Introducing Quantum Entanglement and Superposition to Secondary School Students Using Portable, Hands-on Exhibits

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Introducing Quantum Entanglement and Superposition to Secondary School Students Using Portable, Hands-on Exhibits

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I. INTRODUCTION

Historically, the teaching of quantum mechanics has been reserved for advanced undergraduate physics courses, mostly due to how far removed from classical intuition the subject is. Extensive mathematical background is usually a prerequisite for college level introductory quantum mechanics courses[1–3]. However, several ways to introduce quantum mechanics at the secondary school level have been suggested and developed[4–7]. Unlike most other topics in physics, it is difficult to find intuitive examples of quantum phenomena outside of a specialized laboratory; additionally, straightforward hands-on demonstrations, activities, and experiments are somewhat limited[8–13].

There has been an increased interest in the development of Quantum Information Science (QIS); this field uses quantum mechanics to store, transmit, manipulate, and measure information. QIS is likely to impact society significantly. To aid the development of QIS it is important to introduce concepts, applications, and relevance to society of QIS at the middle and high school levels. Introducing QIS at these levels provides a larger pool of students the opportunity to learn about this field. With this goal in mind it is necessary to develop further resources at the middle and high school levels[14–16].

In this article we introduce two hands-on exhibits that were designed and constructed at the Lederman Science Center at Fermilab. These exhibits have the goal of introducing, explaining, and reinforcing the concepts of quantum entanglement and quantum superposition in a visual and intuitive manner. Both exhibits are portable and can be used by students to observe a direct analogy with quantum mechanical behavior. We explain the design, theoretical background, and how to use these exhibits in the following sections.

II. THEORETICAL BACKGROUND

Consider a physical system of a particle with two possible states $|0\rangle$ and $|1\rangle$, the general state of this system can be written as

$$|\Psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle\,, \tag{1}$$

where α and β are complex numbers such that $|\alpha|^2 + |\beta|^2 = 1$, the squared magnitudes of α and β represent the probability of observing the $|0\rangle$ or $|1\rangle$ state respectively after making a measurement on the system with state $|\Psi\rangle$. We say that the state $|\Psi\rangle$ is a superposition of the basis states $|0\rangle$ and $|1\rangle$. In general there exist infinitely many superposition states, each with its own unique probability of being observed after a measurement is performed on the system[17].

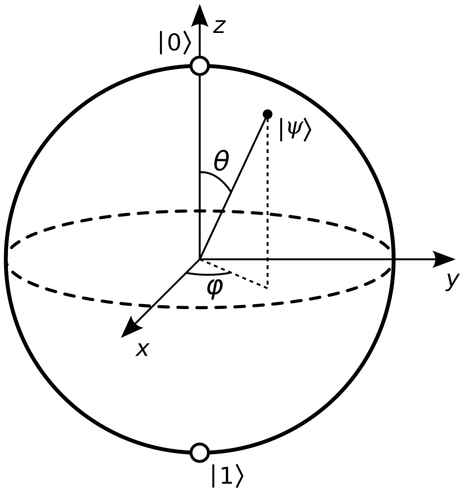


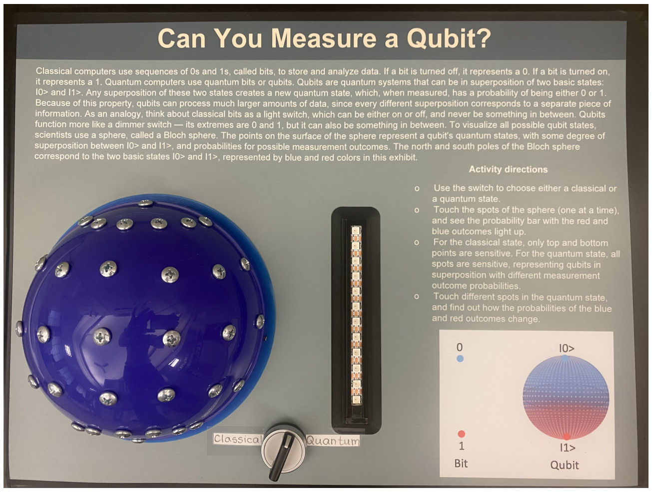
FIG. 1. A Visualization of the possible states for a two level quantum system using a Bloch sphere. Quantum mechanical states lie on the surface of the sphere and are determined by the two angles θ and ϕ of spherical coordinates. The basis states are located at the poles. (License notice: Smite-Meister (https://commons.wikimedia.org/wiki/File:Bloch_sphere.svg), „Bloch sphere“, https://creativecommons.org/licenses/by-sa/3.0/legalcode)

