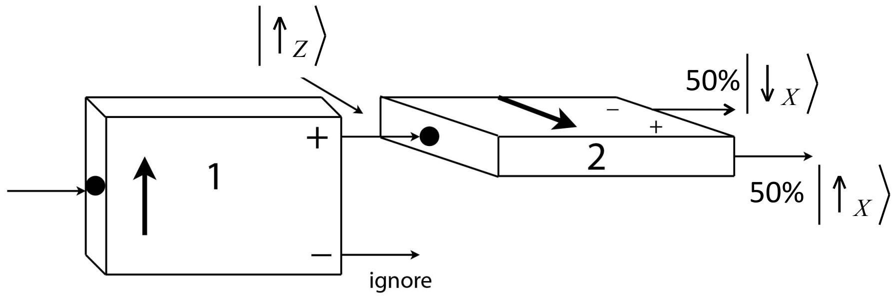
$$\langle m_X \rangle = P\left[\left|\uparrow_X\right\rangle\right](+m_B) + P\left[\left|\downarrow_X\right\rangle\right](-m_B)$$
$$= (0.50)(+m_B) + (0.50)(-m_B) = 0$$



Interpretation One

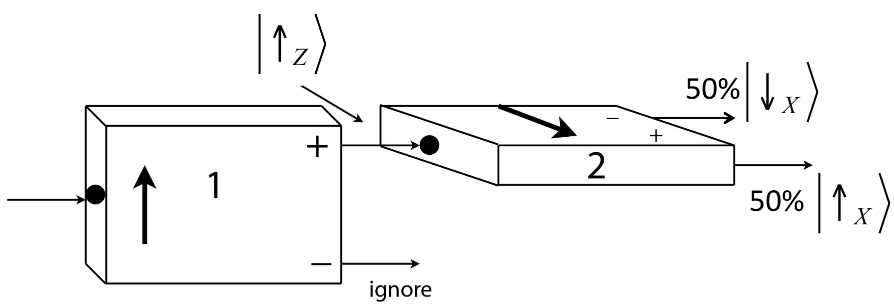
An atom with a definite value of m_Z also has a definite value of m_X but that value changes so rapidly that we can't predict it ahead of time.

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



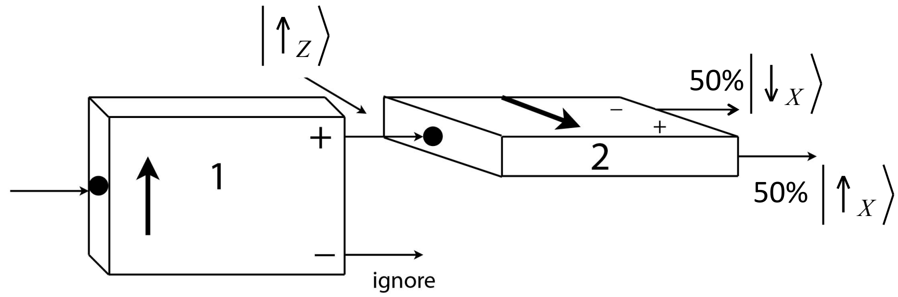
Other Interpretations?

A. ?
B.
C.
D. …



Interpretation Two

An atom with a definite value of m_z also has a definite value of m_x but measuring m_z disturbs the value of m_x in some unpredictable way.



Interpretation Three

An atom with a definite value of m_Z doesn't have a definite value of m_X. All we can say is that there is a 50% probability for either value to be found when we make the measurement.

Which interpretation sounds most reasonable to you?

A) **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.

B) **Interpretation Two**: An atom with a definite value of m_Z also has a definite value of m_X but measuring m_Z disturbs the value of m_X in some unpredictable way.

C) **Interpretation Three**: An atom with a definite value of m_Z doesn't have a definite value of m_X until measured.

D) **A & B seem equally reasonable.**

E) **Something else…**

Hidden Variables

By either of the first two interpretations, the ***value of m_X*** for an atom in the state $|\uparrow_Z\rangle$ 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.

21

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.

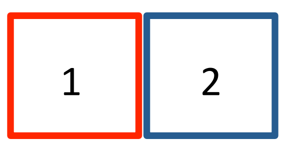
What do they mean by ***complete***?

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***.

