Teaching quantum to high school students

Donn M. Silberman*, Optics Institute of Southern California (United States)

ABSTRACT

This paper describes and provides examples of getting high school students interested in quantum information and then teaching them some aspects that draw them in and keeps their attention. These examples are informal education for afterschool programs that can begin with a presentation during a regular science class period. The goal of this paper is to provide methods that have been successful and can be duplicated in other geographic locations globally. These methods include providing other volunteers, such as Optica and SPIE Student Chapter members at colleges and universities and professionals in industry, with easy-to-follow written materials and easy to acquire hands-on materials for low-cost laboratory experiences. The importance of bringing the hands-on experiences to the high school students early in the process is highlighted and getting them to understand that the quantum world is basically at the atomic level and not the macroscopic world we experience every day.

While there are many programs worldwide aimed at teaching quantum to high school students, they each have their strengths and challenges with a variety of outcomes. Here the author provides the best practices he has found from some of these programs and merges them with his own experiences in the optics and photonics education outreach endeavors to deliver a concise path for quantum outreach volunteers to use in their programs.

Keywords: Quantum education, career pathways, outreach, high school, college, students, Kahoot, laser

1. INTRODUCTION AND MOTIVATION

In a previous paper[1] presented by the author at this conference in 2003, the organizational summary, mission and purpose of the Optics Institute of Southern California was described. The paper cited that in, "Optics Education – A Blueprint for the 21st Century" A project of the Optical Society of America and SPIE – The International Society for Optical Engineering – December 2001; "there exists specifically identified barriers to teaching optics in the K-12 grades and that has created a void in filling the demand for trained people in the optics industry." Since then, the author and his colleagues, primarily but not limited to those in the Optical Society of Southern California (www.ossc.org), have implemented and documented their journeys to fill this void in Southern California and beyond. Publications and on-line photo albums documenting these efforts can be found on the OISC website. During the most recent years, particularly since December 2018, when the United States federal government passed the National Quantum Initiative Act – H.R.6227[2], the author and others have added quantum to the previous optics and photonics educational efforts.

Now we provide a brief orientation to quantum science and education and our motivation for teaching quantum to high school students. A discussion is provided about creating a quantum education pipeline from middle school to high school to community colleges and universities for students to follow, that leads to these students finding career pathways in the 2nd quantum revolution. Examples include mentoring a new "Schrödinger's (Quantum) Club" at a local high school, the Samueli Academy in Santa Ana, California, where various optics, photonics and quantum educational tools were used that included hands-on labs with polarization filters, atomic spectra sources, diffraction gratings and laser pointers. Quantum cryptography materials from the University of Waterloo's Institute for Quantum Computing course for high school students were used and are described. We conclude our current presentation by reviewing our experiences with the Qubit x Qubit quantum computing program for high school students and then a brief note about fields trips to two local universities to visit research groups that study, use and teach quantum technologies.

The question of "how we teach physics and to whom?" seems like a good question to ask when we are considering teaching quantum to high school students. Basically, students will self-select themselves to learn this type of material. Throughout recorded history, only people with 'time and ability' could learn topics like math and science. Now many more people have both 'time and ability' to learn science. But are they being made aware of the opportunities that exist in fields that

*donn@oisc.net; phone 1 949-636-6170; fax 1 949-284-3254; oisc.net

involve optics, photonics, physics and quantum? Getting the message to these students that optics, photonics, and quantum is fun and interesting is what we will now focus on. On the OISC website, there is a dropdown menu titled "Quantum" that has the following menu items: Quantum for Students, Quantum for Volunteers, Quantum Ed & Work, Quantum Cybersecurity, Donn's Quantum Explorations and EdQuantum – Industry Survey. These webpages provide readers with pathways to more information and references on each topic for each group. Much of the material presented in the remainder of this paper can also be found through these webpages. There is also a webpage titled, "Career Assistance" under the "Misc" tab where students and others can find both education and career pathway information, including the 2022 SPIE Optics & Photonics Global Salary Report.

Last August a paper[3] was presented and published titled, "Quantum education and pathways: an open-source modifiable presentation to high school and college students." This paper describes a presentation prepared by the author that can be used by anyone seeking to present this material to high school students without the need to create a new presentation from scratch. It may be ideal for college and university optics, physics, photonics, and engineering students who are looking for ways to engage high school students in their local areas.

The 'Kahoot! For Schools'[4] used in this open-sources modifiable presentation was a tool new to the author that he incorporated into the presentation at the encouragement of the engineering instructor[5] at the Samueli Academy.

The motivation for teaching quantum to high school students was documented in a paper[6] we published in a special section on Education and Training in Quantum Sciences and Technologies of the SPIE Journal Optical Engineering in April of last year. Section 6 of the paper described the alignment with the National Science Board's Vision 2030 Roadmap[7], where we wrote about using educational tools and recruiting networks for K-12 so people in their local regions can prepare students for college programs that include quantum technologies.

2. CREATING THE QUANTUM EDUCATION PIPELINE

The 2014, presentation and paper[8] describing an Optics & Photonics Education Pipeline, shown in Figure 1, went from middle to high school to Community College, where we introduced OptoBotics.

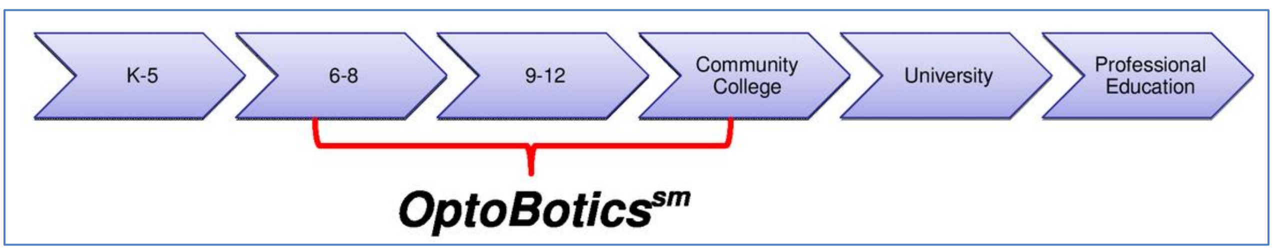

Figure 1. This Optics education pipeline shows where OptoBotics fits into the progression of optic education outreach.

This was recently updated, as shown in figure 2, to include quantum concepts that parallel the Quantum Workforce: Q-12 and the National Q-12 Education Partnership to the EdQuantum Project for Community Colleges. The Qubit x Qubit program fits nicely at the high school level, and I have added the Hands-on Quantum to our local projects. We have built the quantum educational outreach programs on top of historical optics, lasers, photonics, semiconductor, and general physics fundamentals.

