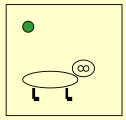
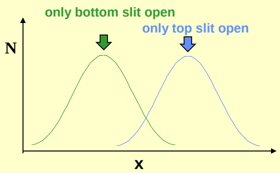
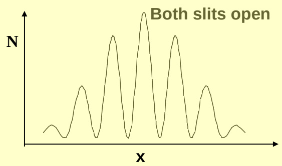
Lecture 23 Measurement and Reality

Measurement and Reality
The Truth is Stranger than Fiction









Announcements

- Schedule:
  - Last Time: Does God play Dice?
    Probablity Interpretation, Uncertainy Principles
    Today: Measurement and Reality - The Truth is stranger than Fiction - Two-slit experiment - Schrodinger's Cat
    March (Ch 18), LIghtman Ch 4
  - Dec. 3 and 8:
    The Big Picture:
    The smallest quantum scale of nature:
    The fundamental particles (Chap 19)
    The largest scale of nature
    The Universe (Chap 20)
  - Dec. 10 Review
- Homework: Hmwk 8 due Wed, December 3
- Essay/Report: Due Monday, December 8
- Final Exam: Friday, Dec. 19, 7-10 PM
  - CONLFICTS ????

Introduction

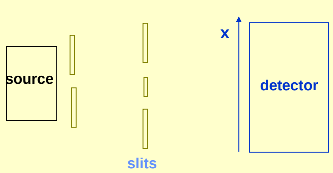
- Last Two lectures: Schrodinger Equation; Ψ^2 as a Probability; Heisenberg Uncertainty Principles
  - The Schrodinger equation determines the wavefunction Ψ
  - The solutions Ψ are wave patterns with definite frequency, i.e. definite energy.
  - $|\Psi|^2$ is a probablity - the theory only predicts the probability of the result of any given measurement
  - The Heisenberg Uncertainty Principle:
    - Nature puts a limit on predictability:
      $\Delta p\ \Delta x > h/2$. $\Delta E\ \Delta t > h/2$.
- Experiments support quantum theory
  - Consequences of Schrodinger's Eq. verified in great detail
  - Objects have both particle and wave character
  - Scientists agree on the results and use quantum mechanics on a daily basis.

Introduction -- Continued

- Today: interpretation of Quantum Mechanics
  - Scientists do not agree on the interpretation!
- Does the uncertainty introduced in quantum mechanics lead to uncertainty about "objective reality" itself?
  - The puzzles of Schrodinger's Cat (1935)
  - The puzzles still exist today!
- Experiments to test the ideas
  - The "two-slit experiment"
  - Einstein, Podolsky, Rosenberg (1935)
- Truth is stranger than fiction!

The Two-Slit Experiment

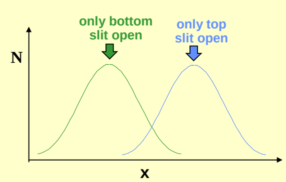
- We will first examine an experiment which Richard Feynman says contains "all of the mystery of quantum mechanics".
- The general layout of the experiment consists of a source, two-slits, and a detector as shown below;

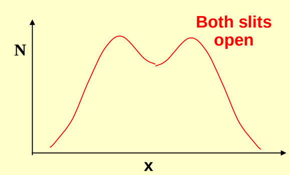


The idea is to investigate three different objects: a classical particle (bullets), a classical wave (water), and a quantum object (electron or photon). We will study the spatial distribution (x) of the objects that arrive at the detector after passing through the slits.

Classical Particles

- Classical particles are emitted at the source and arrive at the detector only if each particle passes through one of the slits.
- Key features:
  - Particles arrive "in lumps", i. e. the energy deposited at the detector is not continuous, but discrete. The number of particles arriving per second can be counted.
  - The number which arrive per second at a particular point (x) with both slits open (N_{12}) is just the sum of the number which arrive per second when only the top slit is opened (N_1) and the number which arrive per second when only the bottom slit is opened (N_2).





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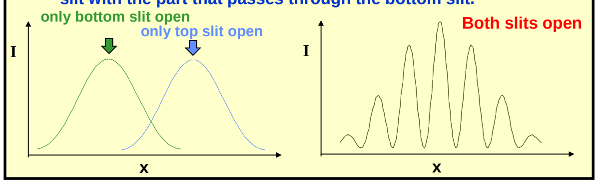
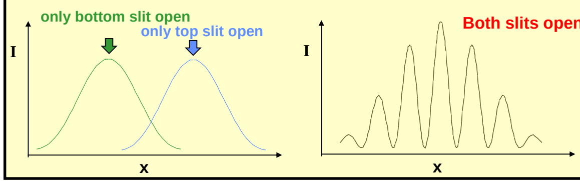
Classical Waves

- Classical waves are emitted at the source and arrive at the detector only if the wave passes through the slits.
- Key features:
  - Waves arrive continuously. A detector can measure the energy carried by the waves, which is proportional to the square of the height of the wave at that point.
  - The energy of the wave at a point (x) with both slits open (I_{12}) is NOT the sum of the energy of the wave when only the top slit is opened (I_1) and the energy of the wave when only the bottom slit is opened (I_2). An interference pattern is seen, formed by the superposition of the part of the wave that passes through the top slit with the part that passes through the bottom slit.