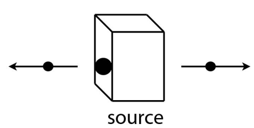
Local Realism says that hidden variables exist and that quantum mechanics is an incomplete description of reality.

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

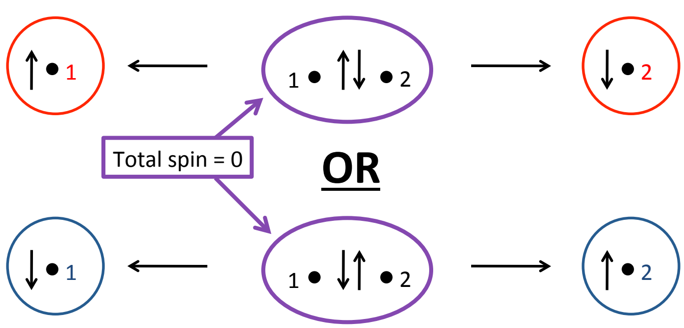
Can we devise an experiment to test whether the assumptions of ***Local Realism*** are correct?

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

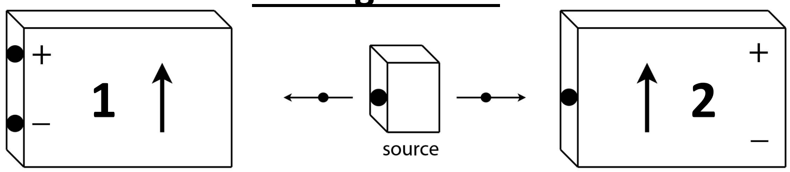
Entanglement



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



Entanglement

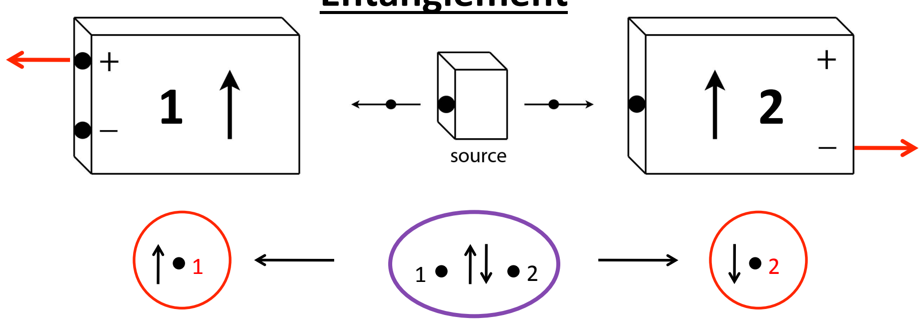


Place two Stern-Gerlach analyzers to the left and right of the source, and oriented at the same angle.

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

How would we represent this?

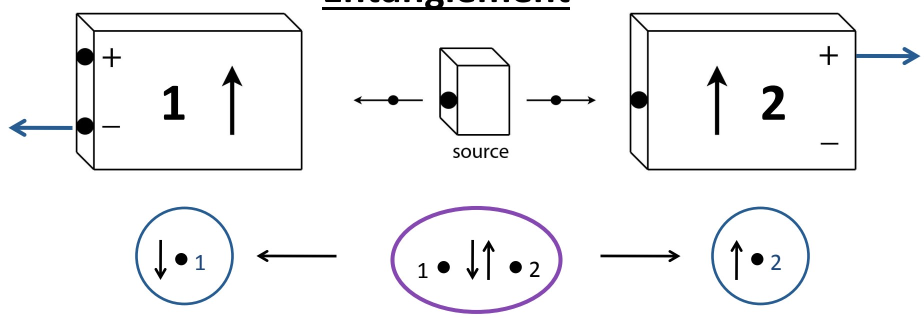
Entanglement



If **Atom 1** exits through the plus-channel of **Analyzer 1**, then **Atom 2** will ***always*** exit through the minus-channel of **Analyzer 2**.

