Interpretive Themes in Quantum Physics: Curriculum Development and Outcomes

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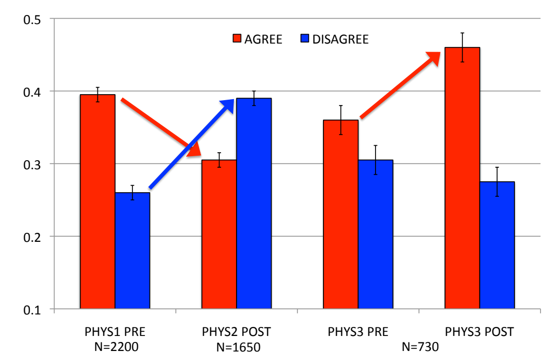
It is possible for physicists to carefully perform the same experiment and get two very different results that are both correct.



General Idea

Classical physics instruction and everyday experience reinforce *realist* perspectives:

- Deterministic/Local
- Intuitive

Topics from quantum physics require students to develop new perspectives:

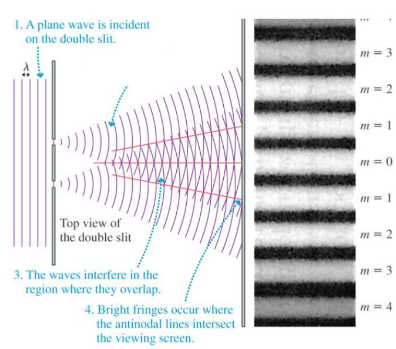
- Probabilistic/Non-Local
- Unintuitive

COURSES STUDIED

- PHYS 2130 – General Physics III
  (modern physics for engineers – ENG)
- PHYS 2170 – Foundations of Modern Physics
  (for majors – PHYS)

Typically, 1/3 Special Relativity, 2/3 Quantum Mechanics
All courses discussed today were large-lecture (N>60), and used interactive engagement (clickers, etc…).

Double-Slit Experiment

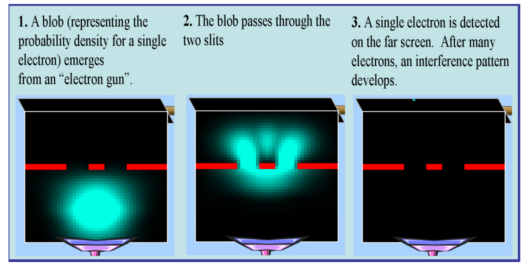


Double-Slit Experiment with Single Electrons (1989)

http://www.hitachi.com/rd/research/em/doubleslit.html

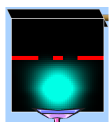
A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki and H. Ezawa, "Demonstration of Single-Electron Buildup of an Interference Pattern," Amer. J. Phys. 57 (1989) pp.117-120.

The Double-Slit Experiment with Single Electrons



http://phet.colorado.edu/new/simulations/sims.php?sim=QWI

Three students discuss the Quantum Wave Interference *simulation, in which a blob shown in the figure at right emerges from an electron gun, goes through two slits, and then a small dot appears on the screen, which is recognized as a "hit" of the electron. After a long time (many electrons) an interference pattern of "hits" is observed on the screen.*



- **[REALIST]** Each electron is a tiny particle that went through one slit or the other.
- **[MATTER-WAVE]** Each electron is a wave that went through both slits and interfered with itself.
- **[AGNOSTIC]** We can't say what the electron is doing between being emitted and detected.

Comparative Course Outcomes

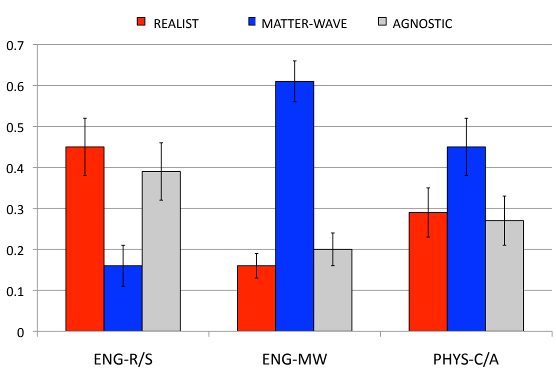
ENG-R/S: Modern physics for engineers
- Taught from a realist/statistical perspective