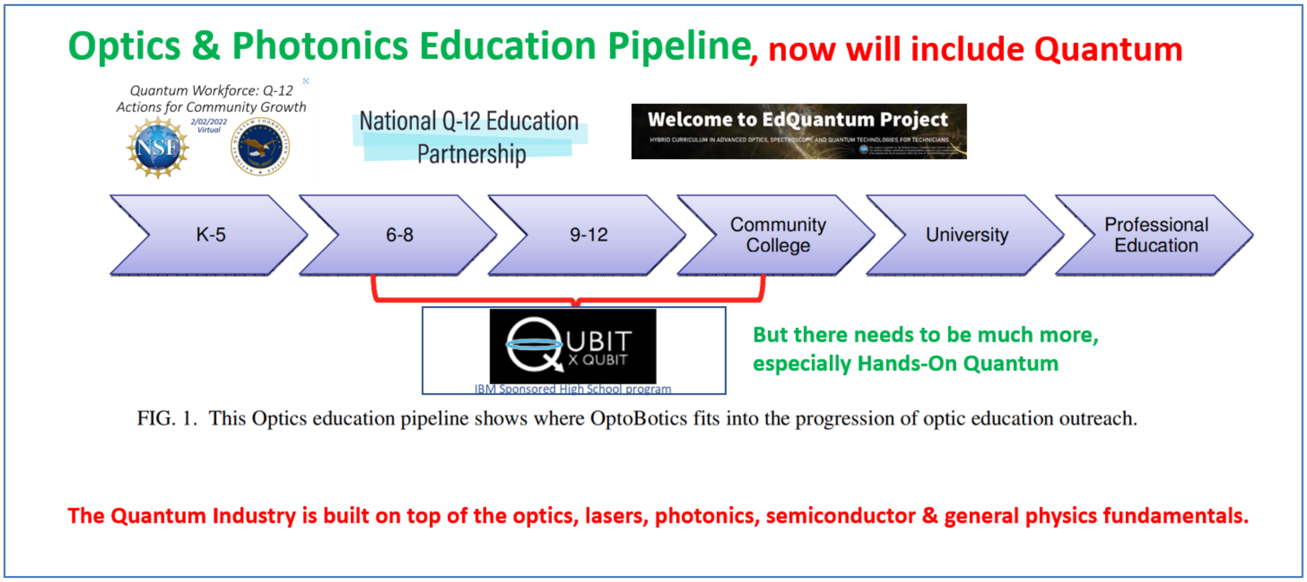

Figure 2. Updated version of Optics & Photonics Education Pipeline, now including Quantum Education.

For five years prior to COVID, the author was an active volunteer with Vital Link (http://vitallink.org), and he now serves on their Board of Directors. In 2014, he created and used an exhibit called "What is Light?", shown in figure 3, in conjunction with their career exploration programs visiting many middle and high schools in Orange County California. Recently, this exhibit was updated to include the atomic spectroscopy hands-on demonstration with diffraction gratings as shown in figure 4.

Vital Link offers programs that introduce students to the world of robotics, engineering, manufacturing, healthcare and medical, computer programming, digital media arts, automotive technology and more. Through these hands-on programs, we inspire students to feel confident and excited to pursue a fulfilling career.

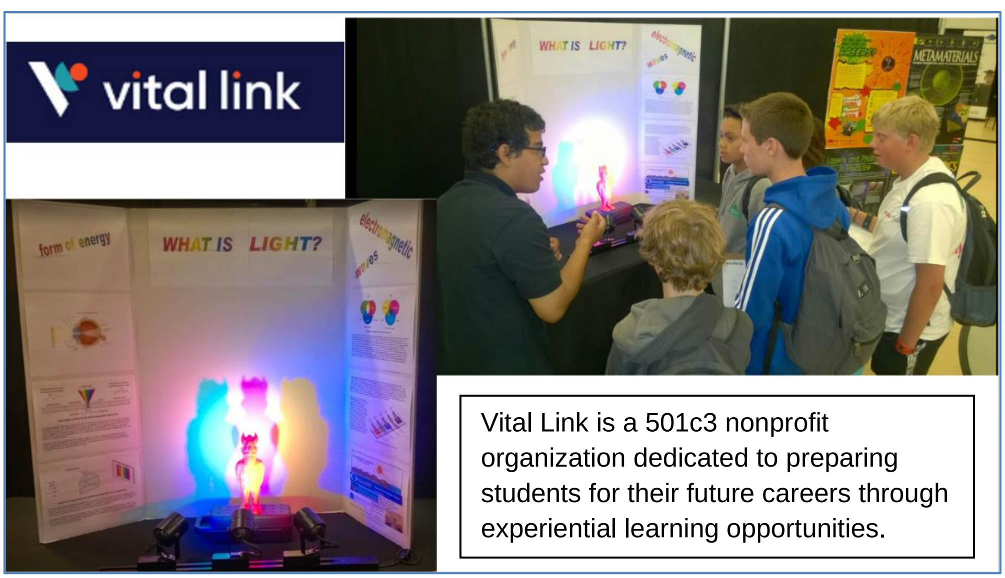

Figure 3. Example of Light & Optics career exploration exhibit (pre-COVID)

Figure 4. Recently updated Light & Optics career exploration exhibit for Vital Link.

This will be described in more detail in a later section of this paper.

3. QUANTUM EDUCATION & OUTREACH – PATHS FORWARD

The quantum education and outreach paths forward include the hands-on in-person work we are doing with Vital Link to get in front of as many middle and high school students we can and surprise them with diffractive optics and atomic spectroscopy demonstrations. However, to reach a much broader population nationally and globally, we have partnered with Optica, where they have included a link to our “Quantum for Students” webpage on their “Optics 4 Kids” webpage as shown in figure 5. We have also proposed that we engage many more SPIE, Optica, and IEEE Photonics Students and Chapters and give them tools to make it easy for them to go to local high schools and get those students interested in our research and industries. We have already begun this effort with the UC San Diego SPIE Student Chapter, the UC Irvine Optica Student Chapter and the Cal State University Pomona Society of Physics Students Chapter. We will continue to reach out to more Southern California colleges and universities with our presentations, workshops and materials to encourage them to go out to local high schools.

