SUPPLEMENTARY MATERIALS

Refined Characterization of Student Perspectives on Quantum Physics

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APPENDIX A – INTERVIEW PROTOCOL, NARRATIVE AND DISCUSSION

A.1. INTERVIEW PROTOCOL

BACKGROUND INFORMATION
Name, declared major, previous physics and mathematics courses, both at CU and in high school, motivations for enrolling in the course

ASK STUDENTS TO DESCRIBE AN ELECTRON

DESCRIBE AN ELECTRON IN AN ATOM
Do students use a planetary model as a first-pass description? Are students aware of the limitations of the Bohr model? Do electrons move in orbits as localized particles? Does the student describe the electron in terms of an *electron cloud*, or a *cloud of probability*? What is this cloud? Does it represent something physical, or is it a mathematical tool? If the electron is described as a wave, what is it that's waving? Is there something moving up and down in space?

RESPOND TO THE STATEMENT:
An electron in an atom has a definite but unknown position at each moment in time.
IN AGREEMENT OR DISAGREEMENT AND EXPLAIN REASONING
Is the student's response consistent with their earlier descriptions of atomic electrons?

DESCRIBE THE SETUP FOR THE DOUBLE-SLIT EXPERIMENT
What is observed? Can the experiment be run with both light and electrons? What is observed when only single quanta pass through the apparatus at a time? What happens if you block one of the slits? What happens if you place a detector at one of the slits to see which slit individual quanta passed through? How do students explain the fringe pattern? If they explain the experiment in terms of localized particles, what is the source of interference? If they prefer a wave-description of quanta, how did the student explain why single quanta are detected as localized points? Is it possible for a particle to pass through two slits simultaneously? Does a wave packet description of individual particles reflect an ignorance of that particle's true position or momentum?

Fig. A1. A sequence of screen shots from the Quantum Wave Interference simulation. A bright spot (representing the probability density for a single electron) emerges from an electron gun (A), passes through both slits (B), and a single electron is detected on the far screen (C). After many electrons, a fringe pattern develops (not shown).

RESPOND TO THE ONLINE SURVEY QUESTION ON THE DOUBLE-SLIT EXPERIMENT:

> **Three students discuss the Quantum Wave Interference simulation (as depicted in Fig. A1):**
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> **Student 1**: The probability density is so large because we don't know the true position of the electron. Since only a single dot at a time appears on the detecting screen, the electron must have been a tiny particle, traveling somewhere inside that blob, so that the electron went through one slit or the other on its way to the point where it was detected.
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> **Student 2**: The blob represents the electron itself, since an electron is described by a wave packet that will spread out over time. The electron acts as a wave and will go through both slits and interfere with itself. That's why a distinct interference pattern will show up on the screen after shooting many electrons.
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> **Student 3**: Quantum mechanics is only about predicting the outcomes of measurements, so we really can't know anything about what the electron is doing between being emitted from the gun and being detected on the screen.

Ask students to read each statement one at a time, and respond before moving on to the next statement. Are student responses to the essay question consistent with their earlier descriptions of the experiment? Are student responses consistent with their earlier descriptions of atomic electrons? If no, why not? Is the student aware of inconsistencies?

QUESTIONS REGARDING INTERPRETATIONS OF QUANTUM MECHANICS
Is the student aware there are multiple interpretations of quantum mechanics? Can they name any of them or describe their features? Has the student heard of the Copenhagen Interpretation, and can they describe what it entails? Does the student know what the word *determinism* means

within the context of physics? Did they have an opinion as to how they think their instructor would have wanted them to respond to earlier interview questions?

RESPOND TO THE STATEMENT IN AGREEMENT OR DISAGREEMENT AND EXPLAIN REASONING: *It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.*

RESPOND TO THE STATEMENT IN AGREEMENT OR DISAGREEMENT AND EXPLAIN REASONING: *The probabilistic nature of quantum mechanics is mostly due to the limitations of our measurement instruments.*

A.2. INTERVIEW NARRATIVE AND DISCUSSION

Considering the contextual nature of student responses, we began each interview in the present study by asking students to simply describe an electron, in words or pictures, thereby allowing students to provide their own context. Three of the Quantum students differed from most other students in that their initial descriptions of electrons did not reference atoms – instead, these three students first described electrons as "wave packets", or "packets of energy". Fifteen of the remaining sixteen students described electrons first and foremost as constituents of atoms, and all but one of the remaining four students eventually discussed electrons within the context of atoms without any prompting from the interviewer. This approach allowed for an initial exploration of student beliefs about atomic electrons without the need for explicit questioning.