Quantum Objects (electrons)

- Electrons are emitted at the source and arrive at the detector only if they pass through the slits.
- Key features:
  - Electrons arrive "in lumps", i. e. the energy deposited at the detector is not continuous, but discrete. The number of electrons arriving per second can be counted -- like particles!
  - The number which arrive per second at a point (x) with both slits open (N_{12}) is NOT the sum of the number which arrive per second when only the top slit is opened (N_1) and the number which arrive per second when only the bottom slit is opened (N_2). An interference pattern is seen -- like waves !

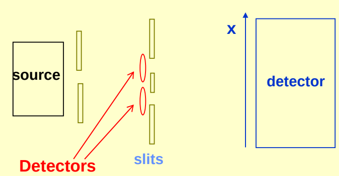


What Happens at the Slits??

- Does the electron go through only one of the slits?
  - Since electrons arrive in the detector as "lumps", it would seem reasonable that each individual electron went through only one slit.
  - But, the rate of arrival at the detector with both slits open is NOT the sum of rates of arrival when only one slit at a time is open.
  - Does one electron go through both holes?
- Answer the question by doing an experiment.
  - Add detectors that will determine whether electron goes through top slit, bottom slit, or both slits.
  - For example, as in text, add loop of wire around each slit which will be sensitive to field of the electron as it passes through slit.

The Two-Slit Experiment - continued

- If one detects which slit the electron goes through, the interference pattern is destroyed!
- The act of measuring causes a change in the result!



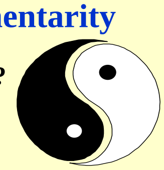
- The results of the measurement depend upon whether or not the experimenter decides to measure which slit the electron went through!
- How can we understand this??

Bohr and Complementarity

- The problem posed by quantum mechanics
  - Einstein (1924): "We now have two theories of light [as particles and as waves], both indispensable, but, it must be admitted, without any logical connection between them, despite 20 years of colossal effort by theoretical physicists"
- Bohr tries to provide this "logical connection" with what he calls complementarity
  - "Copenhagen Interpretation"
- Complementarity
  - Attributes of particles like mass, charge can be well-defined
  - But other attributes like position and velocity depend upon the manner in which they are observed
- The outcomes of the measurement is intrinsically intertwined with the measurement itself

Bohr and Complementarity

What is "complimentarity?



- Quote from Bohr:
- "The quantum postulate forces us to adopt a new mode of description designated as complementary in the sense that any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of phenomena."
- Bohr believes it is impossible to invent a new language to describe "quantum reality". The modes of description we need (observation & definition of states) have been developed in classical physics. Quantum theory forces us to choose only one of these descriptions for a given situation.. which one is determined by the choice of experimental apparatus!

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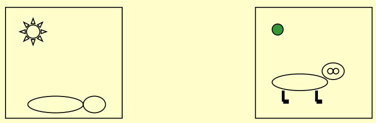
Schrodinger's Cat

- Schrodinger invented a parable to counter Bohr -- designed to bring out the issues in interpretation
- Suppose a cat is in a sealed box with a radioactive nucleus, which has the probability of decaying of 50% per hour.
- If the nucleus decays, the cat dies. If the nucleus does not decay, the cat lives.



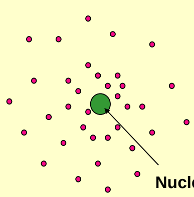
- After one hour the box is opened.

