Quantum Measurement

The Copenhagen interpretation
EPR
Photons
Measurements

March 27 Quiz on Quantum Mechanics
March 29 Term paper outline/ partial draft

Next time:
More on EPR

Quantum Vocabulary/Concepts

- Schroedinger equation
- Wavefunction
- Amplitude, phase,
- Spin, polarization
- Constructive/destructive interference
- Energy levels, quantized values
- DeBroglie wavelength
- Heisenberg uncertainty principle
- Correspondence principle
- Random/deterministic

- Copenhagen interpretation
- Complementary variables
- Collapse of wavefunction
- Measurement problem
- EPR “experiment”
- Hidden variable
- Locality
- Bell’s theorem
- Schroedinger’s cat

The Copenhagen Interpretation
(Bohr 1930)

- Particles have some fixed quantities: charge, mass, spin.
- Also dynamic attributes: position, momentum
- The wave function contains all knowledge of a system, but it can't always tell you what will happen.
- These attributes are contextual: an electron's position depends on how you measure it.
- There is no reality to its (position, momentum) together. What is the color of something? It depends on the viewing light.
- Position only become defined when it interacts with the outside world, a measurement.
- This is an inversion of the classical picture.
  - Classical: bottom up. Macroscopic objects made from atoms....
  - Quantum: top down. Electrons don't have positions until we measure them...
- But what is a measuring apparatus and what is a quantum system? Where is the dividing line between the classical and quantum world?
- One should not ascribe reality to events that cannot be observed.

Heisenberg approach

- Write theory in terms of observable quantities alone. Measurement is limited
- Probability amplitudes are complex numbers that change by matrix multiplication.
- Bohr: reality is limited. An electron really doesn't have a precise position and velocity.
- Heisenberg was strongly influenced by Einstein's relativity.
- BUT "*It may be heuristically useful to keep in mind what one has actually observed, but in principle, it is quite wrong to try founding a theory on observable magnitudes alone. It is the theory which decides what we can observe*." Einstein
- Observation is very complicated and depends on processes which theory is supposed to explain.

ENJOY YOUR BREAK!

Quantum Mechanics and Relativity

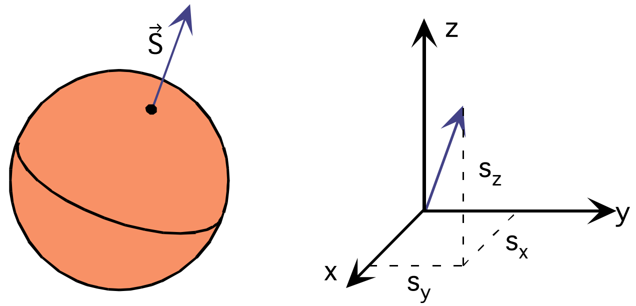
- Classical and Newtonian concepts were developed in a different physical regime.
  - "h" is small → QM restricted to microphysics
  - "c" is large → relativity is restricted to fast objects
- Both theories reduce to previous theory in the old regime: "the correspondence principle."
- Limitations change our concepts
  - Impossible to synchronize moving clocks→ Newtonian time inadequate. Space & time depend on frame.
  - Impossible to measure both x and p→ complementary variables. (x,p) are subjective.
- "*A good joke should not be repeated too often.*" Einstein

“Collapse of the wavefunction”

- What happens in a measurement?
- During a measurement they electrons acquire positions and momentum. Their wavefunction changes.
- It is not the disturbance which causes the collapse, but the transfer of information to the outside world.
- According to the Copenhagen interpretation there are 2 steps
  - An unmeasured wavefunction advances deterministically.
  - A measurement forces nature to choose between classical possibilities. It does so randomly. Afterwards there is a new wavefunction.
- The collapse happens faster than the speed of light, even backwards in time. How can that be?
- Observations are consistent with relativity but “reality” is not.

Spin and Quantum Mechanics

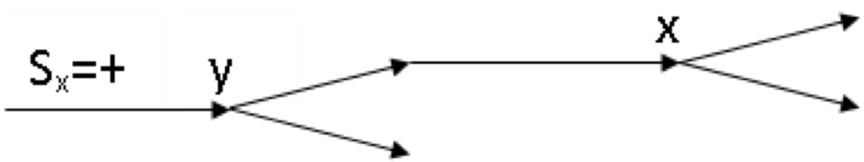
- In QM, many physical systems have complementary pairs of observables which cannot be measured at the same time. e.g. the product of the uncertainties in position (x) and momentum (p_x) must exceed $\hbar$.
- Another physical quantity, spin, will be important in arguments to follow. Think of a classical spinning ball. Its spin angular momentum points along the axis of rotation and has a length equal to the rate of rotation times the moment of inertia. It is a vector and all three components can be specified.



