LECTURE 12: The Einstein-Podolsky-Rosen Paradox

Goals of the lecture: Discuss the EPR Paradox and the non-local nature of Quantum Physics

What I expect you to learn:

- What is the EPR Paradox

(Roughly corresponds to sections 2.4 and 2.5, and chapter 17.1, 17.2 of textbook)

The EPR Paradox

We saw in the last lecture that the interference pattern for an electron going through a double-slit experiment is destroyed if we try to determine which slit it went through using a photon.

The "act" of measuring the position of the electron affects its trajectory. We argued that this was a consequence of the Uncertainty Principle.

Can we get around it? Einstein, Podolski, and Rosen argued that you could. In a nutshell:

Let two particles be correlated (say by conservation of momentum) and make a measurement of particle 1 very far away from particle 2. If you measure the correlated quantity of particle 1, how can particle 2 know about this right away? (example on blackboard)

Interpretations of Quantum Mechanics Part I

1-Quantum mechanics works:

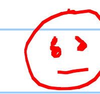
- -It has never been shown to fail! (*)
  - (*) we do not understand how to reconcile it with General Relativity and extend it to very high energies
- -Most accurate theory in science

2-So QM works. But!! What is really going on? how can I interpret it?

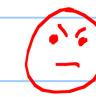
- -physicists will agree on point #1 above but not on point #2!
- -This theory is hard for many to accept "as is" without a deeper explanation of why microspopic particles behave this way

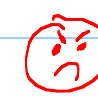
Interpretations of QM Part I (cont.)

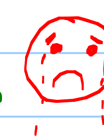
QM seems strange compared to Newtonian Mechanics.
The classical mind has difficulty accepting the fact that it:

- -violates determinism: every later state of a system is uniquely determined by any earlier state; 

- -violates principle of continuity: initial and the final state of a system can be linked through every intervening state 

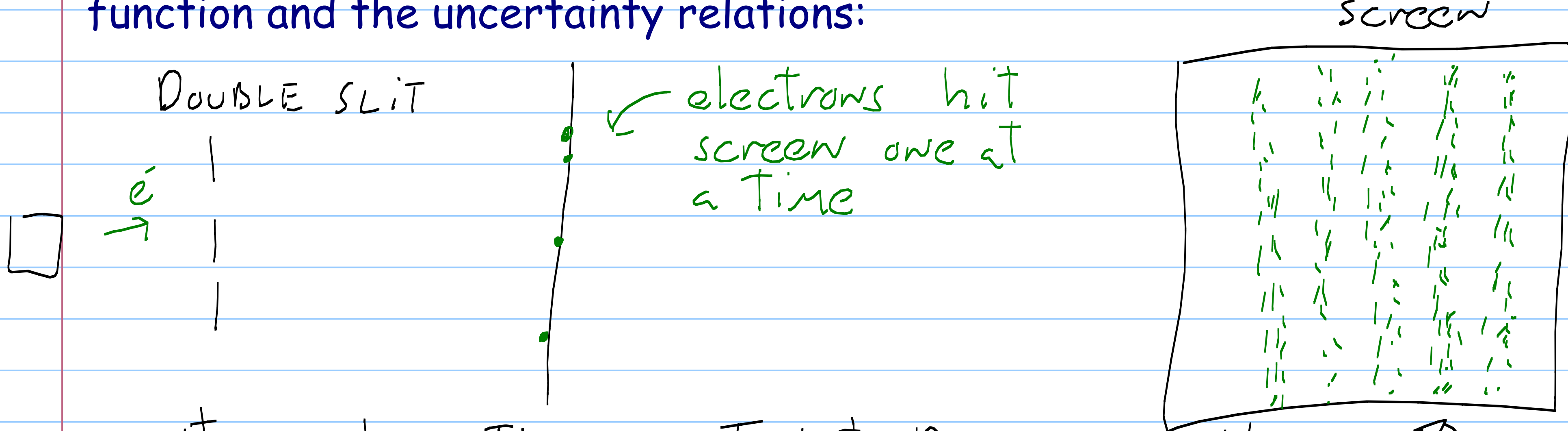
- -violates the idea that a physical particle has a definite position and momentum (which implies both can be known) 

- -violates Principle of Conservation of Energy 

- -violates the principle of locality: if two systems are sufficiently separated (outside of light cone), they cannot affect each other 