We can write this state as: $\left|\Psi_{12}\right\rangle = \left|\uparrow_1\right\rangle \left|\downarrow_2\right\rangle$

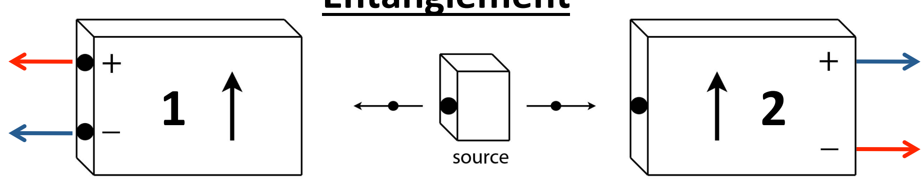
Entanglement



If **Atom 1** exits through the minus-channel of **Analyzer 1**, then **Atom 2** will ***always*** exit through the plus-channel of **Analyzer 2**.

We can write this state as: $|\Psi_{12}\rangle = |\downarrow_1\rangle|\uparrow_2\rangle$

Entanglement



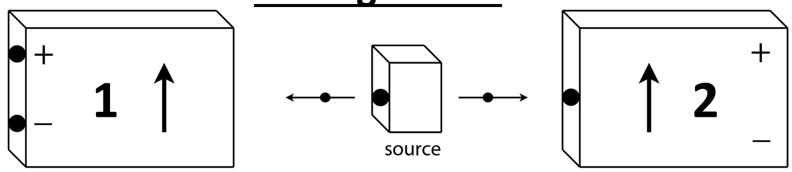
- We can't predict what the result for each individual atom pair will be.
- $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle$ and $|\Psi_{12}\rangle = |\downarrow_1\rangle|\uparrow_2\rangle$ are both equally likely.
- ***Quantum mechanics*** says to describe the quantum state of each atom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

What is the wave function (state):

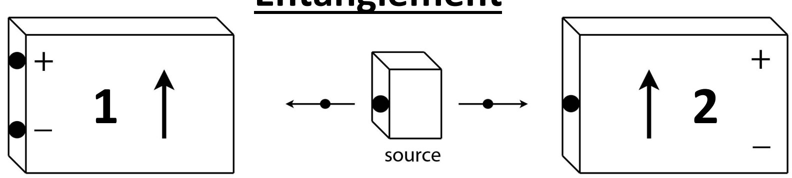
a) $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle$

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

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

d) We can tell anythign

Entanglement



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

What is the wave function (state):

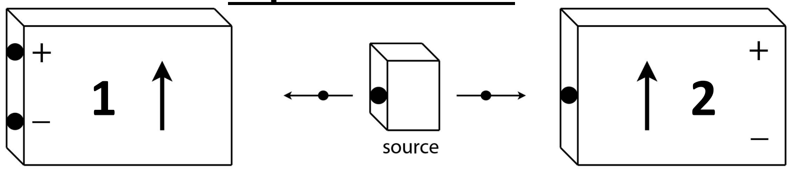
a) $|\Psi_{12}\rangle = |\uparrow_1\rangle|\downarrow_2\rangle$

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

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

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

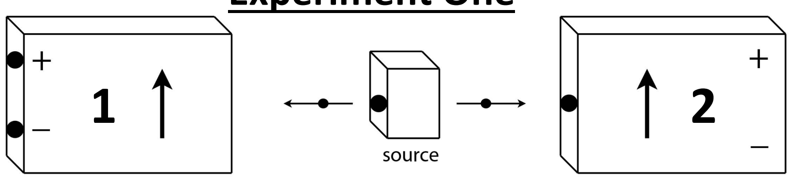
$$|\Psi_{12}\rangle = |\uparrow_{1,X}\rangle|\downarrow_{2,X}\rangle \quad \underline{\textbf{or}} \quad |\Psi_{12}\rangle = |\downarrow_{1,X}\rangle|\uparrow_{2,X}\rangle$$

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

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

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

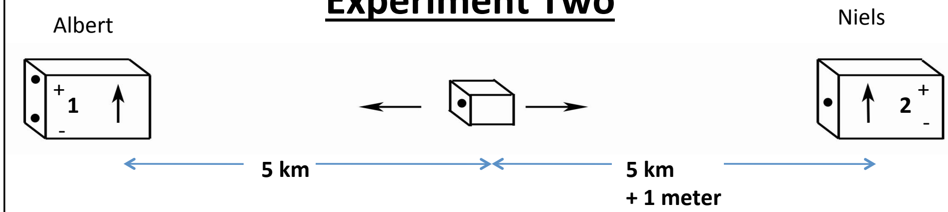
Experiment One



- 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?