ENG-MW: Modern physics for engineers
- Taught from a matter-wave perspective
- Revisions to 1st transformed curriculum*

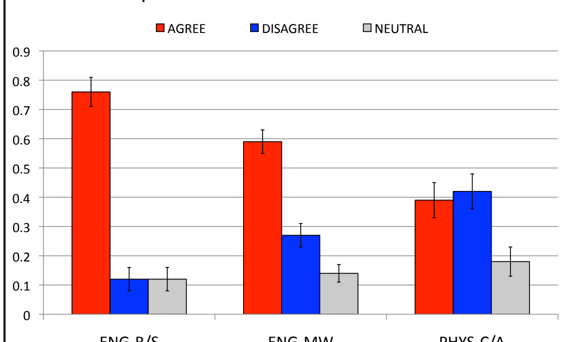
PHYS-C/A: Modern physics for majors
- Taught from an agnostic perspective.
- Similar to ENG-MW (less emphasis on interpretation)

*http://per.colorado.edu/modern

Double-Slit Essay Question



"An electron in an atom has a definite but unknown position at each moment in time."



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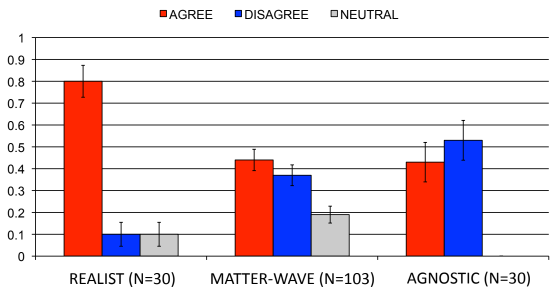


RESPONSE TO DOUBLE-SLIT ESSAY QUESTION

IMPLICATIONS

- Instructors have a measurable impact on student thinking in topic areas where instruction is explicit.
- Students are more likely to prefer realist perspectives in topic areas where instruction is less explicit.
- Student thinking is sensitive to context, and is not necessarily consistent.

QUESTIONS/COMMENTS?

STUDENTS EXPRESS ATTITUDES ON SPECIFIC INTERPRETIVE THEMES

1. Hidden Variables?
   (e.g. Objective Reality of Position)
2. Reality of Wave Function
   (Information-Wave or Matter-Wave?)
3. Wave Function Collapse?
   (Change in Knowledge or Physical?)

STUDENTS EXPRESS ATTITUDES ON SPECIFIC INTERPRETIVE THEMES

Example: THE POSITION OF A PARTICLE
- OBJECTIVELY REAL?

NO: "I don't think of [the electron] as orbiting the nucleus because it doesn't, it just exists in that region of space. [...] That's really what the electron is: a smeared out volume of charge."

YES: "An electron has to [always exist at] a definite point. It is a particle, we've found it has mass and it has these intrinsic qualities, like the charge it has, so it will have a definite position."

STUDENT INTERVIEWS

- Student perspectives on interpretive themes in quantum physics can be characterized and understood.
- Difficulty articulating deterministic ideas:
  - chaotic/random behavior of particles
  - unfamiliar with "**determinism**" in context of physics
- Don't learn about interpretive themes in quantum physics
  - some recognized the phrase ***Copenhagen Interpretation***
  - very few could say anything about what it entailed

Quantum Interpretation as *Hidden Curriculum*

- Interpretive themes are generally only superficially addressed.
  → not meaningful outside of specific contexts.
- Students develop their own ideas when their beliefs go unattended.
- Those ideas tend to be intuitively realist in contexts where alternatives are not promoted.

