QUANTUM (Q)-KIT

Entanglement:

Laboratory for Primary Level Students

Student Manual

WOMEN SUPPORTING
WOMEN IN THE SCIENCES

Meet a Scientist

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About me: I recently defended my PhD in Materials Science and Engineering from Nelson Mandela African Institution of Science and Technology in Arusha, Tanzania, and my PhD research focused on wastewater treatment, biochar, ceramics, geopolymers, and sustainable building materials. As a materials scientist with a background in chemistry, I am also passionate about quantum science due to its potential for innovation in materials science. I believe that fostering an understanding of quantum science at an early stage can inspire the next generation of scientists to tackle global challenges.

What is my philosophy? Throughout my career, I have adhered to a principle that has guided me: "I have my lane, and I will follow it with diligence and purpose." This philosophy has allowed me to focus on my own development, rather than comparing myself to others. It has been a journey of continuous learning, resilience, and dedication, where each challenge was met with determination, and each success was a reflection of consistent effort.

Mission Statement

The mission of this laboratory is to teach primary level students (ages ~5-11) about entanglement and measurement of entangled states through analogous experiments and activities.

Contents

1. Introduction to WS2 Laboratory Kits

1.1. Information about WS2

Women Supporting Women in the Sciences (WS2), an international organization unifying and supporting graduate and professional-level women and allies in science, technology, engineering, and mathematics (STEM), was awarded an American Physical Society (APS) Innovation Fund in 2020 to form international teams to design and distribute low-cost physics and materials science lab kits to primary and secondary school students, predominantly in eastern Africa. The lab kits utilized local resources and included topics that are especially relevant to young girls in order to spur their interest in STEM subjects. From 2020-2023, over 5100 students from eastern Africa at over 40 school sites engaged with our lab kits, with 62% being girls.

WS2 was awarded their second APS Innovation Fund in 2025 to support another Lab Kit Initiative, though this time with a focus on quantum topics. For more information about WS2, please visit our website at ws2global.org.

WS2 is sponsored by the APS Innovation Fund, APS Forum on Education, Northwestern University Materials Research Science and Engineering Center, and Northwestern University Multicultural Student Affairs. WS2 is extremely grateful to the lab kit design volunteers for their hard work and external consultants (SciBridge and Projekt Inspire) for their advising. WS2 also thanks and acknowledges PhysicsQuest (https://www.aps.org/initiatives/physics-education/physicsquest) and Quantum Explorations Student Toolbox (QuEST) for example experiments that were used as foundation for the lab kit content.

1.2. Key Vocabulary

- Quantum – smallest possible unit of something
- Entanglement – when two or more particles become linked such that they share the same fate even when separated by a great physical distance
- Superposition – the idea that a particle can exist in multiple states at once until it is measured or observed
- Measurement – the process of observing a quantum system which forces the system to become a definite state

1.3. Key Question

- How does knowing information about one entangled particle impact what you know about the other?

1.4. Purpose

The purpose of this lab kit manual is to introduce quantum entanglement through activities and experiments. Students will think about how entangled particles that are in superposition can then be measured to understand information about both particles instantly, no matter how far apart they are. This will be demonstrated analogously with balloons and balls using two different ways of "measuring".

2. Background on Main Topics

2.1. Entanglement and Correlation

Have you ever flipped a coin and waited to see if it landed on heads or tails? What if the coin could be both heads and tails at the same time until you looked at it? This strange idea is called <u>superposition</u>, and it is a key concept in quantum mechanics, which is basically the study of matter at the very small scale. In fact, <u>quantum</u> means the smallest unit of something. Now imagine that you have two different colored balloons, one blue and one red. You now give one balloon to a friend on the other side of the world and keep the second balloon, but you do not yet know the colors of the balloons. If these were quantum balloons, we would say the balloons are in states of superposition, meaning they are both red and blue. The balloons also have another interesting property in that they are linked, also known as correlated. As soon as you check the color of one balloon, you instantly know the color of the other, even though they are on opposite sides of the world. This mysterious connection is known as entanglement, and it also occurs in quantum systems. Entanglement provides instant correlations between two things upon measurement, which is the process of observation that forces the state of something to become definite (and not in a state of superposition).

So, how do these quantum effects work? When a quantum particle, such as a photon which is the smallest unit of light, is not being observed, it exists in a blend of multiple possibilities. But the moment it is measured, it "chooses" a definite state. Similarly, entangled particles remain mysteriously linked, meaning that measuring one instantly determines the state of the other (as visually demonstrated in Figure 1), no matter how far apart they are. This property challenges our everyday understanding of cause and effect.

Understanding quantum entanglement is important since it forms the foundation of some modern technologies, including secure communications. For example, in something called quantum key distribution (QKD), entangled particles are used to generate secret keys that are extremely secure. Any attempt to spy disturbs the entanglement, immediately alerting users to a breach of security.