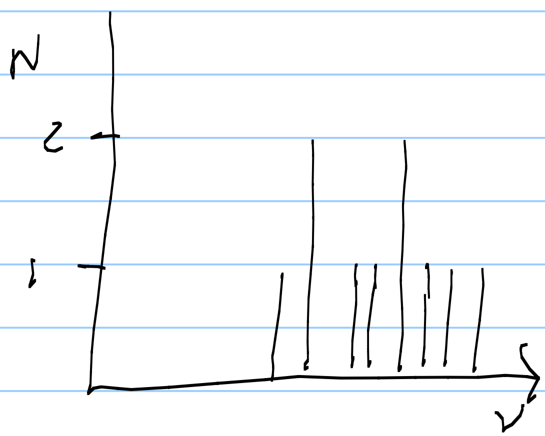
Interpretations of Quantum Mechanics

Regarding determinism: recall the interpretation of the wave function and the uncertainty relations:

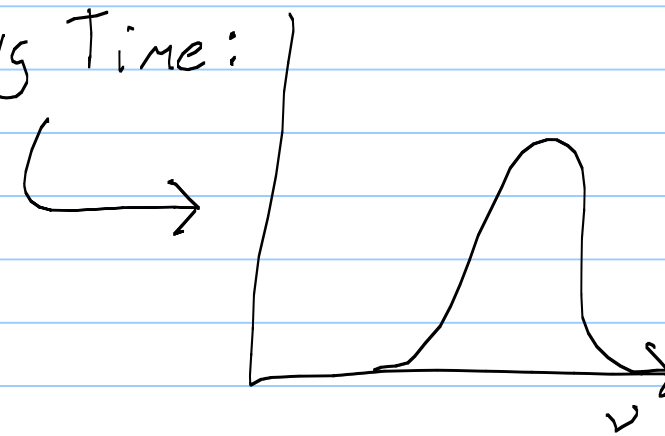


wait a long time, get interference pattern

Measure ν of photons from decay of quantum state



wait a long time:



Some points of view regarding QM:

Realist: believes that indeterminism is evidence of our ignorance. A system has physically well-defined attributes before measurements are made. Quantum mechanics is an incomplete theory. Additional information (hidden variables) needed to provide a complete description of system.

QM traditionalist: indeterminism is part of nature. Measurements force systems to take on measured physical attribute. QM is a complete theory and no hidden variable is needed to describe a system.

Measurement-centric: can I test your interpretation? anything I can measure to decide between interpretations? No? then leave me alone!!! I've got serious work to do...

Interprations of QM Part I (cont.)

Einstein, Realism and Objectivism:

The act of measurement implies a "collapse" of the wave function whose evolution is described by Schrodinger's equation

To Einstein this "collapse" constituted a retreat from realism: it implied that physical quantities usually have no values until they are observed. This implies that the observer must be involved in the physics being observed. Seems to inject subjectivism in physics...

To restore order to this mess, physicists have introduced the idea of hidden variables: our knowledge of the quantum system is incomplete. Particles have well defined positions and momenta and the apparent indeterminism is due to our lack of knowledge of the hidden substructure of the system

Interpretations of QM Part I (cont.)

Some hidden variable theories:

-de Broglie: wave function is physically real field coupled to a particle which has a well-defined position and momemtum. This coupling between the two gives rise to interference phenomena

-Bohm (1952): constructed a deterministic theory with coupled "pilot-waves" and particles that was able to account for diffraction and interference phenomena

-For those seeking a classical explanation of QM, Bohm's theory suffers from non-locality. Another drawback: its complexity

(if you're a fan of Occam's razor, you're not happy)

Interpretations of QM Part 1 (cont)

The Einstein-Podolsky-Rosen Paradox: in 1935 they proposed the following criteria as a basis of an acceptable theory:

- The quantities in the theory should be physically "real": if without disturbing the system I can know the value of a physical quantity, the this quantity is "physically real".

- The theory should be local

We saw an example on page 2. Another example often used involves Stern-Gerlach setups (example on blackboard)

Bell's inequalities and Aspects's Experiements:

We will come back to these later in the course. But for now we'll summarize:

- Bell (1960s) determined all the conditions that local deterministic theories must satisfy

- Aspect's experiments demonstrated that QM is a non-local theory

- There is still room for non-local hidden variables theories. But a classical deterministic and local theory of our physical world was shown experimentally to be incorrect

PROBLEM SET #2

FROM THE TEXTBOOK: 2.1 and 2.13

- Nuclei typically of size 10^{-14} m emit electrons with energies in the range 1-10 MeV. Show that electrons of these energies can't be contained in the nucleus. (use the uncertainty relation)

- Consider the following wave function:

$$\psi(x) = N x e^{-\alpha x} \qquad x > 0$$
$$= 0 \qquad x < 0$$

  - Find N
  - Where does the probability $|\psi(x)|^2$ peak?
  - What is the probability of finding the particle between 0 and $1/\alpha$
  - Find $\varphi(p)$