Curriculum Development

- Make realist assumptions (determinism, locality) explicit.
- Construct operative notions of *model*, *theory* & *interpretation*.
- Expose students to ideas regarding interpretive themes from the historical development of QM.
  - Complementarity/wave-particle duality
  - Wave function collapse
  - Entanglement/non-locality
- Present recent experiments on foundations of QM.
  - Single-quanta experiments
  - Distant, correlated measurements
- Introduce contemporary topics from quantum information theory.
  - Computing, cryptography, precision measurements…

Course Transformations

- New lecture materials (primarily Weeks 6-8)
- Concept tests/homework & exam questions
- Undergraduate learning assistants (2)
- Problem-solving sessions (instructors and LA's)
- Tunneling tutorial (plus revisions, with LA's)
- Outside readings (Scientific American)
- Discussion board
  - Students pose/answer questions on readings
  - Additional topics according to student interest
- End-of-term essay assignment
  - Topic from quantum mechanics
  - Personal reflection on learning about QM

End-of-Term Essays

Topics:

Quantum computing/cryptography/teleportation
Quantum Zeno effect
Bosons & Fermions
Bose-Einstein Condensation
Wave/Particle Duality
Many-Worlds/Decoherence/Copenhagen
Atomic Transistors

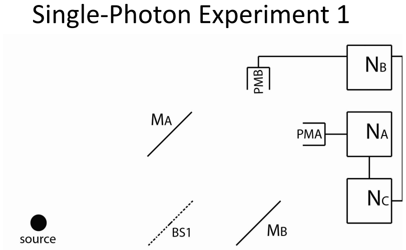
Personal Reflection (~40% of class)

Student Reflections

Topic most cited by students as influencing their perspective on QM:

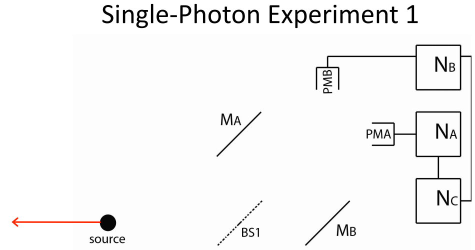
Single-Quanta Experiments

Single-Photon Experiment 1



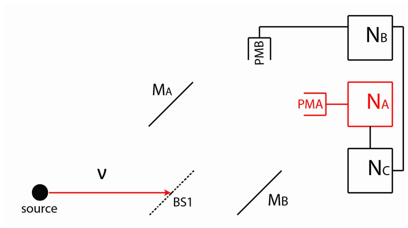
- M_A and M_B are mirrors.
- BS1 is a beam splitter.
- PMA & PMB are all photomultipliers.
- N_A, N_B & N_C are counters that record photon detections.

Single-Photon Experiment 1



A trigger photon opens a gate for τ = 10 ns

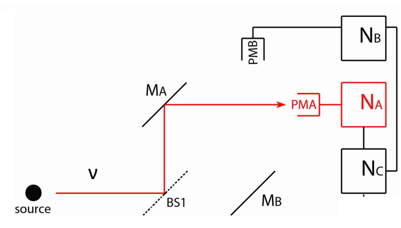
Single-Photon Experiment 1



If the photon (v) is detected by PMA, then it must have been…

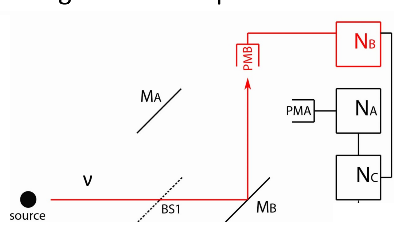
A) …reflected at BS1
B) …transmitted at BS1
C) …either reflected or transmitted at BS1
D) Not enough information.

Single-Photon Experiment 1



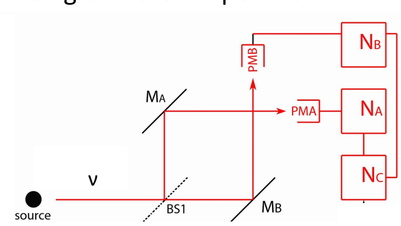
- If the photon (v) is detected by PMA, then the photon must have traveled along Path A (via M_A).

Single-Photon Experiment 1



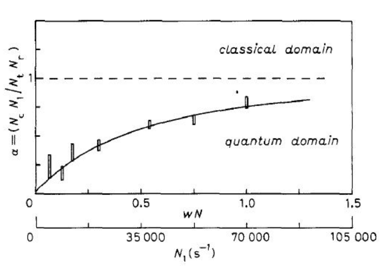
- If the photon (v) is detected by PMB, then the photon must have traveled along Path B (via M_B).