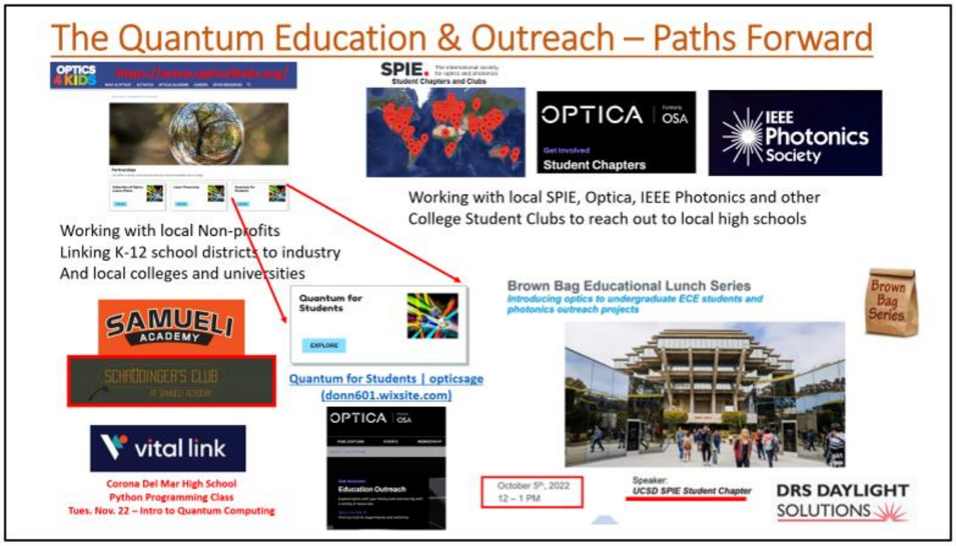

Figure 5. Quantum education and outreach – paths

4. THE SAMUELI ACADEMY'S "SCHRODINGER'S (QUANTUM) CLUB"

Our work with the Samueli Academy last spring began at the Vital Link post-COVID 'Relaunch' celebration with their new current president presiding as the master of ceremonies and their longtime president being celebrated as she retired. Their most recent Board Chair, Bo Wang, a mentee of the author, continued to ask the author to join the board and re-engage with the education outreach activities they had done together during the pre-COVID years. However, it was a young Samueli Academy student that approached the author at this event that got the author reconnected with his old friend and Samueli Academy Engineering Instructor[5]. This led the author to give his modifiable open-source presentation to two (2) Samueli Academy engineering classes, one of graduating seniors and the other to a class of juniors. It was during the later presentation after the 'call to action' that included the concept of starting your own quantum club, that two students mentioned that they would like to start such a club for the next school year.

Figure 6. Samueli Academy's Schrodinger's Club hands-on workshops.

Here, in figure 6, are a couple examples of the hands-on labs the students have done at the Samueli Academy's Schrödinger's (Quantum) Club during the fall 2022 semester. On the bottom left the students are using polarizers and lasers pointers, and on the bottom right they (and the author) are using diffraction gratings to learn about diffraction and spectroscopy.

The top right photo shows the club founder and president during an open house at the engineering Fab Lab where she was explaining to the adult guests about how their club uses the Light & Optics Experiment kit in a box and the Maps of Quantum Physics and Quantum Computing by Domain of Science physicist Dominic Walliman.

The simple hands-on polarization experimental set-up, shown in figure 7, uses a red laser pointer and three linear polarizing filters with a small wooden v-block and a stack of business cards (from the Optical Society of Southern California.) Here we show the students the laser with no polarizing filters, with one filter and then with two crossed filters and finally with a third filter inserted between the two at 45 degrees so that some light now gets through. This can be an epiphany moment for the students, because they wonder how the laser light appears after it has been totally blocked.

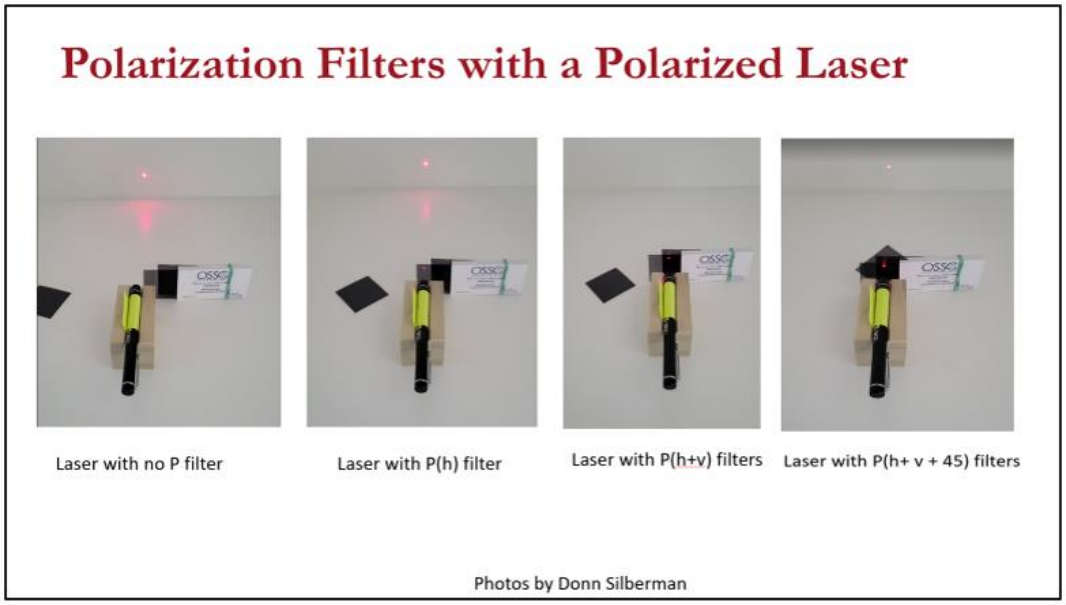

Figure 7. Polarization filters with polarized laser experimental set-up.

5. INTRODUCTION TO QUANTUM CRYPTOGRAPHY – UNIVERSITY OF WATERLOO

The polarization experimentation leads directly into a very nice set of experiments in quantum cryptography and the author used materials directly from the on-line course for educators he took during the summer of 2021 from the University of Waterloo's Institute for Quantum Computing[9]. Figure 8 shows the Introduction to Quantum Cryptography title slide the author used at a workshop at a Samueli Academy's Schrodinger's Club meeting and then again at a Corona del Mar's high school Python Computer Programming class. These materials can be shared with others like the SPIE, Optica & IEEE Photonics students so they can use them to go to local high schools and teach introductory quantum concepts to high school students.

