The Quantum for All Students and Teachers Project: Sample Activities and the Historical Storyline Linking Them

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The Quantum for All Students and Teachers Project is a program funded by the National Science Foundation (#2048691) to expand quantum science education in high schools. The central focus is professional development for teachers, but there is considerable work that goes into developing and validating the instructional materials. In this paper, we provide a general overview of the project. We also provide some details on activities that address specific topics that are included in the Next Generation Science Standards: the electromagnetic spectrum and the dual wave/particle behavior of light. Finally, we discuss a historical storyline that was used with the teachers in the 2024 summer workshop to link several activities dealing with early quantum theory.

Introduction

Quantum for All Students and Teachers (quantumforall.org), a project funded by the National Science Foundation,[1] provides opportunities for high school STEM teachers to learn about quantum topics identified as important for current and future jobs in a wide range of specialties, not just in STEM-focused occupations.[2] STEM teachers, accepted through an application and review process, participate in a week of professional development (PD). The teachers engage in the activities as students, with the master teachers who work with the project modeling the lessons. During the week, teachers learn about the scientific content in a framework that models the pedagogical content knowledge for active learning and integrates appropriate technology[3] related to quantum information science and engineering. The teacher workshop is followed by 4-day STEM camp for high school students. The teachers who attended the workshop the previous week help plan and co-teach the camps using the PD resources.

Lesson modules are designed to integrate into current curriculum, so teachers do not need to "find space" for quantum in their classes. Since camp students are not their students, and the teachers do not have the normal constraints when teaching new material, the participating teachers have an opportunity to "test drive" the resources. Our hypothesis, which is the subject of current research, is that the teachers will be more willing to use the resources in their own classrooms once they have had practice teaching camp students.

The PD instruction uses research-based pedagogy and materials.[4,5] The resources themselves were developed by a leadership team of skilled educators, including teachers and professional physicists from research institutes and universities, who started with available resources, embedded them into 5E learning cycles,[6] and connected them to standards (see below). In addition, some of the physics professors in the leadership team have expertise in physics education research, which is a well-established field in physics,[7,8] and includes specific research around learning quantum-related topics.[9,10]

Evidence collected from pre- and posttesting of teachers[11] and students[12] indicates that the resources developed by the project result in statistically significant gains in both understanding of content and self-reported confidence in their understanding of the content. These results validate the resources and the development process. For the time being, the resources are only available to participants in the workshops since the success of the instruction is tied to the PD that occurs during the workshops. Simply handing someone instructional materials without modeling classroom instruction or providing support in the content and the use of the technology required for the activities is not likely to result in the student gains we observed in the summer science camps. Moreover, at this point we do not have an online listing of developed activities, though some are discussed in papers referenced here.[4,11] However, we do report here some sample activities not yet discussed in prior publications and the connecting historical thread.

Activities to address light as quanta

The *Next Generation Science Standards* (*NGSS*) has considerable content related to electromagnetic waves in the High School Standards.[13] These include light being described by a wave model or a particle (photon) model (HS-PS4-3), and the unique spectrum of each element (HS-ESS1-2) that allows us to understand the composition of distant stars and other objects. These topics form the core of early quantum theory, although the NGSS stops short of discussing topics like particle wave functions. The following two activities are example of how we address early quantum theory.

Invisible light: The Herschel experiment

In 1800, William Herschel discovered infrared light.[14] The idea that light extends beyond the visible, called the electromagnetic (EM) spectrum, is an essential concept for understanding the universe. It also is a basic concept for understanding technology that uses electromagnetism (e.g., radio) or gamma rays in nuclear decay. Herschel's experiment was simple and elegant. He spread out a beam of light with a prism and used a thermometer to determine that there was some source of heat/energy outside of the visible spectrum that could not be seen. This experiment is easily replicated in the classroom.

Figure 1 shows the experimental setup. A prism is held so sunlight casts a rainbow on a piece of paper. A thermometer

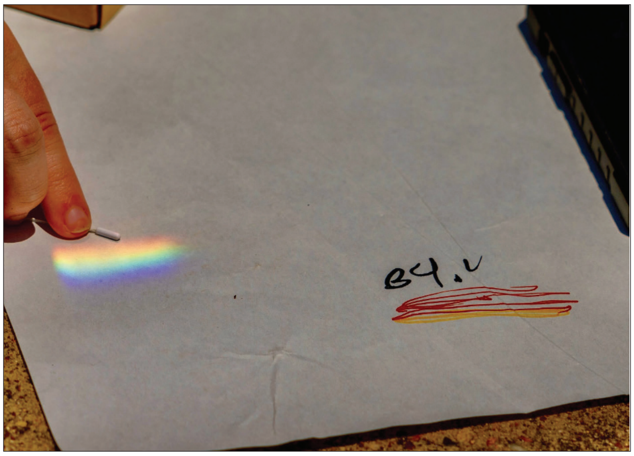

Fig. 1. Setup for Herschel experiment.

(in this case a thermal probe connected to a data recorder) is placed in the rainbow, just outside of the rainbow on the red end of the spectrum, and in the shade (not shown). Students will see that the temperature measured by the thermometer is higher in the rainbow than in the shade. This is completely a natural result for students since all of them have experienced warmth in sunlight. However, the fact that to the right of the red, beyond the rainbow, the thermometer still registers a higher temperature can be a mystery to students. The exact amount of the temperature difference between the ambient temperature and the temperature in the red or the infrared will depend on the dispersion of the light (size of the rainbow) and the intensity of the sunlight, but it will be on the order of several degrees Fahrenheit. The results indicate that the energy in the white light that was spread out by the prism extends beyond the visible range. With this information, one can now talk about the EM spectrum as a whole, and the different wavelengths of EM waves are distinguished by different colors.

