“I think it is safe to say that no one understands quantum mechanics. Do not keep saying to yourself, if you can possibly avoid it, ‘But how can it be like that?’ because you will go ‘down the drain’ into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that.”

Richard Feynmann, American physicist, 1965 Nobel Prize in Physics (1918-1988)

“Atoms are round balls of wood invented by Dr. Dalton.” Answer given by a pupil to a question on atomic theory, as reported by Sir Henry Enfield Roscoe, English chemist (1833-1915)

“The electron, as it leaves the atom, crystallises out of Schrödinger's mist like a genie emerging from his bottle.” Sir Arthur Eddington, English physicist (1882-1944)

Current Assignments ...

Office hours:
3-4 Tuesdays
& Thursdays

For today

- Read Sections 13.2 - 13.6

For Lecture 21

- Read Sections 13.7, 14.1 - 14.4

Homework #4

- Posted March 7. Late deadline 11 AM, March 29.

Homework #5

- Posted March 21. Due 11:00 AM, Friday, April 5

Writing Assignment #2

- Posted Feb. 28. Due 11:00 AM, Thursday, April 4

Suggested Conceptual Exercises

- Chapter 13: 1,3,5,7,9,11,13,15,17,19,21,23,25,27,29,31,33

Tutorial #10

Review of Lecture 20

Textbook, Sections 12.5 - 12.6

- The quantum theory of matter
- Quantum nonlocality and uncertainty

Textbook, Section 13.1

- The Uncertainty Principle

Plan for Lecture 22

Textbook, Sections 13.2-13.6

- The effect of observation
- Quantum nonlocality
- Quantum entanglement
- Toward a post-Newtonian worldview
- Spectroscopy and observing atomic spectra

L20: Double Slit for a Single Electron

The matter field moves through the two slits, and collapses into a single electron when it hits the screen.

Textbook
Figure 12.12

Question: How does the whole electron get through when some of the matter wave is blocked by the screen with the two slits?

The matter wave follow Huygen's Principle when it reaches the slits: Any point on the wave is the source of secondary waves, so each slit radiates spherical light waves. In order for an electron (or a photon) to interfere with itself, it must pass through both slits. Recall that the matter field is quantized. For an electron beam, the energy is mc^2, $2mc^2$, $3mc^2$, etc. where m = mass of electron. So energy mc^2 is deposited on the screen when one electron interacts with it.

More on Quantum Uncertainty

- A common misconception is the belief that quantum uncertainty arises because of unavoidable disturbances that occur upon observation of the microscopic world.
- Bohr, Heisenberg, and other founders of quantum physics saw that **quantum uncertainty** in, say, the position of an electron, **occurs simply because the particle has no precise position** not because of disturbances, and not because of the observer's lack of knowledge about the microscopic world.
- An electron exists "all over its matter field." An electron is described by its matter field, and if that field has no precise position then the electron itself has no precise position.
- Strictly speaking, the electron (i.e., the electron matter field) has no precise position until it is observed; detection collapses the wave packet down to the point of interaction.

The Effect of Observation

- When a wave packet of an electron hits a screen and interacts with a single atom, the size of the wave packet (~1 cm) instantaneously collapses to the size of the atom.
- This is an example of a measurement.
  - → A microscopic particle causes a macroscopic event.
  - → The interaction of the electron with the atom allows the position of the electron to be found with a relatively small uncertainty.
- The size of a wave packet may be extremely large, but the collapse still occurs simultaneously everywhere.
  - → Instantaneous and nonlocal.
- The measurement process is not, according to many physicists, describable according to the ordinary rules of quantum mechanics; this makes it rather a mystery.

What happens in the double-slit experiment with electrons if we place an electron detector just behind one of the slits?

(A) We can then predict the precise point at which the electron will strike the screen.

(B) This tells us which slit each electron comes through, and has no effect on the pattern formed on the screen.

(C) This provides no information concerning which slit each electron comes through, and has no effect on the pattern formed on the screen.

(D) This tells us which slit each electron comes through, but it also changes the pattern formed on the screen.

(E) This provides no information concerning which slit each electron comes through, but it does change the pattern formed on the screen.

Results of Two Single Slit Experiments

A

Textbook

Figure 13.7

B

Only A is open

Only B is open

The sum of these two patterns – but not what is observed!

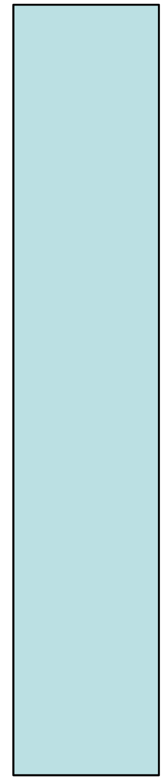
Which slit does an electron go through before it hits the screen?