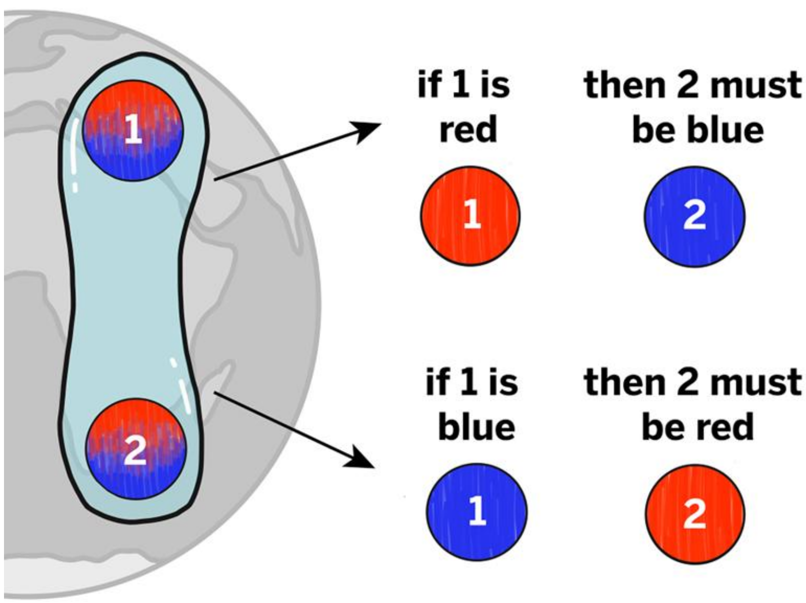

Figure 1. A demonstration of the entanglement rule using two-color entangled particles, where if the first particle is red, then we immediately know that the second particle is blue, and vice versa. Source: https://quantumatlas.umd.edu/entry/entanglement/.

2.2. Supplies List

- Two colors of balloons (like red and blue)
- Opaque bags (like black trash bags)

- String or tape (to tie or attach the balloons)
- Identical cups
- Two types of balls that have very different weights (like metal and plastic)
- Marker
- Fabric (as a blindfold)
- Scale (optional)

2.3. Safety Information

Before the students begin the laboratory, please take into consideration the following safety concerns:

- Small items like balls can be a choking hazard, so avoid putting them in your mouth.
- Students should handle balloons carefully to avoid popping them, which can cause minor injury.
- If moving to different locations or behind a divider, especially when blindfolded, be mindful of obstacles to prevent accidents.
- Always do activities under teacher supervision.

3. Experiments

3.1. Pre-Lab Questions

1. What does it mean for two things to be entangled (in a quantum mechanical sense)?

2. What does it mean for something to be in superposition (in a quantum mechanical sense)?

3. What does it mean to measure something (in a quantum mechanical sense)?

4. How can you force something to be in one definite state and not in superposition?

3.2. Part I: “Measuring” by seeing

3.2.1. *Pre-Activity Questions*

1. If an item, like a balloon (imagine the balloon is not a regular balloon, but a “quantum” balloon), is in a superposition state where it is both red and blue, how could you force it to be one of the two colors?

2. If two “quantum” balloons are entangled such that if one is red, the other must be blue, and then the two balloons are place in superposition states, what does measuring one of the balloons to be red tell you instantly about the other balloon?

3.2.2. *Materials*

- Two colored balloons (like red and blue)
- String or tape
- Opaque bags
- Marker

3.2.3. *Procedure (work in groups of 3-4)*

1. Blow up two similarly-sized balloons of different colors.
2. Name your two balloons (you can write the names on the balloons). These can be silly names like Bluidz, Greenbird, and Quantoon.
3. Tie string or place tape on the balloons so that they are easier to grab and hold on to.
4. All group members except one turn and look away from the balloons.
5. The one group member that is still looking will be the “preparer of the state” and place the two balloons, one each, into opaque bags.
6. The other groups members can now look again.
7. One group member (not the “preparer of the state”) should take one bag (do not look into the bag) and another group member (not the “preparer of the state”) should take the second bag (do not look into the bag).
8. The two group members with bags should go to opposite ends of the room (or at least a few meters apart).
9. On the count of five, one of the group members with a bag should take their balloon out of the bag.
10. Other group members (besides the “preparer of the state”) will race to say the name of the <u>other balloon</u> that is still in the other bag.

11. The group member with the other bag can then remove their balloon from the bag.
12. Repeat steps 4-11 with different students being the “preparer of the state”.

3.2.4. *Post-Activity Questions*

1. If we describe the balloons in the bags quantum mechanically, what were their colors before they were removed from the bags?

2. How did knowing the color of one balloon impact what was known about the other balloon? Did the distance between the two balloons matter?