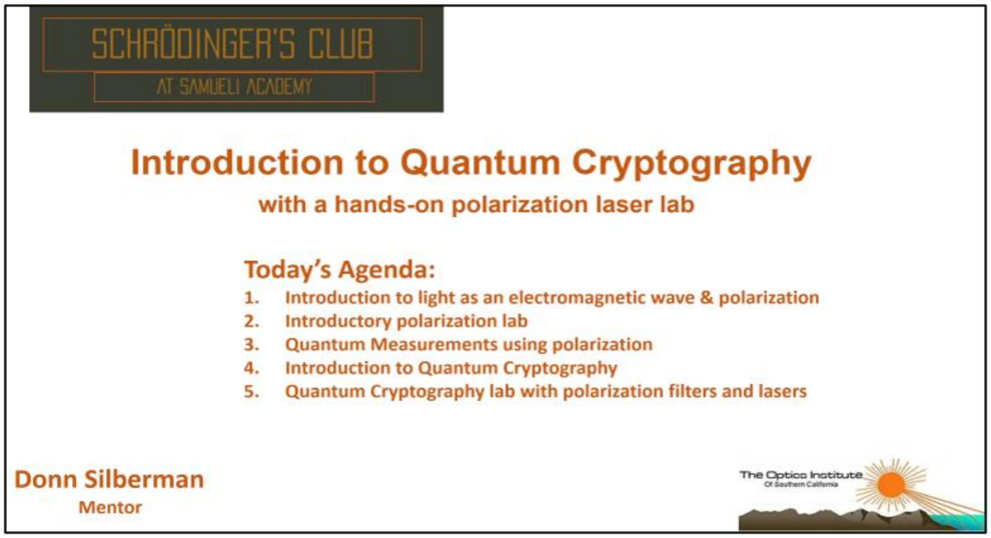

Figure 8. Title slide to High School Quantum Cryptography workshops.

One of the concepts shared with the students using the materials from the University of Waterloo was that other quantum objects like electrons, atoms and ions also can be used in quantum experiments. Figure 9 shows that the three-polarizer experiment is mathematically equivalent to the Stern-Gerlach experiment using Spin-Polarized Electrons.

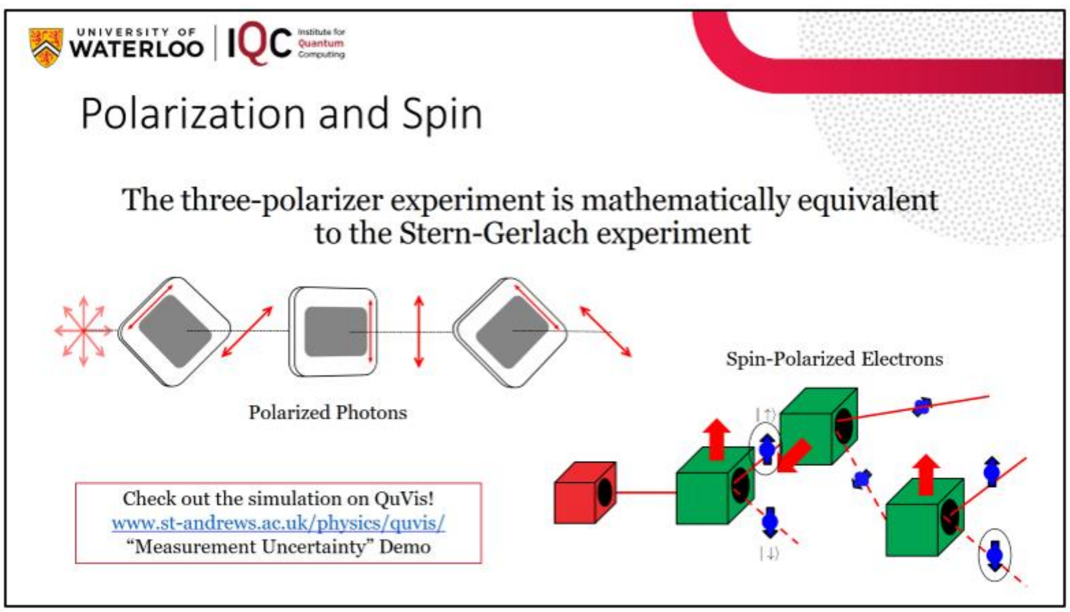

Figure 9. Polarization and Spin slide from the University of Waterloo's workshop.

The link to the University of St. Andrews' QuVis website is another place the students can go for a deeper dive into these concepts and many more. Again, one of the author's goals is to provide these interested high school students places they can go on the internet to find excellent materials. His experience has been that not all the materials on the internet are useful and some are actually confusing.

The Quantum Key Distribution is another concept shared with the high school students and they completed a workshop experiment using the materials from the University of Waterloo. This also built on their experiences with the linear polarizers and the laser pointers.

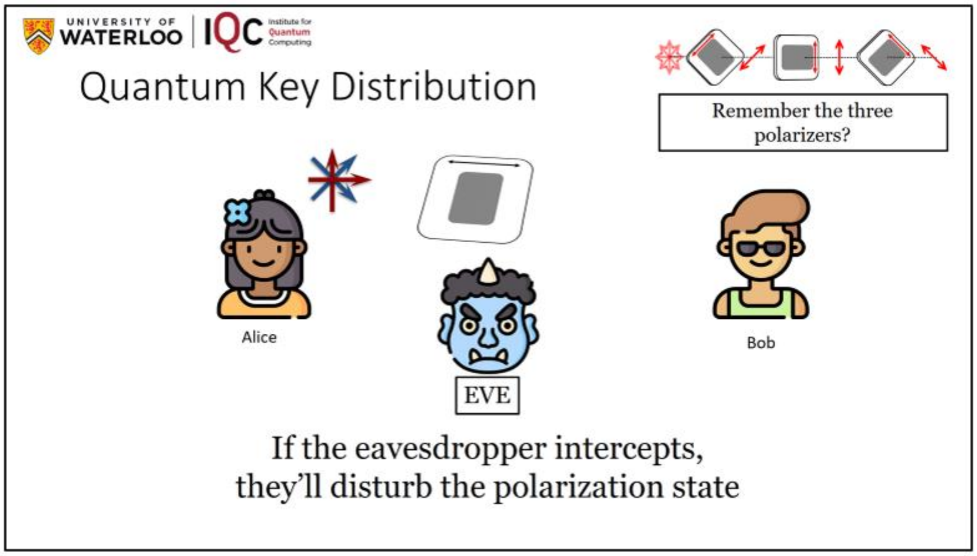

Figure 10. Quantum Key Distribution slide from the University of Waterloo's workshop.