We found that a large majority of students used a planetary model as a first-pass description of atoms, though every student claimed to be aware that the Bohr model has limitations and is not entirely accurate; most students eventually said an atomic electron is more properly described by an *electron cloud*, or a *cloud of probability*. At this point, there were a number of opportunities to explore student ontologies: Do electrons exist as localized particles within that cloud of probability? Does the electron cloud represent something physical? Is it only a mathematical tool describing the probabilities for where an electron could be found? If the electron is acting like a wave, what is it that is waving? Is there anything physically oscillating in space? Once a clear picture had been established of how each student thought of electrons in the context of atoms, students were then asked to agree or disagree (and then explain their reasoning) with a statement from the online survey: *An electron in an atom has a definite but unknown position at each moment in time.* In every case, interview responses to this statement were consistent with the descriptions of electrons that students had just given.

Students were then asked to describe the setup for the double-slit experiment and what is observed. Every student discussed the observed fringe pattern in terms of the constructive and destructive interference of waves, and all but one student (R2) knew that attempts to determine which-path information would disrupt the interference pattern. All nineteen students were also aware the experiment could be run with single quanta, and that an interference pattern would still develop over time. These initial questions were meant to establish that each student had sufficient content knowledge regarding the double-slit experiment, so that a meaningful discussion concerning the implications of the results would be possible. From these responses, we conclude that no link could be discerned between a student's understanding of the particulars of the double-slit experiment, and their preferred interpretation of its results.

At this point in the interview, there were again opportunities to explore student stances on our themes of interpretation without the need for explicit questioning. Regardless of their preferred interpretation, every student explained the fringe pattern in terms of interference. If they thought of the experiment in terms of localized particles, what did they feel was the source of interference? If they preferred a wave description of quanta, how did students explain why single quanta are detected at localized points? Is it possible for a particle to pass through both slits simultaneously? Does a wave-packet description of an individual particle reflect an ignorance of the true state of that particle? As with the discussion of atomic electrons, by this point a clear picture had been established regarding how each student would interpret the double-slit experiment. Students were then asked to read and respond to statements made by three fictional students concerning their interpretations of the double-slit experiment. (See Appendix A) In the interviews, students were asked to read each statement, one at a time, and respond before moving on to the next statement.

Here, students did not necessarily respond to the essay question on the double-slit experiment in a manner consistent with their view on atomic electrons: some switched between Realist and Quantum perspectives, though no student applied first a Quantum perspective on atomic electrons and then a Realist perspective on the double-slit experiment. Nor did students necessarily remain consistent *within* their responses to the individual statements from the essay question. Any apparent inconsistencies in student responses were then explored with further questioning.

The interviews then progressed to a more explicit discussion of interpretation, with the intent of gauging student awareness of interpretive themes as actual themes of interpretation (as opposed to scientific fact). Had students heard of the Copenhagen Interpretation, and could they describe what it entails? Could students name any of the various interpretations of quantum mechanics, or describe their features? Did students know what the word *determinism* means within the context of physics? For all but a handful of students, the answers to the above questions were repeatedly: No. Most every student claimed to be aware that there are multiple interpretations of quantum mechanics, but very few could name even one of them. This pattern of student responses is consistent with our classroom observations: the instructors for the students interviewed rarely (if ever) discussed interpretations of quantum phenomena as actual interpretations; nor did these instructors devote a significant amount of class time (if any) to a discussion of the Copenhagen Interpretation, or any other interpretation of quantum mechanics.

To conclude the interviews, students were asked to respond in agreement or disagreement (and to provide their reasoning) to the following two statements:

- It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.
- The probabilistic nature of quantum mechanics is mostly due to the limitations of our measurement instruments.

Our intent was to explore whether and how students distinguish between the experimental uncertainties of classical physics and the fundamental uncertainties of quantum measurements, with the goal of gauging student perspectives on questions of determinism and probability. Surprisingly, all but one student (QR4) discounted the notion that a more complete (i.e non-statistical) description of quantum measurements would be possible. Student QR4 expressed a belief that scientists would eventually be able to predict the outcomes of individual quantum measurements with ever increasing accuracy. The remaining eighteen students either stated that the behavior of quantum particles is inherently probabilistic, and/or invoked the Uncertainty Principle as placing a fundamental limit on what can be known about quantum systems. Although realist/statistical perspectives have been historically associated with underlying notions of determinism, we find that practically none of our nineteen interview participants favored such ideas in the context of quantum physics. This finding is consistent with prior research showing that, not only do the perspectives of classical physics students become more deterministic over time, the perspectives of these same students become more probabilistic following a modern physics course. [1] For these reasons, a characterization of individual student perspectives with respect to determinacy could only be inferred from their stances on the other issues, and so is not included in this study.