
QUANTUM (Q)-KIT

Entanglement:

Laboratory for Secondary 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 secondary level students (ages ~12-18) 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. Key Vocabulary

- Quantum – fundamental unit involved in interactions at the atomic and subatomic scales (examples: quantum of light is photon; quantum of electricity is electron)
- Entanglement – phenomenon where two or more quantum particles become linked so that measuring the state of one instantly determines the state of the other, regardless of distance
- Superposition – the idea that a quantum 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 single, definite state

1.3. Key Question

- How is entanglement defined in quantum mechanics?

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 balls using “measuring” by feeling and with a game.

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. These quantum 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 resulting from an interaction at some point in their history. This linkage or correlation means that measuring one instantly determines the state of the other (as visually demonstrated in Figure 1), no matter how far apart they are. This challenges our everyday understanding of cause and effect.

Scientists have long been fascinated by these strange quantum properties which are different than what is observed in classical objects. These ideas were first explored theoretically by famous scientists like Albert Einstein, Niels Bohr, and Erwin Schrödinger. Einstein famously referred to entanglement as "spooky action at a distance" because it seemed so bizarre and counterintuitive. Experimental evidence proving that quantum systems behave in this extraordinary way came later, founded on the work of John Bell who formulated Bell's inequality to test the limits of classical versus quantum behavior.

Understanding these quantum behaviors is crucial because it forms the foundation of many modern technologies, including quantum computing, cryptographic space-to-space, space-to-earth, and communication systems. As an example, quantum

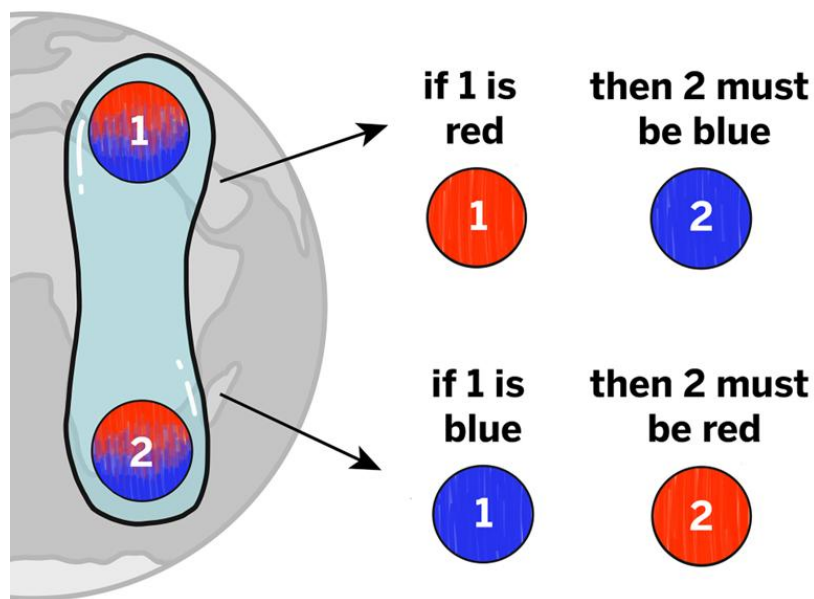


Figure 1. A demonstration of the entanglement rule using two-color entangled particles, where if the first particle is red, then we immediately know that the second particle is blue, and vice versa. Source: <https://quantumatlas.umd.edu/entry/entanglement/>.

communication protocols form the basis for quantum teleportation and quantum key distribution (QKD). In quantum teleportation, entanglement is used to transmit quantum information (state of the particle) without physically transferring the particle. In QKD, entangled particles are used to generate encryption keys that are provably secure. Any eavesdropping attempt disturbs the entanglement, immediately alerting users to a breach.

2.2. Supplies List

- Identical cups
- Two types of balls that have very different weights (like metal and plastic)
- Marker
- Fabric (as a blindfold)
- Coins with two clear sides (labelled heads and tails)
- Tangled game pieces (game cards, game boards, printed scorecards)
- Scale (optional)

2.3. Safety Information

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

- If moving to different locations or behind a divider, especially when blindfolded, be mindful of obstacles to prevent accidents.

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 feeling

3.2.1. 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 placed in superposition states, what does measuring one of the balls to be heavy tell you instantly about the other ball?

3.2.2. Materials

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

3.2.3. Procedure (work in groups of 2-4)

1. If you have a scale, proceed to the next step. If you do not have a scale, skip to step 5.
2. Allow everyone in the group to guess the weights of the two different balls and record the guesses.
3. Weigh the balls one at a time and record the weights.
4. Announce the group member that was closest to the correct weights.
5. 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.
6. 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”.
7. The recorder places the blindfold over the experimenter’s eyes.
8. The preparer puts one ball into one cup each.
9. The preparer hands one cup to the blindfolded experimenter.
10. The experimenter guesses which ball is in the cup they are holding, as well as the other cup.
11. The recorder records the guess.
12. Repeat steps 9-11 five times.
13. The experimenter removes the blindfold and views the results.
14. Repeat steps 6-13 with different roles for the group members.