6. INTRODUCTION TO DIFFRACTION AND ATOMIC SPECTROSCOPY

Since the students had already experienced the laser pointer and polarizers, they were shown that the laser light intensity is a gaussian distribution, being brightest at the center and trailing off towards the edges. Figures 11 shows the progression that led them to the surprising result of a small aperture placed in front of the laser beam.

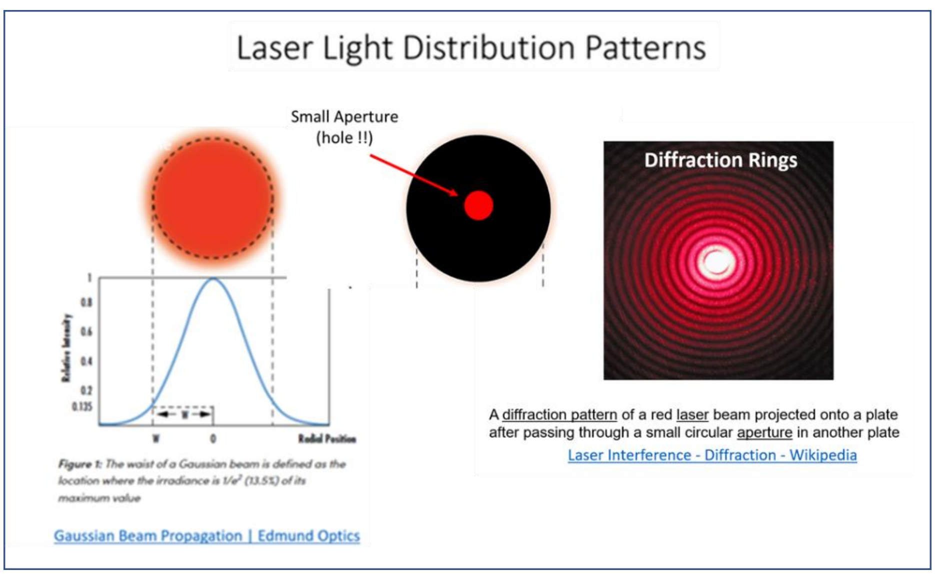

Figure 11. Laser light distribution patterns and diffraction through an aperture.

Next we let the students know that lasers are intrinsically quantum devices by their very nature, as shown in figure 12, and that we share with them the concept of electrons in atoms being excited from their ground state to higher levels of energy by incident photons. And when the electrons drop back down to their ground states, photos are emitted.

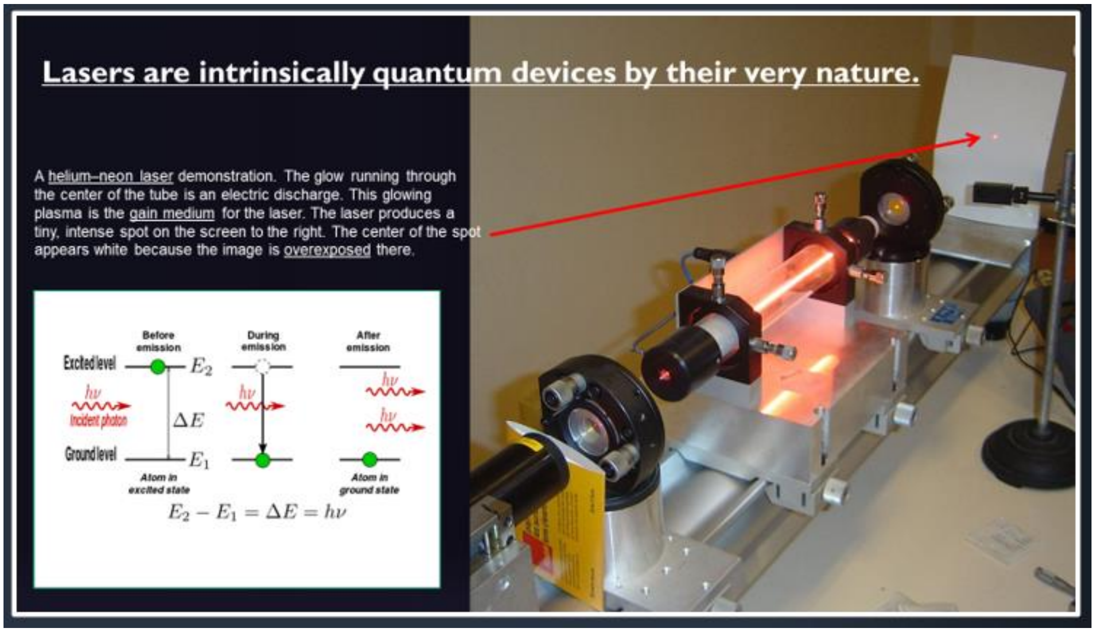

Figure 12. HeNe Laser Demonstration with graphic display of energy levels before, during and after photon emission.

Then we showed them a very complex set of Computer Generated Diffractive Optical Elements with 24 custom DOEs, as shown in figure 13. We also have a nice video showing each of the 24 elements for people using this presentation without the actual DOEs, which is depicted in figure 14.

Figure 13. Custom Computer Generated Diffractive Optical Elements.

Figure 14. Photo from video that shows diffracted light patterns and images through the 24 custom diffractive optical elements.

Next we share the concept that the two very similar looking diffraction gratings shown in figure 15, have a difference that they can't be seen with the unaided eyes. By using the laser, the students can experimentally determine the difference that one grating has 500 lp/mm and the other has 1000 lp/mm.

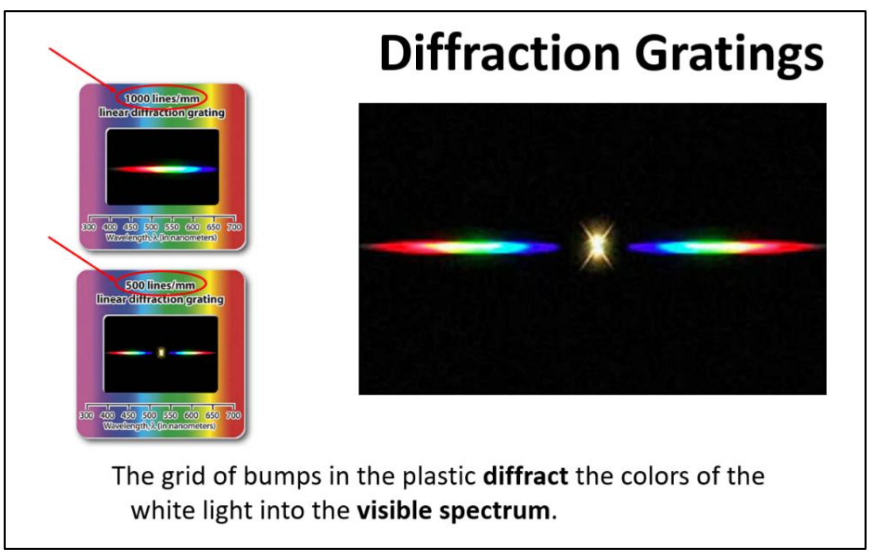

Figure 15. Two diffraction gratings, one with 500 lp/mm and the other with 1000 lp/mm.