- In QM, pairs of spin components satisfy uncertainty relations $\Delta s_j \Delta s_k \geq \hbar$. At most one component of the spin can have a definite value. Results of spin measurements are quantized. When one measures s_x, one always finds a multiple of $\hbar / 2$.

Experimental implications

- If you separate a beam of neutrons into s_x= +1/2 and s_x =-1/2 beams (by running through magnet pole-faces), you can discard the (-1/2) part to get a beam of pure s_x =1/2 neutrons.
- Now try measuring s_y (just using a magnet turned 90°): you find that the measurements still give ±1/2, with a random pattern of + and - results.
- If you take either the s_y= 1/2 or the s_y= 1/2 beam, and again try measuring s_x, you also find random results. The neutrons don't seem to be able to remember both values at once. (the uncertainty relation)

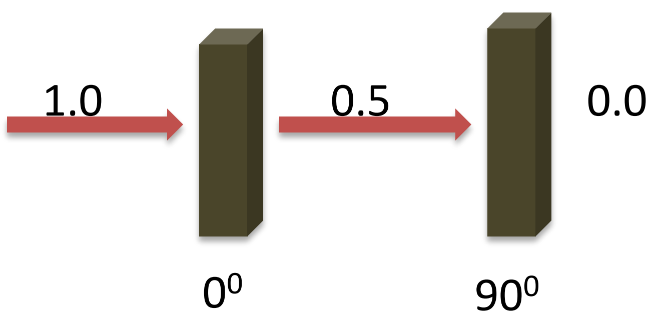


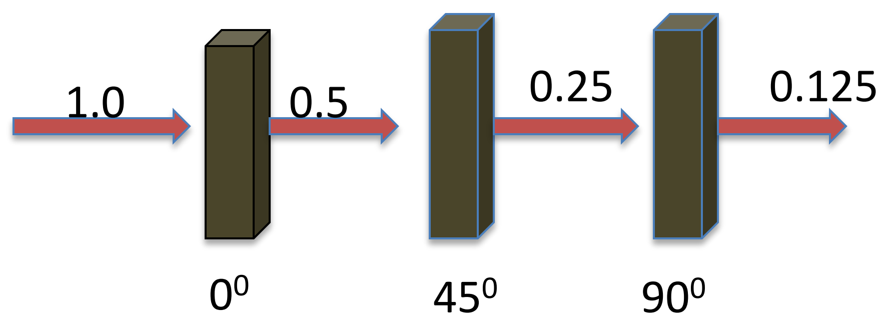
- But if you recombine the s_y= 1/2 and the s_y= 1/2 beams without measuring, i.e. without letting them interact with some sort of detector, the resulting beam is still all s_x= +1/2.

- Each s_x= +1/2 was BOTH s_y= +1/2 and s_y= -1/2, and follows BOTH pathways . Only a "<u>measurement</u>" makes it choose one or the other. Apparently s_y is not specified by a hidden variable, since each s_x= +1/2 neutron seems to have <u>both</u> values of s_y.

Polarization of light

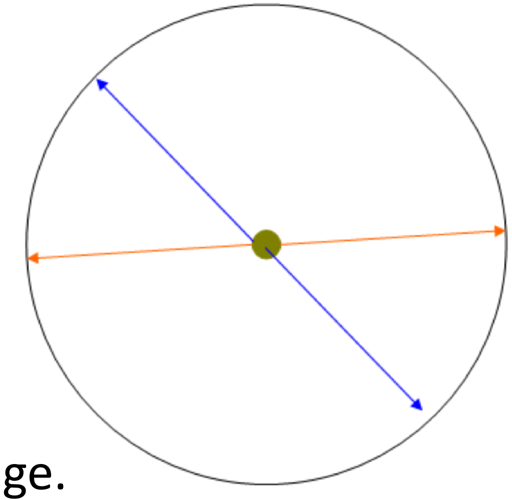
- Light (E&M waves) come with 2 polarization states
- Vertical or horizontal, right or left.
- But light is made of photons (particles)
- A polarizer either stops a photon or lets it go through.
- Remember, relativity implies that photons don't experience time so they cannot change or evolve.
- But we can do something to make them change their polarization





Einstein-Podolsky-Rosen (1935)

- Einstein and collaborators (EPR) proposed that by using the conservation laws, one could show that QM was missing something. Consider a particle that flies apart into two particles, each detected somewhere on a sphere of detectors.
- The blue pair or the red pair might occur, but not a mixture, which would violate conservation of momentum
- Conservation of momentum says the particles have to go opposite directions.
  QM says they don't know which way they're going.