This superposition of two states can be visualized using a Bloch sphere[18–20]. We can rewrite the coefficients α and β in spherical coordinates, using the constraint $|\alpha|^2 + |\beta|^2 = 1$ the general state of the system can be written as

$$|\Psi\rangle = \cos\frac{\theta}{2}\,|0\rangle + e^{i\phi}\sin\frac{\theta}{2}\,|1\rangle\,, \tag{2}$$

where the angles θ and ϕ are restricted as such $0 \leq \theta \leq \pi$, $0 \leq \phi \leq 2\pi$. Using these coordinates any general quantum state $|\Psi\rangle$ can be visualized as a point on the surface of a 3-dimensional unit sphere, see Figure 1. The basis states $|0\rangle$, $|1\rangle$ are visualized as the north and south pole respectively, where the angle θ is the latitude and the angle ϕ is the longitude, in direct analogy with the geographic coordinate system.

Entanglement occurs when two or more particles become connected in such a way that their quantum states are fully correlated. This means that if a certain property (such as spin or polarization) of one of the particles is measured, we have complete knowledge of that property for the other par-



Can You Measure a Qubit?

Classical computers use sequences of 0s and 1s, called bits, to store and analyze data. If a bit is turned off, it represents a 0. If a bit is turned on, it represents a 1. Quantum computers use quantum bits or qubits. Qubits are quantum systems that can be in superposition of two basic states: I0> and I1>. Any superposition of these two states creates a new quantum state, which, when measured, has a probability of being either 0 or 1. Because of this property, qubits can process much larger amounts of data, since every different superposition corresponds to a separate piece of information. As an analogy, think about classical bits as a light switch, which can be either on or off, and never be something in between. Qubits function more like a dimmer switch — its extremes are 0 and 1, but it can also be something in between. To visualize all possible qubit states, scientists use a sphere, called a Bloch sphere. The points on the surface of the sphere represent a qubit's quantum states, with some degree of superposition between I0> and I1>, and probabilities for possible measurement outcomes. The north and south poles of the Bloch sphere correspond to the two basic states I0> and I1>, represented by blue and red colors in this exhibit.

Activity directions

- Use the switch to choose either a classical or a quantum state.
- Touch the spots of the sphere (one at a time), and see the probability bar with the red and blue outcomes light up.
- For the classical state, only top and bottom points are sensitive. For the quantum state, all spots are sensitive, representing qubits in superposition with different measurement outcome probabilities.
- Touch different spots in the quantum state, and find out how the probabilities of the blue and red outcomes change.

FIG. 2. Front view of the exhibit "Can You Measure a Qubit?".

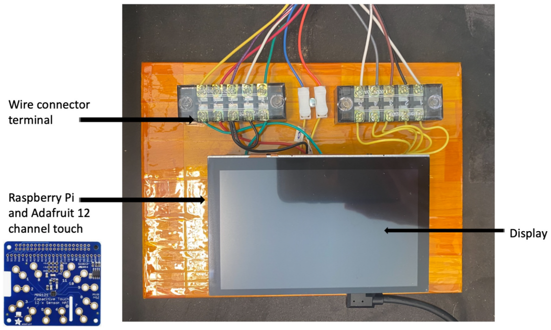


FIG. 3. Internal view of the exhibit "Can You Measure a Qubit?".

ticle; therefore entanglement allows us to obtain information about both particles that make up the entangled system by only measuring one of them. When particles become entangled this correlation endures even when they are separated a large distance[21].

