QUANTUM (Q)-KIT

Entanglement:

Laboratory for Primary Level Students

Teacher Manual

WOMEN SUPPORTING
WOMEN IN THE SCIENCES

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.

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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. Using this Guide

This manual is to be used by the teacher or facilitator of the laboratory kit, and it is similar in content to the student manual but may contain additional material, namely: Fundamental Science Concepts Covered, Practical Skills, Summary of Experiments, Teacher Pre-Lab, and Troubleshooting. These additional sections are intended to provide the teacher with the background and foundation critical for successfully implementing this laboratory kit in the classroom. It is recommended that the teachers of this laboratory kit go through the guide from beginning to end to familiarize themselves with the content prior to teaching the laboratory kit to students. Questions about the content can be directed at any time to ws2global.org@gmail.com, using the subject line "Question about Lab Kit Content".

IMPORTANT NOTES:

- This laboratory kit is intended for use with primary-level students (ages ~5-11), but depending on the specific students' educational background, the content may need to be modified by the teacher to be made simpler or more complex. The teacher is encouraged to also cover the content at the pace that works best for the students; some younger students may need more time and attention from the teacher and/or facilitator to go through the questions and experiments, while older students may be more independent and require less attention from the teacher and/or facilitator. Thus, the content covered, depth of coverage, and pacing are left to the teacher's and/or facilitator's discretion.
- The content in this lab kit manual may not fit into the specific curriculum of the school in which it is being taught. It is up to the facilitator(s) and teacher(s) whether they would like to introduce new content or skip certain sections that are not applicable to their classrooms.
- In certain areas, modifications to the supply list may need to be made depending on the availability of the supplies in the specific area in which the lab is being taught. We have attempted to list some alternatives in the supply list, but we understand this list of alternatives is not exhaustive.
- In the experiments, the students are split into groups of three to four. If supplies allow, students may instead be split into groups of two.

1.3. 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

1.4. Key Question

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

- *<u>Answer:</u> In entangled systems, the particles are linked or correlated, so knowing information about one of them instantly gives you information about the other one.*

1.5. 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".

1.6. Fundamental Science Concepts Covered

This laboratory kit introduces the topic of entanglement, relevant to numerous fields including Physics, Chemistry, and Computing, to elementary and primary-level students. Specifically, the lab kit encourages students to think about how entangled particles in states of superposition can be measured. Students will come away with the following key takeaways: (1) superposition means that an object can exist in multiple states at once, (2) entangled objects are linked such that knowing something about one of them gives information about the other instantly, even if the object is on the other side of the world, and (3) measurement of a system forces the objects to be in definite states.

1.7. Practical Skills

- Students will understand entanglement and superposition, relevant for quantum cryptography and communications.
- Students will work together on teams and rotate roles that they play on those teams.
- Students will gain experience weighing objects and recording results in tables.

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 superposition, and it is a key concept in quantum mechanics, which is basically the study of matter at the very small scale. In fact, quantum 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.

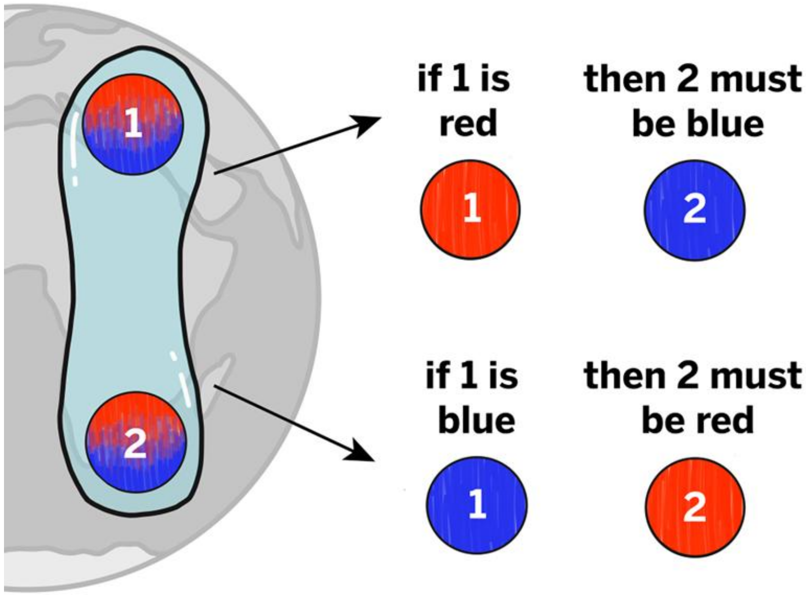

Figure 1. A demonstration of the entanglement rule using two-color entangled particles, where if the first particle is red, then we immediately know that the second particle is blue, and vice versa. Source: https://quantumatlas.umd.edu/entry/entanglement/.