The experimental method that the students use to determine the grating spacing, d, is shown in figure 16 along with the diagram that helps the students understand the calculations. This equation can also be used to confirm the laser light wavelengths, especially when the students have two different lasers each with a different laser wavelength, such as red and green, and two different diffraction gratings each with a different grating spacing.

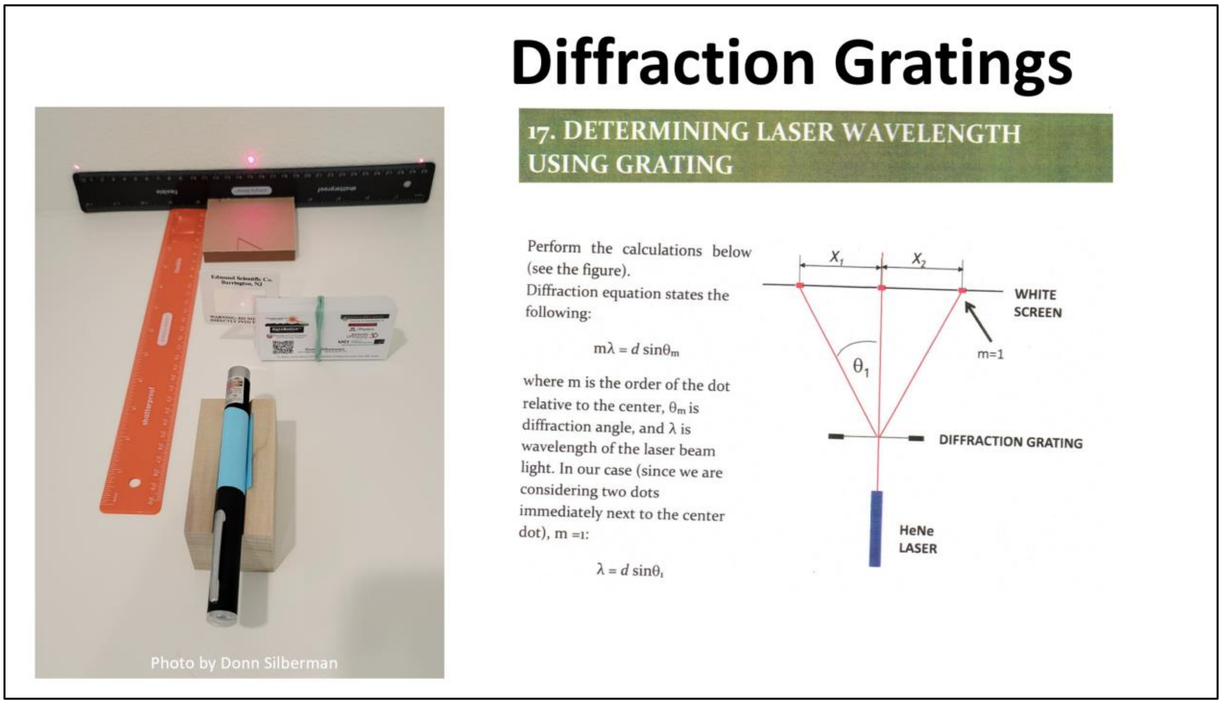

Figure 16. Experimental set-up and diffraction grating equation with diagram.

Moving the students on to learning about atomic spectra, first absorption, we used a light fixture with multiple sockets each on a flexible neck, and each with a different colored coated light bulb. The results of looking through the diffraction gratings at these colored light bulbs is shown in figure 17.

Figure 17. Absorption spectra of colored coated light bulbs.

The students can use worksheets made for this workshop to draw, using colored pencils or crayons, the spectra they see for each color coated light bulb. Note that in real life, the absorption spectra appear much clearer than they do in the photographic images presented in figure 17.

Emission spectra are shown to the students by using standard gas tubes with different chemical elements as shown in figure 18. We also use a Spectrum Analysis poster from Wabash Instrument Corporation to give examples the students can see and compare to the live spectra they observe during the workshops. We also discussed the concepts of diffractive orders as students can easily see the 1st & 2nd diffractive orders using the 500 lp/mm gratings.

These images that students see with their own eyes tend to surprise the students in a very positive way and encourage them to learn more (at least some of the students want to learn more !!)

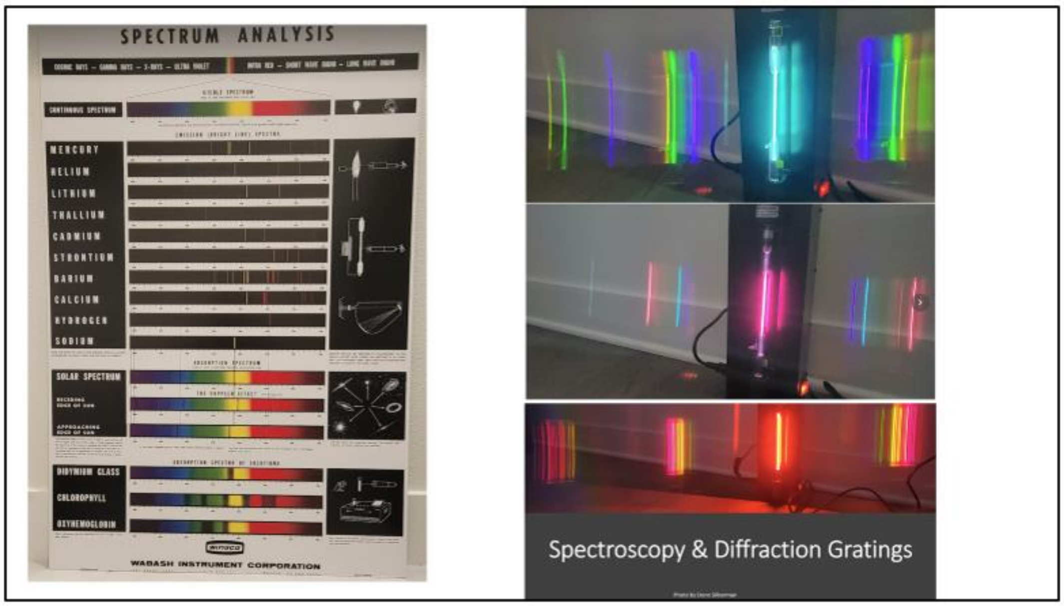

Figure 18. Emission spectra of three gas tubes and a spectrum analysis poster.