Single-Photon Experiment 1



- If both PMA & PMB are triggered during τ, then the coincidence counter (N_C) is triggered.

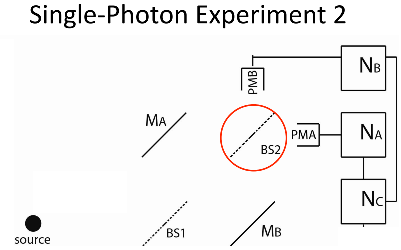
Single-Photon Experiment 1



EM Waves → α ≥ 1 Quantum Particles → α ≥ 0

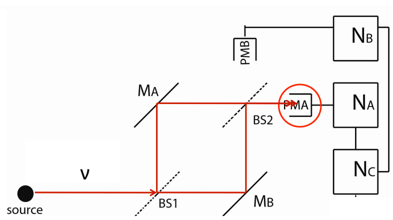
Photons take ***either*** **Path A *or* Path B**, but not both!!

Single-Photon Experiment 2



- Use same experimental setup, but now insert a beam splitter. (BS2)
- Run experiment as before…

Single-Photon Experiment 2



If the photon is detected in PMA, then it may have been…

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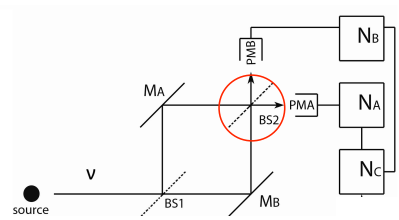
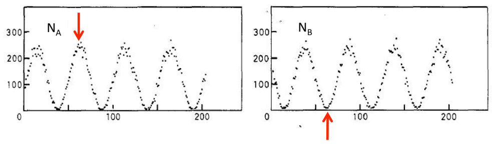
Single-Photon Experiment 2



- Whether the photon is detected in PMA or PMB, we have ***no information*** about which path (**A <u>or</u> B**) any photon took.
- What do we observe when we compare data from PMA & PMB?

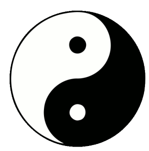
Single-Photon Experiment 2



- Slowly change one of the path lengths (Move M_B, for example), and we observe interference!
- For some path length differences, all the photons are detected by PMA and none in PMB
- For some path length differences, there is an equal probability for either detector to be triggered.
- Each photon is somehow "aware" of ***both paths***!

<u>Complementarity</u>

- ***Sometimes*** photons behave like ***waves***, and ***sometimes*** like ***particles***, but ***never both*** at the same time.
- According to Bohr, ***particle*** or ***wave*** are just classical concepts, used to describe the different behaviors of quanta under different circumstances.
- Neither concept by itself can completely describe the behavior of quantum systems.



Contraria
sunt
Complementa

Latin for:
opposites
are
complements

<u>What is a Photon?</u>

"The photon must change suddenly from being partly in one beam and partly in the other to being entirely in one of the beams."

P. A. M. Dirac, *The Principles of Quantum Mechanics* (1947).

<u>Comparative Course Outcomes</u>

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- Taught from a realist/statistical perspective

ENG-MW: Modern physics for engineers
- Taught from a matter-wave perspective
- Revisions to 1st transformed curriculum*

PHYS – C/A: Modern physics for majors
- Taught from an agnostic perspective.
- Similar to ENG-MW (less emphasis on interpretation)

ENG-FA10: Modern physics for engineers
- 2nd transformed curriculum* (no SR)

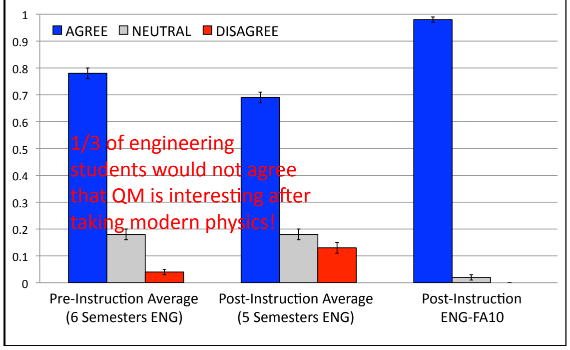
*http://per.colorado.edu/modern

Primary Learning Goals:

- Student Interest
- Internal Consistency
- Classical Uncertainty vs. Quantum Uncertainty

ENG – 6 SEMESTERS

"I think quantum mechanics is an interesting subject."



