Interpretive Themes in Quantum Physics

Charles Baily and Noah D. Finkelstein
Department of Physics, University of Colorado at Boulder - per.colorado.edu

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Introduction

- **Interpretative themes in quantum mechanics are often ignored** or only superficially addressed **in introductory modern physics courses**.
  - Is the wave function physically real, or simply a mathematical tool?
  - Does the *collapse of the wave function* represent a change in information, or a physical transition not described by any equation?
  - Do electrons exist as localized particles at all times?
- Many **students develop *realist* (classical) perspectives** on quantum phenomena in contexts **where interpretation is de-emphasized**, and **explicit instruction** is often **not meaningful** for students **beyond specific contexts** [REF. 1, 2]
- We have **developed a modern physics curriculum** designed to:
  - Address interpretive themes across multiple contexts (e.g. atomic systems, **single-photon experiments**, uncertainty principle).
  - Confront realist expectations of students through **interactive lectures** on recent (and historical) **experimental evidence** for wave/particle duality.
  - **Encourage student interest** and **positively impact student perspectives** on the physical interpretation of quantum mechanics.

Course Transformations

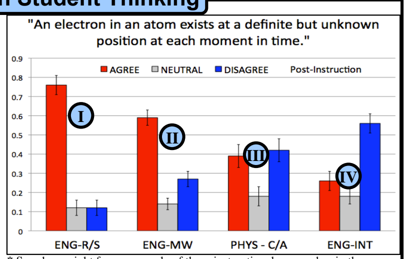
- **Interactive lectures** on the foundations of quantum mechanics engage students in questions of **classical and quantum reality**:
  - **Clicker questions** stimulate student discussion, where the answers can sometimes be a matter of interpretation.
  - **Make *realist* expectations explicit** and help students develop the conceptual tools and language to **articulate their beliefs** in a variety of contexts.
  - **Provide experimental evidence** against *realist* interpretations of quantum systems
- **Online discussion boards** allow students to **pose questions** and **provide answers** to each other, and **continue in-class discussions**.
- **Weekly homework assignments** consist of a broad mixture of **conceptual** and **calculation problems**, requiring short-essay, M/C, and numerical answers.
- **End-of-term reflective essays** help make QM relevant to students by letting them:
  - **Explore a topic from quantum physics** that is personal interest to them, or…
  - **Reflect on their experience** of learning about quantum mechanics.

Positive Impacts on Student Thinking

(I) Students from a modern physics course taught from a **Realist/Statistical (R/S)*** perspective prefer to **agree with** the notion of spatially **localized atomic electrons**.

(II) The **Matter-Wave (MW)*** perspective taught earlier in this course had little impact on student thinking in a later context where interpretive themes were de-emphasized..

(III) A **Copenhagen/Agnostic (C/A)***course for **physics majors** left a significant number of students **preferring realist interpretations**.



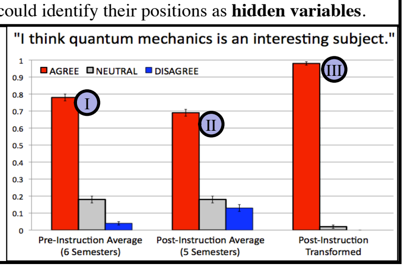
* See above-right for an example of these instructional approaches in the context of a double-slit experiment with electrons.

(IV) Following a course emphasizing interpretive themes (**INT**), more students chose to **disagree with** the notion of **localized atomic electrons**, and could identify their positions as **hidden variables**.

(I) **Incoming interest** for engineering students **is moderately high**.

(II) **Student interest** typically **decreases** – nearly 1/3 of students would **not agree** that quantum mechanics is interesting **after instruction**.

(III) **A transformed modern physics course** emphasizing interpretive themes and experimental evidence was **almost universally favored**.



Experimental Evidence & Interpretation

MATTER DIFFRACTION: A time-lapse film compiled from experimental data visually demonstrates for students…

(A) …the detection of individual **electrons as particles**…

(B) …that collectively **form a fringe pattern** over time. [REF. 3]

t=0 http://www.hitachi.com/rd/research/em/doubleslit.html **t~20min**

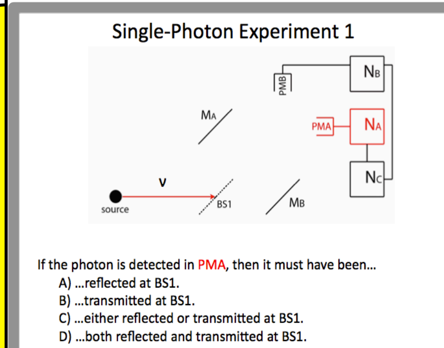
Realist/Statistical (R/S): Each electron passes through one slit or the other, but determining which one disrupts the interference pattern.

Matter-Wave (MW): Each electron passes through both slits, interferes with itself, and then collapses to a point upon detection.

Copenhagen/Agnostic (C/A): Electrons are modeled in terms of waves or particles accordingly; emphasis on mathematical calculation (predicting features of the interference pattern) over interpretation.

Single-Photon Experiments

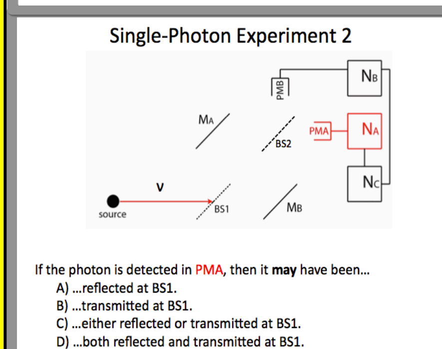
Demonstrate both wave- and particle-like behavior of light under similar circumstances with a low-intensity *single-photon* source. [REF. 4]



EXPERIMENT 1: A single beamsplitter (**BS1**) means only one path exists between the source & each detector (**PMA** or **PMB**).

Individual photon detections are **interpreted** to mean each photon takes only **one path** or the other, but not both.

Which-path information (single paths) implies **particle-like behavior**.



EXPERIMENT 2: A second beamsplitter (**BS2**) means multiple paths exist between the source & each detector.

Interference effects are **interpreted** to mean each photon takes **both paths.**

No path information (multiple paths) implies **wave-like behavior**.

DELAYED-CHOICE EXPERIMENTS: May be taken as evidence for:

1. **Matter-Wave interpretations** (instantaneous collapse of wave function).
2. **Copenhagen interpretations** (mutually exclusive classical descriptions).

References

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2. http://tinyurl.com/baily-dissertation
3. A. Tonomura, et al., Demonstration of Single-Electron Buildup of an Interference Pattern, *Amer. J. Phys*. **57**, 117 (1989).
4. P. Grangier, et al., Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences, *Europhys. Letters* **1**, 173 (1986).

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