- Possible resolutions:
  - The particles don't have to be detected in opposite directions, the conservation laws only hold on the average. (Bohr thought this at one time, but it's completely wrong experimentally.)
  - The particles are always found in opposite directions, because there is some hidden variable which allows them to know which way they are going. QM is incomplete!
  - Even though it is predetermined that the particles go opposite directions, what those directions are is not determined until one is (randomly) detected. The other somehow knows which way to go, faster than the speed of light!
  - Einstein believed that this argument showed the incompleteness of QM.
  - But experiment finds such "spooky correlations at a distance."

- Here's what Bohr had to say about the EPR proposal, in which it seemed that various properties of particles could be shown to have definite values (i.e. "elements of physical reality", by measuring pairs of correlated particles. Counting ALL those properties (S_{1x}, S_{1y}, S_{2x}, S_{2y},…which couldn't all be measured at once) led to violations of the uncertainty relation, and hence of QM.
  - "*The apparent contradiction in fact discloses only an essential inadequacy of the customary viewpoint of natural philosophy for a rational account of physical phenomena….The interaction between object and measuring agencies entails- because of the impossibility of controlling the reaction of the object on the measuring instruments…the necessity of a final revision of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality. The criterion of reality proposed contains an essential ambiguity… regarding the expression 'without in any way disturbing the system' The principal point is that such measurements demand mutually exclusive arrangements*."
- However, this interpretation leaves open the question of *how* our old ideas need to be revised. Again, how does the particle emitter know what measurement situations will be made for the emitted particles?

The measurement problem

How to go from a deterministic theory with superimposed possibilities to a random single experience is known as the ‘measurement problem’.

There are a variety of ideas about how to deal with it- none really satisfactory.

Ideas to deal with the measurement problem

- (folk version of Copenhagen) Ψ collapses, don't ask how
- (formal Copenhagen) Ψ wasn't ever real, so don't worry about how it collapses. It was just a calculating tool
- "macro-realism": Ψ does too collapse, but that involves deviations from the linear wave equation. (Pearle, …)
- mentalism: Ψ does too collapse, due to "consciousness", which lies outside the realm of physics. (Wigner, …)
- "hidden variables" were always around to determine the outcome of the experiments, so Ψ doesn't have to collapse. (Einstein, DeBroglie, Bohm …)
- (Many Worlds). There's nothing but the linear wave equation, you just have to understand what it implies. Ψ doesn't collapse, all those different branches occur but have no reason (until you understand the wave equation) to be aware of each others existence. (Everitt, …)
- (quantum logic). Classical Boolean logic is empirically disproved (as a description of our world) by QM, just as Euclidean geometry was shown by G.R. not to describe our world. (Putnam)

Hidden Variables

- Nature follows the classical picture, with each event following directly from local causes:
  - Einstein, Schrödinger, DeBroglie thought it would work.
  - Bohr, Heisenberg, etc. assumed that it couldn't work.
  - We've seen that Bohr won the debate with Einstein as to whether there was some way around the uncertainty principle.
- Von Neumann had a purported proof that NO hidden variable theory could reproduce the results of QM. The proof was accepted for decades, until Bohm came up with a counter-example. Bohm showed that Von Neumann had snuck in a hidden assumption: that the measured property must depend only on the micro-system, and not also on the measurement apparatus.
- Bohm constructed an HV theory which could explicitly reproduce the results of QM for a single local variable, e.g. spin.
- But John Bell followed up on the original Einstein ideas for ways to show the incompleteness of QM by showing that for spatially extended systems, no LOCAL HV theory can reproduce the results of QM.
- E<u>xperiments agreed with QM</u>, <u>violating the predictions of all local realist theories</u>.

Mentalism

Proposed by von Neumann and advocated by Wigner, among others, especially pop-journalists. There is something special about consciousness. It lies beyond the laws of physics as usually understood. E.g. Mermin: "Physical reality is narrower than what is real to the conscious mind."

- Human observation collapses the wave function, so a superposition is never observed.
- This is a bit hard to argue with since (shades of Berkeley) we don't have much access to a world devoid of consciousness.
- However, there are some serious difficulties:
- The whole proposal requires putting people at the center of the existence of the universe. How does that square with everything else we know, e.g. evolution? The world we see shows overwhelming evidence of having once been free of consciousness. Were the laws of physics entirely different then? Who (bacterium, amoeba, monkey, Wigner,...) was finally conscious enough to collapse the wave function and make positions, etc of particles exist? Just how did Wigner get there before anything had positions?
- There is NO evidence that consciousness plays some role distinct from any other phenomena involving macroscopic masses and times.

QM and reality

After making his surprise endorsement, Ben Carson said that there were "*two different Donald Trumps*" and that the private one was "*very cerebral*." Asked about that comment, Trump replied:

1. "I think there are two Donald Trumps."
2. "I don't think there are two Donald Trumps."
3. "I think there are two Donald Trumps ... I don't think there are two Donald Trumps."

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A superposition, a measurement problem or a multiverse?