3.2.4. 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			

3.2.5. 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. What was the role of the group member who was the “preparer” in a quantum mechanical sense?

3.3. Part II: Tangled!

This section is based on the Tangled activity from PhysicsQuest (American Physical Society).

3.3.1. Additional Background

Quantum mechanics can have some remarkable consequences, and it is hard for us to visualize and relate since we only have experience with things that are very large by comparison. Consider quantum computers that use qubits rather than classical bits (1s and 0s). What is a qubit? A qubit is a system that can be in a mathematical superposition of two different states at the same time. In this activity, we will use a spinning coin to convey the idea, so let us think of the 1 and 0 as heads (H) and tails (T) of a coin. For a fair coin, the superposition state is half H and half T.

In a real quantum computer, qubits are implemented using many different physical systems such as electron spins (up versus down), energy states of an atom or ion, or the direction in tiny superconducting current loops. Measurement destroys the superposition and yields an outcome probabilistically. In our particular example, measurement converts the spinning coin superposition into either heads (H) or tails (T) with equal likelihood.

Entanglement can occur when there are multiple qubits. Classically, this is not possible and multiple simultaneous “real” coin flips do not impact each other but are independent and their probabilities are given by a product. In contrast, in an entangled state, measuring the first “quantum” coin impacts what is possible for the second. This particular kind of entangled state is called a Bell state. In this game, you will observe the distinction between the classical product state and an entangled state through measurement of coins (qubits).

3.3.2. Materials

- Coins (or poker chips) with clear heads and tails (or labelled H and T)
- Game cards
- Game boards
- Printed scorecards

3.3.3. Procedure (work in groups of 2 or 4)

1. Practice spinning your coin like a top. Practice slapping it down to “measure” it and clapping it to stop it in place. Observe the randomness of your measurements.
2. Familiarize yourself with the game board and score sheets.
3. If in groups of 2, each person will have a coin. If in groups of 4, partner up so that two people play against two other people (team members can alternate spinning the coin).
4. Fill out the top of your score card and choose the side that you are playing for, either heads (H) or tails (T). This determines what side of the coin you will score points from.
 - a. Notes: Since the sides are equally likely, there is no advantage to H or T. Also, a player picking one side does not mean the other player cannot pick the same side. Picking the same side does not mean players get the same score.
5. For each round, choose a game state: either (1) non-entangled, (2) entangled state 1: must match (Φ), or (3) entangled state 2: must anti-match (Ψ). It is recommended you try one of each game state per game, at least to start. Place the game state card in view of the players for the round.
6. For each attempt (tangle) in a round:
 - a. Two players spin their coins (like tops) toward the center of their individual game board, from outside its edge. If the coin falls over or goes off the game board, immediately pick it up and keep trying to spin it into the middle.
 - b. The player with the first coin to reach the middle of their board slaps their coin down, “measuring” it.
 - i. If in the product (non-entangled) game state, the second player then immediately slaps their coin down, “measuring” theirs as well.
 - ii. If in either of the entangled states, the second player “claps” their coin between their hands, stopping it from spinning.

1. If in the entangled state 1: Φ , they flip their coin so that it matches player one's coin.
 2. If in the entangled state 2: Ψ , they flip their coin so that it is the opposite of player one's coin.
- c. Tangle scoring:
- i. The player who first got to the middle gets one skill point. Mark this on the scorecard.
 - ii. If that player's measured coin matches their chosen side for the round, they get a state point. Mark this on the scorecard.
 - iii. The second player gets no skill point, but if their coin matches their chosen side for the round, they get one state point. Mark this on the scorecard.
7. Repeat step 6 as many times as necessary to complete the round. There are by default 11 attempts (tangles) per round. At the end of the round, the skill and state points are added, giving a round score.
 8. Repeat steps 5-7 for each game round. The player(s) who wins more rounds wins the game.
 - a. Notes: there are by default 3 rounds per game, with the game state switched each round (recommended) to encourage players to try each game state.
 9. (optional) Try playing a game in which your teams get progressively farther and farther apart.

