Physics 140 – Questions of Reality – Spring 2017

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> *I think I can safely say that nobody understands quantum mechanics.*
> – Richard Feynman

It is well known that on the microscopic level, particles behave in ways that defy our intuition. We find ourselves saying that an object is both a wave and a particle, it has traversed an impenetrable barrier, or it is in two places at once. Each of these statements bears a certain truth. These are phenomena of the quantum mechanical wavefunction, of superposition of single particle states. As we have come to better appreciate entanglement between particles, a new set of mysteries have crystalized. Experiments seem to require that we abandon local cause-and-effect, or free will, or the very notion that an objective physical reality might underlie the probability functions of quantum mechanics. What then is real on the most basic level? What do we hold on to, so that we can still say what it means to do science?

There is a second impulse behind the title of this course. In an era that holds truth to be subjective, I want to claim for physics a preferred truth among truths – preferred because accessible in principle to anyone and dependent only on observation – as that which can reliably be produced in laboratory experiment. If you want to know the way things are, physics gives you the tools to go look. That's the ideal. But as individual physicists, how much do we really know from looking at data, and how much do we take on faith? How do we decide whom to trust? Don't we know most of what we know because someone has written it in a textbook? You may be surprised to learn that the photoelectric effect does not actually imply the particle nature of the photon. If we are to combat fakery, we must first demand discipline of our own claims to knowledge. As our explorations get curiouser and curiouser, we will seek to ground ourselves more and more in the data from experiments.

What comfort can I offer you? The path you have chosen is not clear or easy. As Lenny Susskind once said to me (well, on the syllabus for his course on black holes):

Beware the will o' the wisp and keep your wits about.

Course Outline

This is a course in the foundations of quantum mechanics, half theory, half experiment. We will traffic in superposition, entanglement, and environmental decoherence. *The Quantum Challenge* by Greenstein and Zajonc will be our primary guide and text:

- We start with Chapters 1-2 on wave-particle duality. Some surprises await, despite the neat stories told in intro quantum textbooks.
- As interlude, we will review the basic formalism of quantum mechanics.
- Chapters 5-6 of Greenstein and Zajonc cover entanglement along with the Einstein-Podolsky-Rosen paradox and Bell's theorem, which get to the heart (or lack thereof) of local reality in quantum mechanics.
- Chapters 7-8 discuss decoherence and the measurement problem, one of the thorniest oustanding issues in quantum mechanics. We will approach decoherence through Schrödinger's original statement of the cat paradox and recent experiments on "cat" states in the lab.

For the first time, this decade, the technology has advanced to the point that we can do some of these experiments on our optics bench. Using entangled photons, we will:

1. Demonstrate the particle nature of the photon;
2. Demonstrate the interference of the photon with itself;
3. Test Bell's theorem, showing that barring some truly bizarre conspiracies, there is no possible classical physics hiding beneath the quantum mechanical world as we know it.

Laboratory responsibilities will rotate, so that each person, with a partner or partners, will execute one of the three experiments. The current working lab group will keep us apprised of progress, report out results, and set data analysis problems for the whole class. The experiments get progressively more challenging, and the first groups will be responsible for helping the later groups start where they left off.

Learning Objectives

Through participating in this course, students will grow in their ability to:

(Theory)

1. To articulate and give working examples of the defining features of quantum mechanics: superposition, entanglement, and environmental decoherence.
2. To assert knowledge with reference to data from specific experiments.
3. To delineate the boundaries of our understanding of quantum mechanics.

4. To pursue nuanced understanding of research journal articles through collaborative inquiry.

(Experiment)

1. To align, maintain, and take data with a research-quality optics bench.
2. To understand photon and photon-coincidence counting and statistics.
3. To pursue investigations with precision and perseverence.
4. To communicate experimental technique and results.

Outposts on the internet

TBA. Grades will be posted on Moodle.

Texts

- George Greenstein and Arthur G. Zajonc, *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics*, second edition.
- Eleanor Rieffel and Wolfgang Polak, *Quantum Computing: A Gentle Introduction.*

The first is the required course text. We will use excerpts of the second in our review of fundamentals and at other points where Rieffel and Polak give particularly clear explanations of the physics. The library has Rieffel and Polak on course reserve and in an electronic version you can access online.

In addition to the textbooks, we will study a number of original research papers.

Expectations, for students and instructor

- Attendance and engagement. This means really working to understand the subtle issues at stake, generating questions, refusing to be satisfied with half answers, sticking at the optics bench until the experiments work.
- Honesty in communication and in written work.
- Courtesy and kindness. Good life practice.

Assessment

Course grades will be based on:

- Lab report and presentation – 35%
- Problem sets and short assigments - 15%
- Take-home midterm - 15%
- Take-home final exam - 35%

Your turn in the laboratory will culminate with a formal lab report and research presentation to the class. During this time you will also be responsible for a number of shorter assignments, including progress reports to the class and a draft lab report. These are partly intended to help you progress toward the final report and will receive light grading (4/3/2/1/0), to be wrapped in with other homework assignments.

There will be problem sets. We encourage you to work with your classmates on these, though of course you must write up your own version of answers. We will not give extensions on homework, so please plan accordingly.

The exams will be yours to work on at home over a period of a day or days, to give you time to reflect at length on the subtle interpretational issues we will explore in this course. You may use whatever text or on-line resources you like, but as a matter of trust, you are not to discuss an exam with anyone during the time it's out.

We will be a small group, working lab and Seminar style. Attendance is required. You may miss two classes, no questions asked. Each additional absence will result in a drop by 1/3-letter your overall course grade.

With regard to all of the above policies, if a family or health emergency arises, please let us know and we will adjust as needed.

Student Disability Services

Student Disability Services extends reasonable and appropriate accommodations that take into account the context of the course and its essential elements for individuals with qualifying disabilities. Students with disabilities are encouraged to contact the Student Disability Services Office at (925) 631-4358 or sds@smarys-ca.edu to arrange a confidential appointment to discuss accommodation guidelines and available services. Additional information regarding the services available may be found at the following address on the Saint Marys website: http://www.stmarys-ca.edu/sds.