3. Summary of Experiments

This lab kit consists of one activity, one experiment, and one design challenge to understand the entanglement concepts. This investigation will begin by providing background on entanglement, correlation, and superposition before introducing students to these phenomena through analogies. The goals of the experiments and design challenge are the following:

Part I: To demonstrate superposition and entanglement with balloons and measurement by seeing

Part II: To demonstrate superposition and entanglement with balls and measurement by feeling

Design Challenge: To design a device that uses entanglement and superposition to do something fun or useful

3.1. 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)

3.2. 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.

3.3. Teacher Pre-Lab

Teachers can organize the supplies for the experiments ahead of time. For each student or each group of 2-4 students, the materials needed are: 2 balloons of different colors, 2 opaque bags, 2 lengths of string or tape, 2 identical cups, 2 balls of very different weights, fabric to use as a blindfold, and a pen or pencil. There should be markers and an optional scale that the classroom can share.

4. Experiments

Note for teachers:

Encourage open discussion and questions from the class when introducing the experiments.

4.1. Pre-Lab Questions

1. What does it mean for two things to be entangled (in a quantum mechanical sense)?
    a. *Answer: Entanglement refers to the phenomenon when two objects are linked in such a way that they share the same fate even when separated by great physical distance.*

2. What does it mean for something to be in superposition (in a quantum mechanical sense)?
    a. <u>Answer:</u> *Superposition means that something can exist in multiple states at the same time until it is measured or observed.*

3. What does it mean to measure something (in a quantum mechanical sense)?
    a. <u>Answer:</u> *Measuring something is the process of observing a quantum mechanical system which forces it to become definite.*

4. How can you force something to be in one definite state and not in superposition?
    a. <u>Answer:</u> *You must observe or measure it. This will "collapse" the superposition state.*

4.2. Part I: "Measuring" by seeing

4.2.1. *<u>Pre-Activity Questions</u>*

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?
    a. <u>Answer:</u> *You can force the balloon to be one of two colors by measuring it. In this case, measuring means seeing it as one of 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?
    a. <u>Answer:</u> *Measuring one balloon to be red tells us instantly that the other balloon is blue.*

4.2.2. *<u>Materials</u>*

- Two colored balloons (like red and blue)

- String or tape
- Opaque bags
- Marker

4.2.3. *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 other balloon 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".

4.2.4. *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?
   a. *Answer: The balloons were in a superposition state and were both colors at the same time.*

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?

   a. <u>Answer:</u> *Knowing one color meant we knew instantly the color of the other balloon. The distance between the two balloons did not matter – they could have been on opposite sides of the world.*

3. If we describe the balloons in the bags quantum mechanically, would we say they were entangled or not? Explain why or why not.
   a. <u>Answer:</u> *We would describe the two balloons as entangled. This is because their properties (colors) were linked, and as soon as we knew the color of one balloon, we knew the other.*

4. What was the role of the group member who was the "preparer of the state"?
   a. <u>Answer:</u> *The "preparer of the state" was the person that created the balloon superposition state.*

4.3. Part II. "Measuring" by feeling

4.3.1. *<u>Pre-Experiment Questions</u>*

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?
   a. <u>Answer:</u> *You can force the ball to be one of two weights by measuring it. In this case, measuring means feeling or weighing it.*

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?
   a. <u>Answer:</u> *Measuring one ball to be heavy tells us instantly that the other ball is light.*

4.3.2. *<u>Materials</u>*

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

- Scale (optional)

4.3.3. *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.

4.3.4. *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			

4.3.5. *Post-Experiment Questions*

1. Could you easily tell the difference between the weights of the two balls when holding them?
   a. *Answer: This will vary depending on the specific balls used and the students.*

2. If we describe the balls in the cups quantum mechanically, what were their weights before they were felt by the experimenter?
   a. *Answer: The balls were in a superposition state and were both weights at the same time.*

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?

   a. _Answer:_ *Knowing one weight (relatively) meant we knew instantly the weight of the other ball. The distance between the two balls did not matter – they could have been on opposite sides of the world.*

4. If we describe the balls in the cups quantum mechanically, would we say they were entangled or not? Explain why or why not.
   a. _Answer:_ *We would describe the two balls as entangled. This is because their properties (weights) were linked, and as soon as we knew the weight relatively of one ball, we knew the other.*

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.
   a. _Answer:_ *This will vary depending on the student. Possible reasons they did not guess them correctly could be that the balls were too similar in weight or the student made a mistake. Encourage creative thinking.*

6. How was the role of "measuring" different in this experiment versus the previous activity with the balloons?
   a. _Answer:_ *Here, measuring was done by feeling the relative weight whereas earlier measuring was done by seeing the color. Though the measurements were different, they both led to collapsing the superposition state.*

5. Design Challenge

The Challenge: 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.).

5.1 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?

Possible answers to questions (encourage discussion of class):

There are many possible uses and applications for entanglement and superposition, including teleportation, cryptography, sensors, computers, games, and entertainment. The goal is to get the students thinking creatively and to encourage sharing of ideas. Ultimately, students should come up with an idea and the sketch it below.

5.2 Design Sketch

Sketch the design of your tool or machine below.

6. 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