We also define partial entanglement, which occurs when the states of the entangled particles are only partially correlated. This means that measuring the state of one of the particles has only a certain probability of providing information about the state of the other particle. This probability increases as the particles become more strongly entangled. Therefore, in partially entangled systems we can not predict singular experimental outcomes, but we can do several measurements to find how strongly correlated the particles are. It is worth noting that the concept of entanglement can be difficult to understand for first time learners, it is important to consider how learners conceptualize entanglement when designing activities with the objective of teaching this concept[22,23].

III. 1ST EXHIBIT: CAN YOU MEASURE A QUBIT?

The exhibit is built into a 46 cm x 36 cm x 16 cm silver suitcase. It comes with a power cord and requires electricity to function, it consists of a plastic purple semi-sphere with 37 touch sensors, one switch, and a probability bar with 12 LED lights. Internally the exhibit contains a power supply, an electronics board, a raspberry Pi, a monitor, and the necessary wiring. See Figures 2 and 3. A list of the materials used to build this exhibit and additional information about the exhibits is on the Supplementary Material[24]. Detailed information on how this exhibit was constructed is available on request from the authors.

The main goal of the exhibit is to introduce and explain the concepts of superposition and measurement, and the use of the Bloch sphere as a convenient way to visualize single qubit states. Each sensor corresponds to a qubit with some superposition state $|\Psi\rangle$. After pressing one of the sensors, the probability bar to the right of the semi-sphere will showcase the probabilities for the outcomes of measuring the state corresponding to that sensor. For example, for a state with $\alpha = \beta = 1/\sqrt{2}$ the probability bar will show equal amounts of red and blue lights (both states are equally likely). As the measured state moves away from the center of the sphere the probability bar will show different ratios of red and blue. For states located at the south/north pole of the semi-sphere the probability bar will be entirely red/blue.

The exhibit's center switch has "Classical" and "Quantum" settings. In the "Classical" setting, only the touch sensors located at the poles will function; this is because a classical bit exhibits no superposition, so the only states possible are 0 and 1. The only possible outcomes will be a fully blue or a fully red probability bar. In the "Quantum" setting all touch sensors will be functional and the probability bar will be purple, representing qubits in superposition with different measurement outcome probabilities. Once a sensor is pressed the probability bar will show the probabilities for either outcome for a quantum state located at the pressed sensor.

Note that this exhibit does not measure the qubit, it only shows the probabilities for the possible outcomes of a measurement.

A. Use in the Classroom

The following activity is targeted for middle school and high school students. As explained above this exhibit can be used to explain the concepts of quantum superposition and measurement via a Bloch sphere visualization. In addition, this exhibit can also be used to showcase the statistical nature of quantum mechanical phenomena. It is recommended to break students into groups of 4-5 students for this activity. It is recommended that these activities are done as part of larger teaching unit focused on quantum physics[2–7,14,15], as a way to introduce or reinforce concepts taught in class.

Initially, each group is asked if they have heard the term "quantum superposition" previously, and if yes, to give a personal definition of it and if they have any examples of this phenomena. Afterwards, provide students with a more precise definition for quantum superposition, emphasizing how this behavior is only possible in quantum mechanics.

Proceed to present the exhibit: how each sensor represents a qubit in a superposition state, and how to read the probability bar. Explain the concepts of the Bloch sphere and how it can be used to represent qubits. Since these quantum states are restricted to lie on the surface of the Bloch sphere, a direct analogy with the geographical coordinate system can be made to help introduce the Bloch sphere to students.

With the exhibit in the "Classical" setting, give each group 1 minute to write down their prediction of which sensors will function and what the result of pressing the functional sensors will be. Emphasize that in this "Classical" setting there is no superposition, so our bit can only be located at either pole. Afterwards let each group use the exhibit and have them compare their prediction with the observed results.