3.3.4. Post-Activity Questions

1. In a quantum mechanical sense, what did the spinning coin represent?

5. What was most fun about this game?

6. What was most challenging about this game?

4. Design Challenge

The Challenge: Design a device that uses entanglement and superposition

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 from before). Prior to measurement, the particles existed in superposition, meaning they simultaneously existed as multiple states. As we discussed in the background, there are many intriguing applications for entanglement and superposition, including in quantum computing, quantum teleportation, and quantum encryption. Now, we will use what you have learned to design a device that could use entanglement and/or superposition to do something useful or fun. For the purposes of this challenge, you can also imagine that quantum mechanical behavior like entanglement and superposition 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 consider real world applications or imaginary ones in which entanglement and superposition extend to large objects around you. Be creative and think broadly.

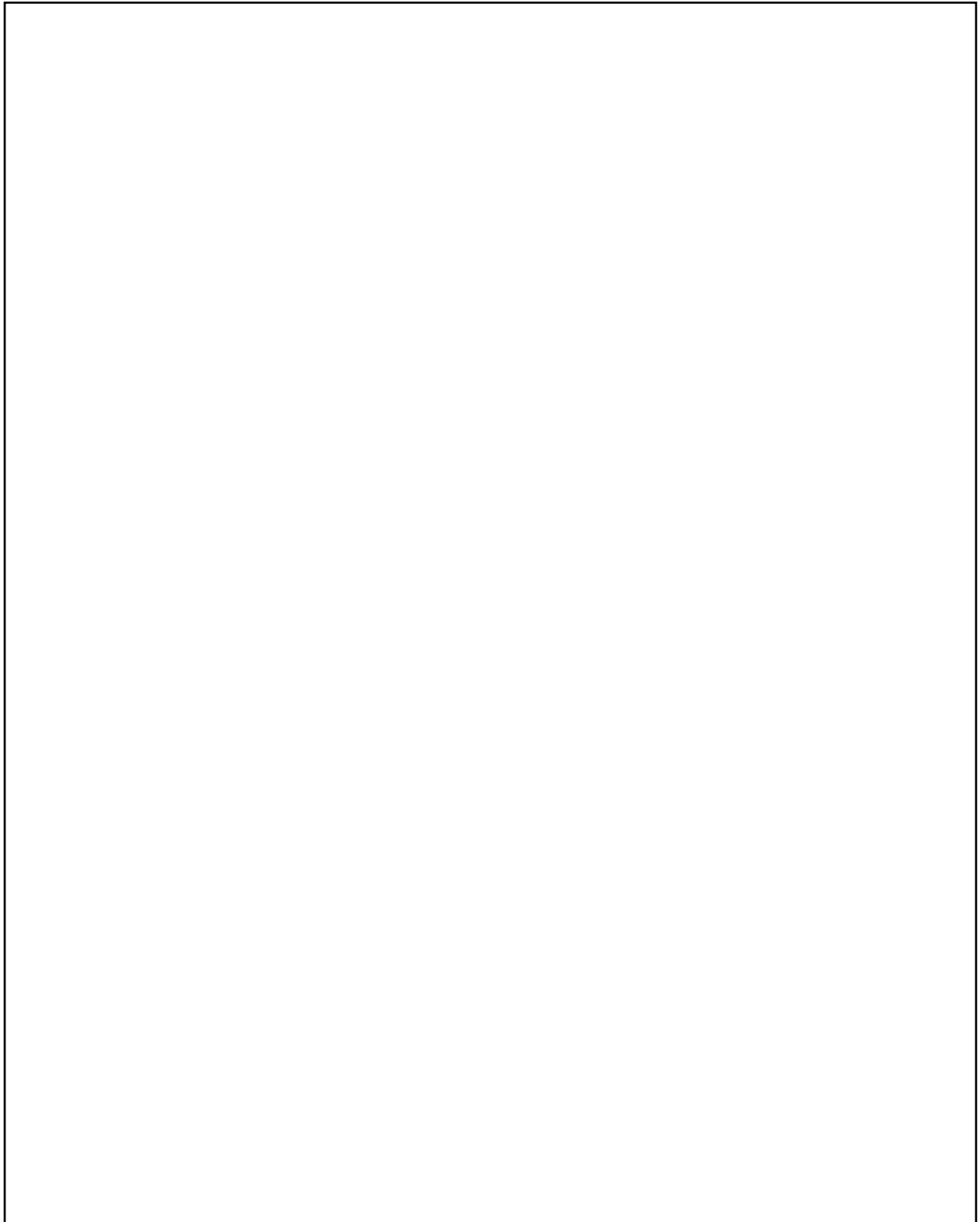
2. What will you use entanglement and superposition for in your device? Is your device a real-world or imaginary-world device?

3. How will your device meet a need in your life or in your community?

4. What kinds of materials will you need to create your device?

4.2 Design Sketch

Sketch the design of your device 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>

PhysicsQuest 2025: Tangled, American Physical Society.