Schrodinger's Cat

- Prediction of Quantum Mechanics: If one does the experiment many times, when the box is opened 50% of the time the cat will be alive, 50% dead
- Question: In any one experiment, what is the state of the cat before the box is opened?
- Is the cat dead or alive before the door is opened?
- Does the act of opening the door determine the cat's fate?
- Copenhagen Interpretation:
  - The theory is about our state of knowledge of the cat, not about the cat.
  - Before the box is opened there is no knowledge of the state of the cat. The cat's wave function is in a quantum state : neither dead nor alive.
  - Bohr says the theory is complete -- the cat is not in a definite state -- there is no definite external "reality" outside of our observations

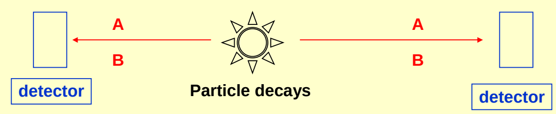
Schrodinger's Cat

- What is the state of the cat before the box is open?
- Just like the two slit problem!
  - If the experimenter does not provide any way to determine which slit the electron goes through, then the interference pattern is produced. The electron pattern is that produced by an electron which went through both holes. If the holes are labeled "dead" and "alive" the electron is in a state that is a combination of "dead" and "alive". One knows if the electron is "dead" or "alive" only if one looks!
- Just like the hydrogen atom problem!
  - If the electron is found at a given point in one experiment, does that mean it "was" at that point before the experiment?
  - Or was it simple not at any one point until the observation declared it to be at a point



EPR Paradox & Bell Inequality

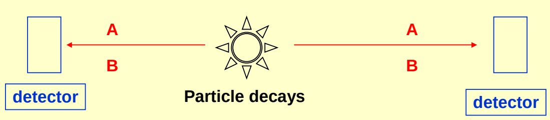
- Einstein, Podolsky, Rosen suggested an experiment



- A large number of nuclei decay each emitting two outgoing particles
  - Each of the two particles can be in state "A" or in state "B"
  - The decay is such that they must both be "A" or both be "B"
  - One cannot predict when any one nucleus will decay or whether it will produce two "A" particles or two "B" particles
- Each detector sees a random sequence of "A" and "B" particles

EPR Paradox & Bell Inequality

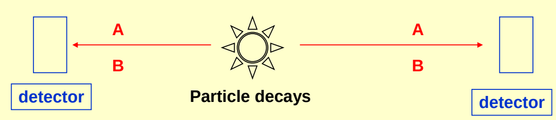
- Einstein, Podolsky, Rosen experiment (continued)



- From previous slide: Each detector sees a random sequence of "A" and "B" particles
- Question: If the left detector reads "A" does the right detector also read "A"?
- Does the act of reading the left detector affect the outcome of the right detector?
- Even if the detectors are far apart?? ! !

EPR Paradox & Bell Inequality

- Einstein, Podolsky, Rosen experiment (continued)



- EPR said that each particle is "real" -- it is "A" or "B" no matter what any detector says.
- Quantum Mechanics predicts the two particles are "intertwined" in one wave function. Neither particle is in a definite state ("A" or "B") until it is detected!
- John Bell (1964) constructed a simple inequality which could be measured to decide who is right.
- Result: Quantum Mechanics is right!

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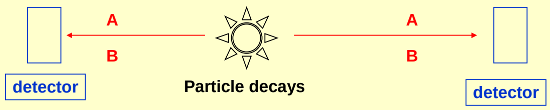
EPR Paradox & Bell Inequality

- Einstein, Podolsky, Rosen experiment (continued)



- New experiments are still going on to test quantum theory
- Example: Experiment in Switzerland in 2000
- Two photons emitted - travel over fiber optic cable to different cities
- Observation of one affects the observation of the other!

Summary - I

- All experiments up to now support quantum theory
  - Particles act like waves; waves act like particles
  - Schrodinger's Eq. predictions verified to great precision
  - Used daily by working scientists
- Quantum theory only predicts the probability of results of measurements
  - We can only measure individual events that have a range of possibilities
  - Results change depending upon whether observer decides to do a measurement or not.
  - Measurer (observer) becomes involved in the outcomes of the experiment!
- The truth is stranger than fiction!

Summary - II

- Two Slit experiment:
  - Interference depends upon the possibility that each particle went through either slit
  - If one detects which slit a particle went through, the interference disappears!
  - Thus the observer is involved. The act of observation affects the outcome!
- Schrodinger's Cat Parable:
  - Is the cat definitely either dead or alive BEFORE the box is opened?
- Bell's proof shows one of Einstein's ideas was NOT correct
  - Each particle does not have objective reality!
  - It's properties are affected by measurement on another particle (far away!) It is not "dead" or "alive" until the "box is opened"!

Summary - III

- What scientists do not agree on is the "meaning" of Quantum Mechanics
  - Is there an objective reality outside the observer?
    Three answers:
    - Bohr (Copenhagen Interpretation):
      The theory only describes our state of knowledge, not an objective reality.
      We cannot "know" the objective reality.
    - Einstein: The is an objective state of reality, but our present theory is incomplete
      Quantum Mechanics is incomplete
    - Feynman: Stick to what we can measure. It is sheer arrogance to think the rules should make sense! That we should understand it!