Textbook Figure 13.8

(a) No detector

Which slit does an electron go through before it hits the screen?

Textbook Figure 13.8



(b) Detector on

- We cannot determine this without interacting with the electron somehow.
  - → This destroys the interference pattern.

Result

(a) When the detector is switched off, the usual interference pattern is seen on the screen.

(b) When the detector is switched on, it shows that about half of the electrons are passing through slit B and half are not.

Is Newtonian physics correct - does each electron really pass through only one slit, not both?

NO! When the detector is switched on, something strange happens. The interference pattern disappears and the noninterference pattern (b) appears. This is what we expect as the result of electrons passing through only one slit not both.

Switching the detector on and off causes the pattern to jump between (a) and (b).

Single Slit or Double Slit?

- If we insist that the electron must go through one slit or the other by looking for it, all we get is a single-slit pattern.
- This even happens if the detector is turned on AFTER the electron must have come through the slit(s)!!!
- The double-slit interference pattern only appears if the electron's matter wave can pass through both slits.
- This is consistent with the predictions of quantum physics.

So, what happens in the double-slit experiment with electrons if we place an electron detector just behind one of the slits?

(A) We can then predict the precise point at which the electron will strike the screen.

(B) This tells us which slit each electron comes through, and has no effect on the pattern formed on the screen.

(C) This provides no information concerning which slit each electron comes through, and has no effect on the pattern formed on the screen.

(D) This tells us which slit each electron comes through, but it also changes the pattern formed on the screen.

(E) This provides no information concerning which slit each electron comes through, but it does change the pattern formed on the screen.

Quantum Nonlocality

- Quantum nonlocality is the instantaneous alteration of an entire spread-out EM or matter field, due to an interaction of some kind.
- Whenever two particles interact, their quantum states merge.
  - → They become a single system with a single (more complicated) field.
  - → These particles are said to be entangled.

Quantum Entanglement

AFTER they interact, they are <u>entangled</u>.

Textbook Figure 13.10

BEFORE: particles 1 and 2 are separate until they interact.

Entangled particles are part of a single quantum object: a two-particle wave packet.

The Nonlocality Principle

Quantum theory predicts that entangled particles exhibit behavior that can be explained only by the existence of real nonlocal (that is, instantaneous and distant) correlations between the particles.

That is, a physical change in one particle, such as might be caused by a measurement made on that particle, causes instantaneous physical changes in all other particles that are entangled with that particle, no matter how far away those other particles may be.

Quantum Entanglement

- Experiments have shown that the connection between entangled particles occurs faster than the speed of light, and appears to be instantaneous.
- This does not contradict special relativity, which says that neither matter nor energy can travel faster than the speed of light, but it is disconcerting nonetheless.
- Quantum entanglement has been proposed as the basis of a quantum computer. As every set of bits is in all states at once, the computing power is, potentially, enormous.

Quantum Reality

- Uncertainty is a key feature of quantum theory.
  - → It is not an uncertainty due to insufficient knowledge; it is an inherent uncertainty.
  - → Wave packets simply do not have a precise position or a precise velocity.
- The measurement of a particle’s position does not tell us where the particle was before we measured it.
  - → The measurement actually creates the particle’s position.

The Effect of a Measurement

Velocity

Textbook
Figure 13.13

Position

Can two microscopic [or quantum] particles be entangled even when they are exerting no forces on each other?

(A) Yes, because they can still communicate with each other by means of EM radiation.

(B) Yes, they could be entangled but so far apart as to exert no significant forces on each other.

(C) No, because entanglement occurs only by means of the electromagnetic force and the other fundamental forces.

(D) No, because in order for a particle to be trapped in the field of another particle, it must feel the second particle's force field.

Toward a Post-Newtonian Worldview

Four key features of the Newtonian worldview:

- Atomism – atoms form the fundamental reality
- Objectivity – nature can be studied without human influences
- Predictability – the future can be exactly predicted from the present
- Analysis – we can understand the universe by understanding its simplest components

Contemporary physics denies all four.

Spectroscopy

- Recall Lecture 10 - we discussed the EM spectrum and blackbodies.
- How do we measure spectra of radiation?
  - → Using spectroscopes (or spectrometers).
- A <u>spectroscope</u> measures how the intensity of radiation (light) varies with wavelength.
- This radiation could be <u>emitted</u> by a hot gas or other glowing object, or <u>absorbed</u> as it passes through some medium.
  - → Emission spectra and absorption spectra.

Observing Atomic Spectra

A spectrum = the set of frequencies/ wavelengths emitted by (or absorbed from) the source of the radiation. Or the intensity as a function of frequency/wavelength.

Textbook
Figure 13.14