Afterwards place the exhibit in the "Quantum" setting, and give each group 1 minute to write down their predictions. Emphasize that in this "Quantum" setting there is superposition so our qubit state can be anywhere on the surface of the sphere. Have students come and use the exhibit themselves and explain that for quantum states we have two possible outcomes, each with its own unique probability, and until a measurement is performed we have no way of knowing exactly which outcome will appear - only how likely they are.

Have each group compare and contrast their predictions with their observations from using the exhibit. Some useful guiding questions are: "What is the main difference between the "Classical" and "Quantum" settings?", "For the "Quantum" case, how do the probabilities change as we move from the equator of the Bloch sphere towards one of the poles?", "What do states with the same longitude have in common?". Finally, ask each group to give a short explanation of what they observed and how it relates to the concepts discussed at the beginning of the session.

A possible extension for high school students is for them to use the results shown on the probability bar to numerically calculate the coefficients α and β for the quantum state $|\Psi\rangle$ at each latitude θ, with fixed altitude $\phi = 0$. The numerical probability is obtained by taking the number of LEDs in the probability bar of the same color and dividing it by 12 (the total amount of LEDs in the probability bar). The probability for the other state can be found by using the relation that the sum of both probabilities must add to 1. Finally the coefficients α and β are found by taking the square root of each probability. See Table I for the probabilities at each latitude in the case $\phi = 0$.

Once the students have calculated the probabilities, ask them if they can see any patterns in how the probabilities are distributed along the Bloch sphere.And if they can write out the quantum state $|\Psi\rangle$ for each value of the latitude θ (remember that $|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$). See Table II for the expressions of quantum states at each latitude in the case $\phi = 0$.

Latitude (θ)	Probability of $|0\rangle$ (blue)	Probability of $|1\rangle$ (red)	α	β
0 degrees	1	0	1	0
24 degrees	5/6	1/6	$\sqrt{5/6}$	$\sqrt{1/6}$
35.2 degrees	2/3	1/3	$\sqrt{2/3}$	$1/\sqrt{3}$
45 degrees	1/2	1/2	$1/\sqrt{2}$	$1/\sqrt{2}$
54.7 degrees	1/3	2/3	$1/\sqrt{3}$	$\sqrt{2/3}$
65.9 degrees	1/6	5/6	$1/\sqrt{6}$	$\sqrt{5/6}$
90 degrees	0	1	0	1

TABLE I. Values of each probability and the coefficients of the quantum state $|\Psi\rangle$ for the values of θ available in the exhibit. These values are for the case $\phi = 0$.

Latitude (θ)	$|\Psi\rangle$
0 degrees	$|0\rangle$
24 degrees	$\sqrt{\frac{5}{6}}|0\rangle + \frac{1}{\sqrt{6}}|1\rangle$
35.2 degrees	$\sqrt{\frac{2}{3}}|0\rangle + \frac{1}{\sqrt{3}}|1\rangle$
45 degrees	$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$
54.7 degrees	$\frac{1}{\sqrt{3}}|0\rangle + \sqrt{\frac{2}{3}}|1\rangle$
65.9 degrees	$\frac{1}{\sqrt{6}}|0\rangle + \sqrt{\frac{5}{6}}|1\rangle$
90 degrees	$|1\rangle$

TABLE II. Expressions for the quantum state $|\Psi\rangle$ for the values of θ available in the exhibit. These expressions are for the case $\phi = 0$.