One key aspect of this activity is *not* to make comparisons between thermometer readings in different colors in the rainbow. What students would find is that the temperature measured by the thermometer in the blue is lower than the temperature measured in the red. Students may incorrectly conclude that red light is "hotter" or more energetic than blue light. This would be reinforced by the commonly used "rainbow color scale" in which red is "hot" or maximum and blue is "cold" or minimum. While other perceptual features of a representation can overcome the tendency to default to the rainbow color scale,[15] in this case the common experience with the rainbow color scale and the observation of a higher temperature in the red than in the blue would likely lead students to a strong misconception that red light is more energetic than blue, exactly the opposite of reality. Once students acquired this idea through their own experimentation, supported by prior knowledge, it would be exceptionally difficult to undo this mistaken concept.[16] This would impede learning about photons as quanta of light since blue photons are more energetic than red photons.

If students do observe the varying temperature and bring up the issue, a teacher could respond by stating the total amount of energy, or intensity of the light, varies with color/wavelength. In addition, the process by which random molecular motion arises from electromagnetic radiation being absorbed is complex, with excitation of molecular vibration and rotation playing a principal role. These modes are more easily excited by infrared wavelengths, while shorter wavelengths might produce electronic transitions in atoms, which do not contribute to random molecular motion. These issues are well beyond what should be the focus of this activity (not all light is visible), and students who have questions should be encouraged to do their own research on the topic. But in general, it is probably best not to open this particular can of worms.

Resolving the ultraviolet catastrophe with quanta

Another key factor that motivated the development of the quantum hypothesis by Planck was the failure of classical theory to account for glowing hot objects. The glow was clearly light, electromagnetic radiation, but how to explain it? Objects could be modeled as a collection of electromagnetic resonators driven by thermal motions. Classical theory of equipartition of energy would spread out the energy over an infinite number of frequencies, leading to the "ultraviolet catastrophe," where the amount of energy radiated at high frequencies would grow so that the total energy radiated would be infinite. Planck solved this problem by assuming that electromagnetic energy could not come in arbitrary amounts. Instead, he proposed that they come in "quanta" with each unit of energy equal to the frequency times a constant, *h*, which became known as "Planck's constant." With that assumption, the high-frequency quanta became much less probable, and now the theory agreed with experimental results.

To communicate this in an accessible fashion, we developed an activity using LEGO bricks (Fig. 2). LEGO bricks of different colors (same size) are put into a container and randomly drawn out. In the first case, all the bricks are one unit in size, where "size" is the amount of energy in the parcel of light. They have an equal probability of being drawn out of the container. In the second case, the size of the bricks is related to the color (frequency), with higher-frequency quanta having more energy. Now the blue quanta (three blue bricks)

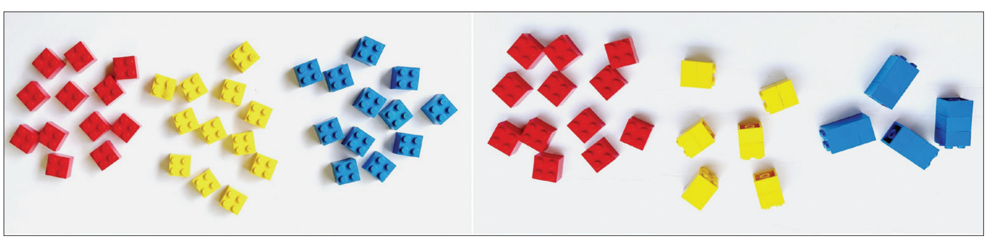

Fig. 2. LEGO brick arrangments for explaining blackbody radiation with equipartion on the left and the quantum hypothesis on the right.

are much less likely to be drawn than the red quanta (one red brick). This illustrates how Planck's quantum hypothesis solved the blackbody problem by limiting the amount of high-frequency light emitted by a hot object. The rest of the activity explores the blackbody spectrum and its dependence on temperature. One chemistry teacher participating in the 2024 PD remarked that this was the highlight of the week because it demonstrated how to teach about the UV catastrophe.

The historical thread and conclusion

The two activities described above form the beginning of a learning cycle that limited space precludes describing in detail. The historical thread used to link these activities begins with the idea that light is an electromagnetic wave, then proceeds to the ideas that there is energy in light that cannot be seen and that the only way to understand why hot objects glow is to assume that light comes in fixed quanta where the energy is proportional to the frequency of the light.

The last part of the lesson demonstrates the photoelectric effect and how it depends on the frequency of light. Einstein used Planck's quantum hypothesis to explain the photoelectric effect and thus argue that quanta were real, not just an accounting trick to solve the blackbody problem. Once the reality of quanta was established, one could consider quantizing other things, like the angular momentum of an electron in an atom. This led to the Bohr model and the explanation of spectra of elements as a quantum phenomenon, which is demonstrated using activities related to spectra and the Bohr model. The next step in the story is to ask "If waves can be particles, can particles be waves?" The answer is *yes*. The fact that particles have wave behavior and can be described by wave mechanics leads to the Heisenberg uncertainty principle (HUP). We have developed an activity with wave packets that shows the fundamental origin of the HUP, which has nothing to do with measurement per se, although this is a common misconception one still finds in books.

To conclude, the Quantum for All Students and Teachers Project has developed a range of age-appropriate activities that enable high school students and teachers to conceptualize basic topics in quantum physics. Embedding some of the topics into a historical storyline helps track the development and importance of early quantum theory.

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