7. INTRODUCTION TO QUANTUM CONMPUTING WITH QUBIT X QUBIT

The last main topic is the Qubit x Qubit (QxQ) program on Quantum Computing for High School Students. The author completed taking this 2 semester course so he could learn from these quantum computing education experts on how they have set up and implemented this program that in his opinion is one of the best on-line courses for high school students and anyone else who is interested in learning this technology. QxQ is the online learning initiative of The Coding School, a 501(c)(3) organization that aims to empower the next generation through computer science education.

As described in figure 19, in addition to the 2 semester long on-line quantum computing courses for high school students, QxQ offers K-12, colleges and universities free workshops and courses that can be delivered on-line and in hybrid fashion in partnership with schools. The QxQ programs have been developed in partnership with IBM Quantum and they use IBM's Qiskit as the basis for the programming experiences during their courses and workshops. IBM also has many on-line tutorials and other help to get anyone started on their quantum computing journey by beginning on their website at www.ibm.com/quantum.

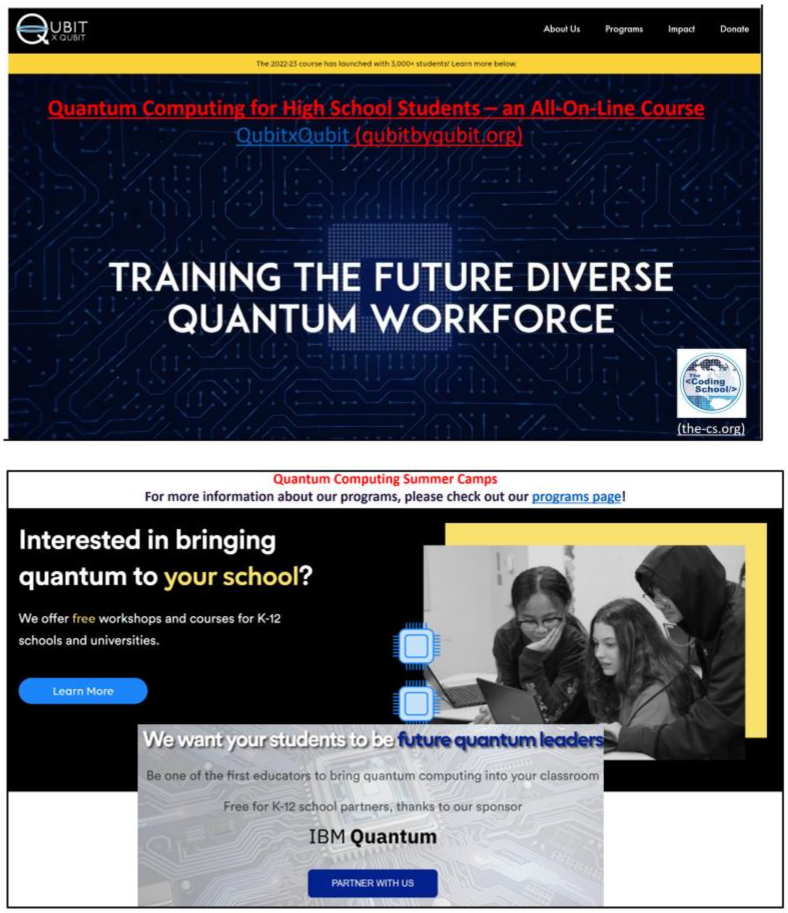

Figure 19. Qubit x Qubit Quantum Computing for high school students.

The next few figures are examples of the author's QxQ journey with IBM Qiskit. Figure 20 shows the Welcome page all the high school students see when they logon during the QxQ course and when they are doing their homework and labs. In the center you can see some quick links back to homework and lab projects previously saved.

Figure 21 shows the introduction to Lab: Week 6 – The Z Gate and Multi-Qubit Circuits. On the left sidebar we have many of the homework and lab projects that can be brought over to the main working section to refer back or work on them more. Sections from previous programs can be copy, pasted, modified and used in the current homework or lab project; building on past learning experiences.

Figure 22 shows a simple example of the Python code for a Z-Gate and a Bloch Sphere representing a quantum state, which is the output from the code.

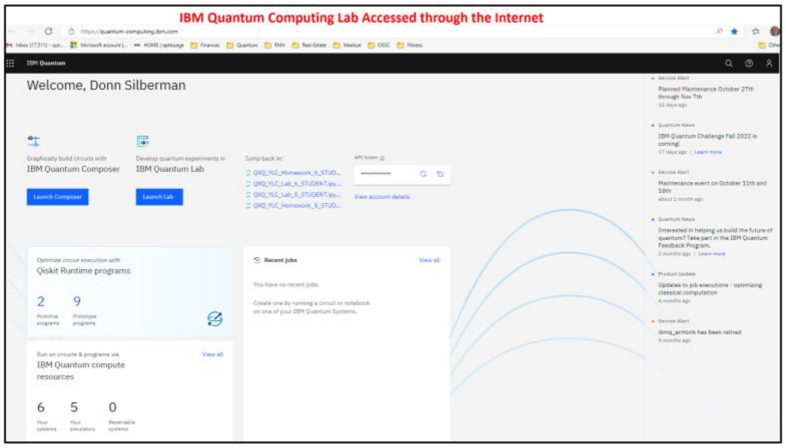

Figure 20. IBM Qiskit Welcome webpage seen by high school students

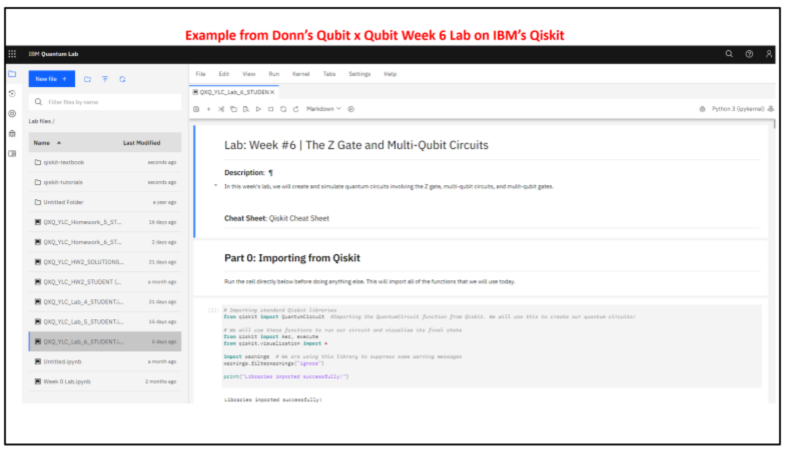

Figure 21. IBM Qiskit Welcome webpage seen by high school students.