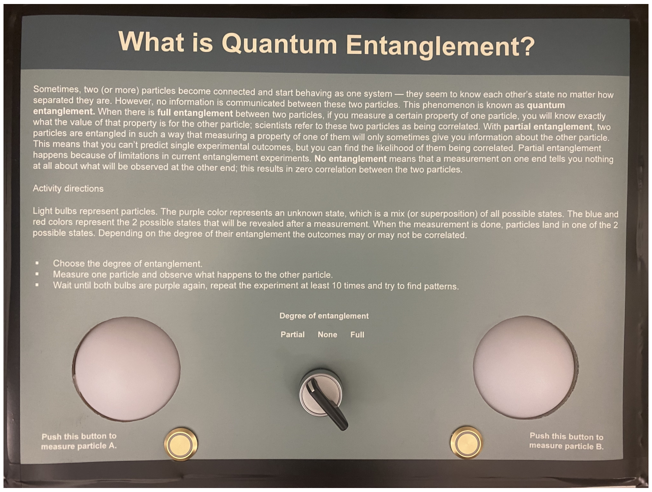
Some further questions are: "Do the probabilities change for different values of ϕ?", "Due to space the exhibit only contains certain angles, what do you expect the probabilities to be at an angle of 45 degrees north? 75 degrees south?". These calculations and discussions help teach how to interpret superposition states in quantum mechanics and using probabilities and statistics to understand simple quantum systems.

The session can be concluded by a brief presentation and discussion on the topics of superposition, quantum states, and probability.

IV. 2ND EXHIBIT: WHAT IS QUANTUM ENTANGLEMENT?

The exhibit is built into a 46 cm x 36 cm x 16 cm silver suitcase. It comes with a power cord and requires electricity to function. It consists of 2 light bulbs, 2 touch sensors, and a switch (see Figure 2). Internally the exhibit contains a power supply, an electronics board, a raspberry Pi, a monitor, and the necessary wiring. See Figures 4 and 5. A list of the materials used to build this exhibit and additional information about the exhibits is on the Supplementary Material[24]. Detailed information on how this exhibit was constructed is available on request from the authors.

The main goal of the exhibit is to introduce and explain the concept of quantum entanglement via a hands-on activity. Each light bulb represents a particle that has two basis



What is Quantum Entanglement?

Sometimes, two (or more) particles become connected and start behaving as one system — they seem to know each other's state no matter how separated they are. However, no information is communicated between these two particles. This phenomenon is known as **quantum entanglement.** When there is **full entanglement** between two particles, if you measure a certain property of one particle, you will know exactly what the value of that property is for the other particle; scientists refer to these two particles as being correlated. With **partial entanglement**, two particles are entangled in such a way that measuring a property of one of them will only sometimes give you information about the other particle. This means that you can't predict single experimental outcomes, but you can find the likelihood of them being correlated. Partial entanglement happens because of limitations in current entanglement experiments. **No entanglement** means that a measurement on one end tells you nothing at all about what will be observed at the other end; this results in zero correlation between the two particles.

Activity directions

Light bulbs represent particles. The purple color represents an unknown state, which is a mix (or superposition) of all possible states. The blue and red colors represent the 2 possible states that will be revealed after a measurement. When the measurement is done, particles land in one of the 2 possible states. Depending on the degree of their entanglement the outcomes may or may not be correlated.

- Choose the degree of entanglement.
- Measure one particle and observe what happens to the other particle.
- Wait until both bulbs are purple again, repeat the experiment at least 10 times and try to find patterns.

FIG. 4. Front view of the exhibit "What is Quantum Entanglement?".

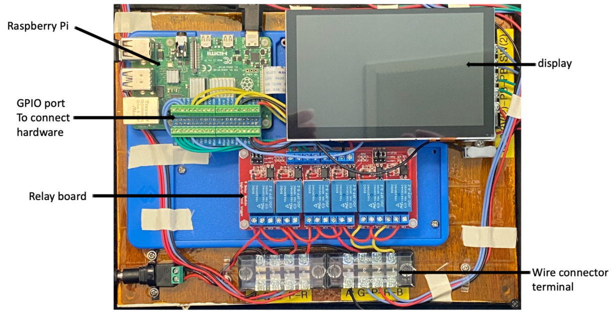


FIG. 5. Internal view of the exhibit "What is Quantum Entanglement?".

states, where the two different states are represented as different colors, and the $|0\rangle$ and $|1\rangle$ states are represented as the light bulb shining red and blue respectively. A purple light is used to visually represent the general superposition state $|\Psi\rangle$.