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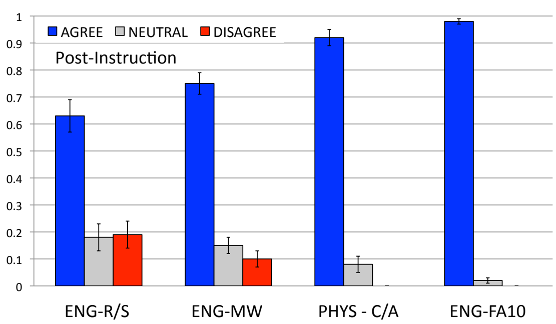

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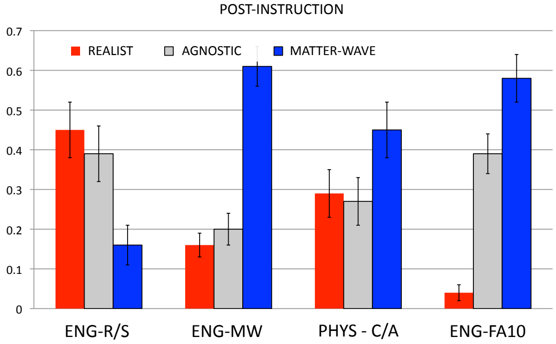
Double-Slit Essay Question

POST-INSTRUCTION



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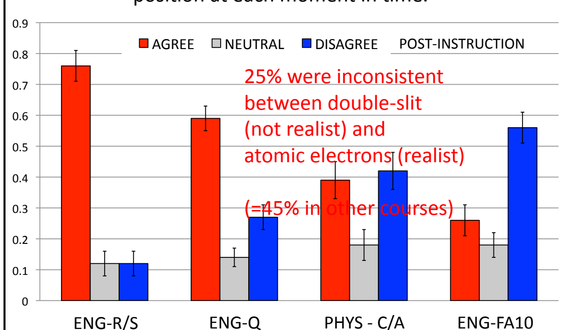

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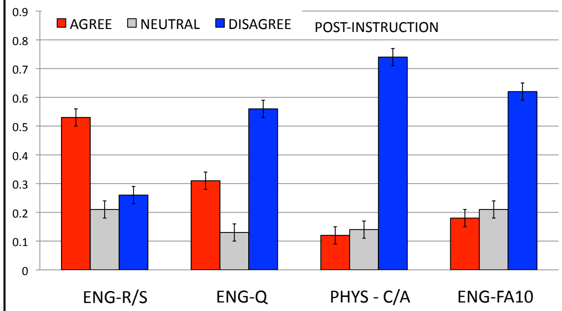
"The probabilistic nature of quantum mechanics is mostly due to the limitations of our measurement instruments."



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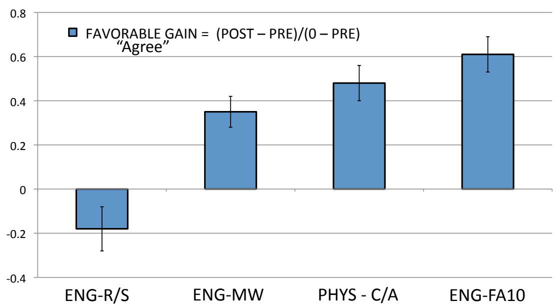

Important Conclusions

Students develop perspectives on the physical interpretation of QM
- Whether instructors attend to them or not
- When they do, instruction has influence
- When not, greater tendency to be intuitively *realist*

Student perspectives on QM can be understood:
- Wave/particle duality is challenging and contextual
- Can be characterized in terms of attitudes on specific themes

We may positively influence student perspectives on QM across a variety of measures by:
- Making *realist* expectations explicit
- Providing *evidence* against realist expectations
- Attending to interpretive themes across many topics

Fin

Much more at: per.colorado.edu