3. If we describe the balloons in the bags quantum mechanically, would we say they were entangled or not? Explain why or why not.

4. What was the role of the group member who was the “preparer of the state”?

3.3. Part II. “Measuring” by feeling

3.3.1. *Pre-Experiment Questions*

1. If an item, like a ball (imagine the ball is not a regular ball, but a “quantum” ball), is in a superposition state where it is both heavy and light, how could you force it to be one of the two weights?

2. If two “quantum” balls are entangled such that if one is heavy, the other must be light, and then the two balls are place in superposition states, what does measuring one of the balls to be heavy tell you instantly about the other ball?

3.3.2. *Materials*

- Cups
- Two types of balls that have very different weights (like metal and plastic)
- Fabric for blindfold
- Scale (optional)

3.3.3. *Procedure (work in groups of 2-4)*

1. Name your group something fun (like “Superheroes” or “Quantum Friends”).
2. If you have a scale, proceed to the next step. If you do not have a scale, skip to step 6.
3. Allow everyone in the group to guess the weights of the two different balls and record the guesses.
4. Weigh the balls one at a time and record the weights.
5. Announce the group member that was closest to the correct weights.
6. Allow everyone in the group to feel the two balls to understand their differences in weights. You may want to number the balls #1 and #2 or give them names to make their identification easier.

7. Assign roles to group members:
    a. One student will be the "preparer".
    b. One student will be the "experimenter".
    c. One student will be the "recorder".
8. The recorder places the blindfold over the experimenter's eyes.
9. The preparer puts one ball into one cup each.
10. The preparer hands one cup to the blindfolded experimenter.
11. The experimenter guesses which ball is in the cup they are holding, as well as the other cup.
12. The recorder records the guess.
13. Repeat steps 10-12 five times.
14. The experimenter removes the blindfold and views the results.
15. Repeat steps 7-14 with different roles for the group members.

3.3.4. *Results*

Use this table to record the guesses for the ball weights. The correct weights of the balls can be listed in the first row.

Name	Ball #1 Guess	Closest?	Ball #2 Guess	Closest?
Correct Weight				

Use these tables to record experimenter guesses for which ball is in the cup the experimenter is holding and the ball that is in the other cup the experimenter is not holding. There are multiple tables for when the roles in the group are re-assigned.

Recorder:

Experimenter:

Trial	Guess for ball in cup experimenter is holding	Guess for ball in cup experimenter is not holding	Correct? (Yes or No)
#1			
#2			
#3			
#4			
#5			

Recorder:

Experimenter:

Trial	Guess for ball in cup experimenter is holding	Guess for ball in cup experimenter is not holding	Correct? (Yes or No)
#1			
#2			
#3			
#4			
#5			

Recorder:

Experimenter:

Trial	Guess for ball in cup experimenter is holding	Guess for ball in cup experimenter is not holding	Correct? (Yes or No)
#1			
#2			
#3			
#4			
#5			

3.3.5. *Post-Experiment Questions*

1. Could you easily tell the difference between the weights of the two balls when holding them?

2. If we describe the balls in the cups quantum mechanically, what were their weights before they were felt by the experimenter?

3. How did knowing the weight of one ball impact what was known about the other ball? Did the distance between the two cups/balls matter?

4. If we describe the balls in the cups quantum mechanically, would we say they were entangled or not? Explain why or why not.

5. How often did the experimenter guess the correct balls in the cups? If they did not guess them correctly every time, discuss why you think this happened.

6. How was the role of “measuring” different in this experiment versus the previous activity with the balloons?

4. Design Challenge

<u>The Challenge:</u> Design a tool or machine that uses entanglement!

You have learnt that entanglement creates a shared quantum state between two parties or particles and that measuring one of them gives you information about the other (think about the two balls or the two balloons from before). As we discussed in the background, the correlation, or linkage, between two things also means that if someone or something disturbs the entanglement, the states of the two things become definite. This idea is used in quantum encryption to identify if someone is spying on communication through a quantum channel. Now, we will use what you have learned to design a tool or machine that could use entanglement to do something useful or fun. Be creative and pretend that quantum mechanical behavior like entanglement extends to large objects around you (like balloons, cups, balls, etc.).

4.1 Design Questions

1. What could entanglement and superposition be useful for in the real world (you can pretend that entanglement and superposition extend to large objects around you)? Be creative and think broadly.

2. What will you use entanglement and superposition for in your tool or machine?

3. What kinds of materials will you need to create your tool or machine?

4.2 Design Sketch

Sketch the design of your tool or machine below.

5. Sources

Quantum entanglement, https://quantumatlas.umd.edu/entry/entanglement/.

What is quantum in physics and computing?, by Mary Shacklett and Gavin Wright, https://www.techtarget.com/whatis/definition/quantum