Each touch sensor corresponds to making a direct measurement on its respective particle. The corresponding light bulb will turn red or blue to signal that a measurement has occurred. An analogy can be made between the color of the light bulbs and spin states of subatomic particles; a red/blue light bulb is interpreted as the particle having its spin pointing up/down at the time of measurement. After a measurement is performed, both light bulbs will return to purple after three seconds. The center switch has three different settings: partial entanglement, no entanglement, and full entanglement.

Once a setting is chosen and the exhibit is turned on, both light bulbs will be purple until one of the touch sensors is pressed. In the partial entanglement setting the measured particle will turn red/blue, while the other particle will have a 50% probability to stay purple (no correlation), and 50% chance to to turn blue/red (the particles are correlated).

In the no entanglement setting the measured particle will turn red/blue, while the other particle will remain purple 100% of the time. This shows that there is zero correlation between the particles.

In the full entanglement setting the measured particle will turn red/blue, while the other particle will turn blue/red 100% of the time. This shows that there is full correlation between the particles.

A. Use in the Classroom

As explained above this exhibit can be used to explain the concept of quantum entanglement between two particles. With additional instruction this exhibit can also be used to showcase the statistical nature of quantum mechanical phenomena. The following activities are targeted for middle school and high school students. It is recommended to break students into groups of 4-5 students for this activity. It is recommended that these activities are done as part of larger teaching unit focused on quantum physics[2–7,14,15], as a way to introduce or reinforce concepts taught in class.

Initially, each group is asked if they have heard the term "quantum entanglement" previously, and if yes, to give a personal definition of it and if they have any examples of this phenomena. Afterwards, provide all students with a more precise definition for quantum entanglement, making sure to also define the full, partial, and no entanglement cases. Ensure that each group has written down these definitions and understands the differences between all three cases.

Proceed to present the exhibit, explain how the light bulbs represent particles, and what each color means. With the exhibit in the "None" setting, give each group 1 minute to write down their prediction of what will happen once one of the particles is measured (the touch sensor is pressed). Once all groups have their prediction provide them with a table as shown on Table III. On the second column they will write down which particle was measured (A or B). And which color it became after measurement (red or blue). For the third column they will write which particle was not measured (A or B). And which color it was after the measurement of the other particle occurred (red, blue, or purple). A completed table is included as an example.

After each group has their corresponding table proceed to do 10 trials on the exhibit, make sure all groups write down the result for each trial. If time allows, have students come and perform measurements themselves. Afterwards repeat the above steps for the "Partial" and "Full" settings. Compare and contrast the predictions from each group with their observations for the trials. Some useful guiding questions are: "Is measuring particle A different from measuring particle B?", "In what setting did you always get the same result for the non-measured particle?", "Could you use your measurement results to find out which setting the exhibit is on?". Finally, each group is asked to give a short explanation of their measurements and how they line up with the concepts discussed at the start of the session.

Trial #	Measured Particle	Non-measured particle
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Trial #	Measured Particle	Non-measured particle
1	A, Red	B, Purple
2	B, Blue	A, Red
3	A, Red	B, Blue
4	B, Red	A, Purple
5	A, Blue	B, Red
6	A, Red	B, Purple
7	B, Blue	A, Red
8	A, Red	B, Blue
9	B, Red	A, Purple
10	A, Blue	B, Red

TABLE III. Left: table for classroom activity, students will perform 10 trials on each exhibit setting and record the results of both particles on this table. Right: a example of a filled out data table for the "Partial" setting.

Explain why it is important to run several trials, emphasizing that quantum mechanics is probabilistic in nature, so in real experiments measurements must be performed hundreds or thousands of times. If time allows, perform another set of trials on each setting. Have students analyze if the results of this second set of trials is consistent with the first set of trials.