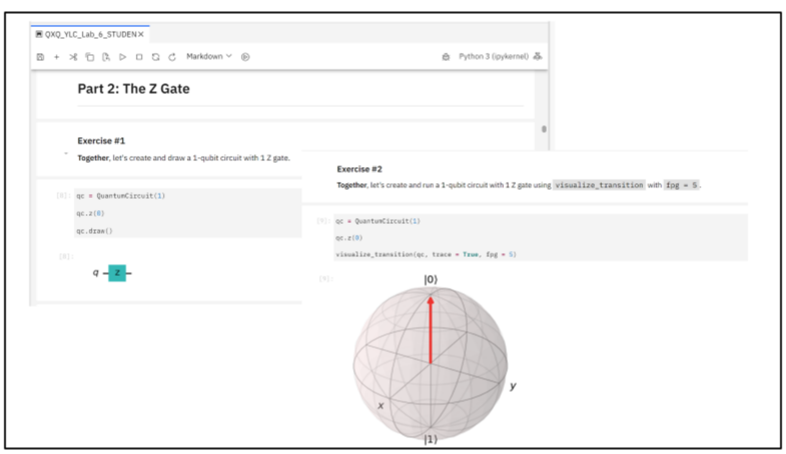

Figure 22. a simple example of the Python code for a Z-Gate and a Bloch Sphere representing a quantum state, which is the output from the code.

Figure 23 shows A quantum circuit representation and a histogram of the quantum states after running the circuit. The students learn that if they run the quantum circuit multiply times, they will not get the same answers in the histograms due to the probabilistic nature of the quantum world.

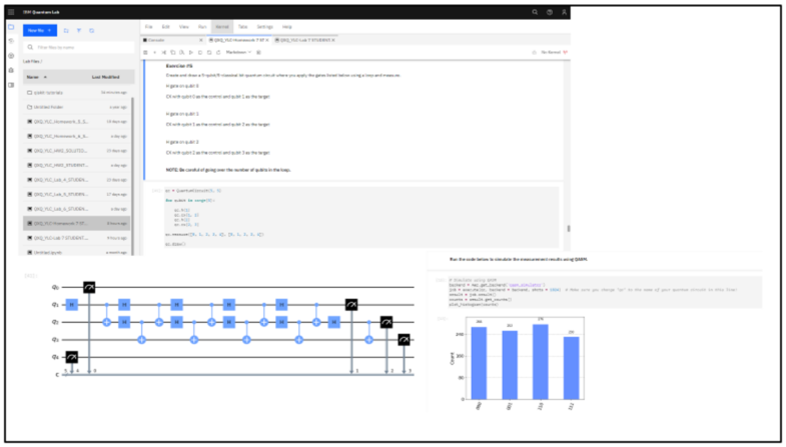

Figure 23. A quantum circuit representation and a histogram of the quantum states after running the circuit.

9. FIELD TRIPS, SUMMARY & FUTURE PROJECTS

During the current spring semester, the students in the Samueli Academy Schrodinger's Club wanted to take some field trips to local university research labs and hear from professors and their students working in quantum and related fields. Figures 24 and 25 shows the students at UC Irvine's Dollar Research Group's Ultrafast laser plasma interactions lab and Chapman University's Institute for Quantum Studies and the Greinke Family Catalysis Research Lab.

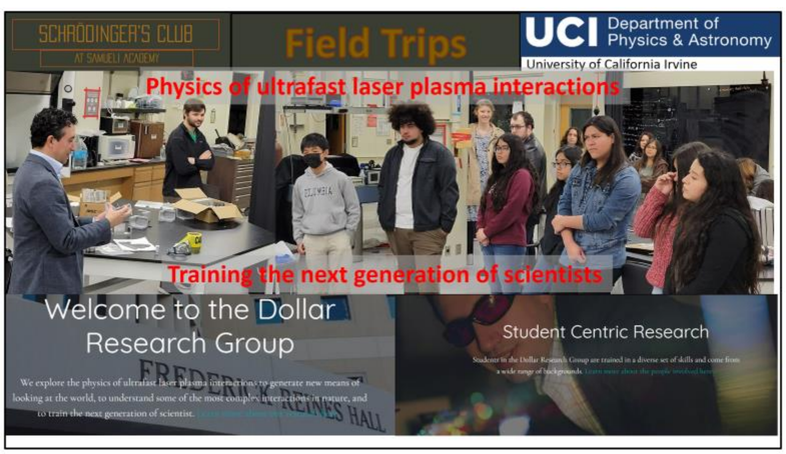

Figure 24. Dr. Franklin Dollar and his group talked to the students about the ultrafast laser plasma interactions.

Dr. Franklin Dollar[10] and his group talked to the students about the ultrafast laser plasma interactions they are working on and encouraged them to pursue their interests in the colleges and universities of their choice. And Dr. Andrew Jordan[11] and his group talked to the students about the some of the theoretical quantum physics projects they are working on and then we visited The Greinke Family Catalysis Research Lab (or CAT LAB for short) where Dr. Jerry LaRue and his students study the physics of chemical reactions and biochemical interactions. This is done with advanced laser spectroscopy systems in a vacuum chamber shown in figure 25.

Figure 25. Dr. Andrew Jordan and his group talked to the students about the some of the theoretical quantum physics projects they are working on. And the students also visited The Greinke Family Catalysis Research Lab and several other teaching labs in the same building.

In summary, this paper, and the work we shared is in the spirit of providing ideas and content for others to use freely. All our work is open source so it can be used to help students in any geographic area. We have referenced back to the beginning of the Optics Institute of Southern California and its mission of providing educational outreach programs using optics, photonics, lasers, and related physics and how over the past several years we have added specific quantum technologies on top of those basics and incorporated excellent materials from other experts in the field. We have provided real life examples of teaching quantum to high school students and proposed engaging more college and university students and other interested people from various Optica, SPIE, SPS, IEEE Photonics, and other professional and student run organizations both locally and globally.

Going forward, we will continue our local efforts with Vital Link, local K-12 schools, community colleges and universities, as well as encourage others nationally and globally through professional societies. This paper and presentation documents our efforts and provides content and contact information for others to use in their efforts to reach out to students in their local areas.

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