For high school students, this second set of trials can be done while hiding which setting the exhibit is on, and asking each group how many measurements do they think they need to determine the setting. An useful guiding question for this part could be: "Is the amount of measurements the same for every setting? Why or why not?".

The "Partial" setting is unique in that the non-measured particle has a 50% probability of not changing color when a measurement is performed. Another possible extension for high school students can be to have each group do several measurements on the "Partial" setting, collect data to try figure out what is the probability that the non-measured particle changes color. This helps showcase the probabilistic nature of quantum mechanics, and the importance of doing several trials in scientific experiments.

The session can be concluded with a short assessment to test student understanding: provide each group with a previously filled out data table, and ask them to analyze the table to figure out which exhibit setting it corresponds to. In this activity we emphasized the concepts of quantum superposition, state change under measurement, probability, statistics, and quantum entanglement.

V. AUDIENCE RESPONSE

Both exhibits were tested at public science outreach events with non-scientist audiences ranging in age from preschoolers to adults, we present a brief summary of the responses from the audience at these events.

A. Can You Measure a Qubit?

It was challenging to explain to younger children the concept of a Bloch sphere, so we let them play with it like a toy and experiment with different modes. They were able to notice and describe the difference between the “classical mode” (when only 2 points are sensitive) and “quantum mode” (when the whole surface becomes sensitive). We made an analogy between classical bits being like a light switch that can be either “on” or “off”; while qubits are more like dimmer that can be “on”, “off” and anything in between.

Adults were more interested in “latitude probabilities”. They noticed that there was 50/50 chance to end-up with red or blue state on the “Equator”. They also noticed the measurement outcomes were same on the same latitudes. In general, both adults and children found the concept difficult to comprehend but they had fun with the exhibit and learned how regular bits differ from qubits.

B. What is Quantum Entanglement?

Most of the audience had never heard about the concept of quantum entanglement, so we used analogies to explain it. We made an analogy between entangled particles and twins. We asked them to imagine twins sleeping in different rooms that are separated by long distance. You wake up one twin and the other wakes up immediately, even though no one interacts with the other twin. To make this “spookier”, every time one twin wakes up on the left side, the other wakes up on the right side. No matter how many times you repeat this experiment, the pattern remains the same.

We let children to play with the exhibit and see the patterns. They thought, the twin’s analogy worked well for “full entanglement”, however when they switched to the “partial entanglement”, they realized that the twins were not always waking up on the opposite sides. They asked questions like “is this because they are not “entangled” anymore?”. We explained that this could be because we (as observers) are not able to measure their wake-up time/position precisely (e.g., our measurement devices are not perfect), or they are not entangled anymore. When they switched to the “no entanglement” mode and experimented with it, they concluded that the two were not twins, or they had completely lost their “entanglement”.

As for the adult audiences, depending on their background, we sometimes used the same “twins’ analogy” to introduce the concept, and sometimes just let people explore the exhibit, experiment, collect data, and find patterns. In general, people were curious about the concepts, they enjoyed playing with the exhibit, observing correlations, and coming up with their own analogies.

VI. CONCLUSIONS

The hands-on exhibits and activities presented here can be used to illustrate some of the more fundamental concepts in quantum mechanics to middle and high school students in a direct and engaging way.

We described extensions that allow for a more in-depth learning experience for more advanced high school students, these activities and exhibits should allow students to gain a better understanding of some of the more counter-intuitive concepts in quantum mechanics such as superposition and entanglement.

[1] K. W. Ford, "The Key Ideas of Quantum Mechanics," The Physics Teacher 4, 361–367 (1966).

[2] C. G. Hood, "Teaching about quantum theory," The Physics Teacher 31, 290–293 (1993).

[3] R. Müller and H. Wiesner, "Teaching quantum mechanics on an introductory level," American Journal of Physics 70, 200–209 (2002).

[4] M. B. Schneider, "Quantum mechanics for beginning physics students," The Physics Teacher 48, 484–486 (2010).

[5] P. Bitzenbauer and T. Zenger, "Online course on quantum physics: Reading primary sources with secondary school students," The Physics Teacher 60, 572–577 (2022).

[6] M. d. l. Fanaro, M. R. Otero, and M. Arlego, "Teaching basic quantum mechanics in secondary school using concepts of feynman path integrals method," The Physics Teacher 50, 156–158 (2012).

[7] C. Hughes, J. Isaacson, J. Turner, A. Perry, and R. Sun, "Teaching quantum computing to high school students," The Physics Teacher 60, 187–189 (2022).

[8] P. E. Fleming, "A quantum mechanical game of craps: Teaching the superposition principle using a familiar classical analog to a quantum mechanical system," Journal of Chemical Education 78, 57 (2001).

[9] B. d. B. Neto, "Dice throwing as an analogy for teaching quantum mechanics," Journal of Chemical Education 61, 1044 (1984).

[10] T. A. Corcovilos, "A simple game simulating quantum measurements of qubits," American Journal of Physics 86, 510–517 (2018).

[11] A. López-Incera and W. Dür, "Entangle me! A game to demonstrate the principles of quantum mechanics," American Journal of Physics 87, 95–101 (2019).

[12] A. López-Incera, A. Hartmann, and W. Dür, "Encrypt me! a game-based approach to bell inequalities and quantum cryptography," European Journal of Physics 41, 065702 (2020).

[13] A. Goff, "Quantum tic-tac-toe: A teaching metaphor for superposition in quantum mechanics," American Journal of Physics 74, 962–973 (2006).

[14] P. Bitzenbauer and J.-P. Meyn, "A new teaching concept on quantum physics in secondary schools," Physics Education 55, 055031 (2020).

[15] M. L. Chiofalo, C. Foti, M. Michelini, L. Santi, and A. Stefanel, "Games for teaching/learning quantum mechanics: A pilot study with high-school students," Education Sciences 12 (2022).

[16] P. Bitzenbauer, "Practitioners' views on new teaching material for introducing quantum optics in secondary schools," Physics Education 56, 055008 (2021).

[17] C. Cohen-Tannoudji, B. Diu, and F. Laloë, Quantum mechanics; 1st ed. (Wiley, New York, NY, 1977).

[18] W. Dür and S. Heusler, "What we can learn about quantum physics from a single qubit," (2013), arXiv:1312.1463 [physics.ed-ph].

[19] W. Dür and S. Heusler, "Visualization of the Invisible: The Qubit as Key to Quantum Physics," The Physics Teacher 52, 489–492 (2014).

[20] W. Dür and S. Heusler, "The Qubit as Key to Quantum Physics Part II: Physical Realizations and Applications," The Physics Teacher 54, 156–159 (2016).

[21] D. J. Wineland, "Nobel lecture: Superposition, entanglement, and raising schrödinger's cat," Rev. Mod. Phys. 85, 1103–1114 (2013).

[22] B. Zwickl and H. J. Hersom, "Investigating students' understanding of entanglement," in Physics Education Research Conference 2024, PER Conference (Boston, MA, 2024) pp. 467–472.

[23] M. Brang, H. Franke, F. Greinert, M. Ubben, F. Hennig, and P. Bitzenbauer, "Spooky action at a distance? a two-phase study into learners' views of quantum entanglement," EPJ Quantum Technology 11 (2024).

[24] Supplementary Material

VII. AUTHOR BIOS

Luis Mendoza obtained a PhD in Condensed Matter Physics from Florida State university. Areas of expertise are quantum phase transitions, science education, and QIS curriculum development. Currently he is a quantum education program leader at Fermilab. lmendoza@fnal.gov

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Doga M. Kurkcuoglu completed a PhD in condensed matter physics with minor in computer science at Georgia Institute of Technology. Dr. Kurkcuoglu has published papers in many subfields of quantum physics – cold atom physics, particle physics, superfluidity, quantum machine learning, and more. Currently he is a staff scientist at Fermilab. dogak@fnal.gov