QMI
Phys 651

Lecture #26

Conceptual and philosophical problems of quantum mechanics

QM

indeterminism:

if before a measurement the wave function of the system is not an eigenfunction of the operator whose observable is to be measured, then only the probability of various outcomes can be determined

CM

- determinism: the evolution of a system is fully determined by its initial state and by the forces acting on it

  ↑ even in a "purely random" experiment like tossing a coin!

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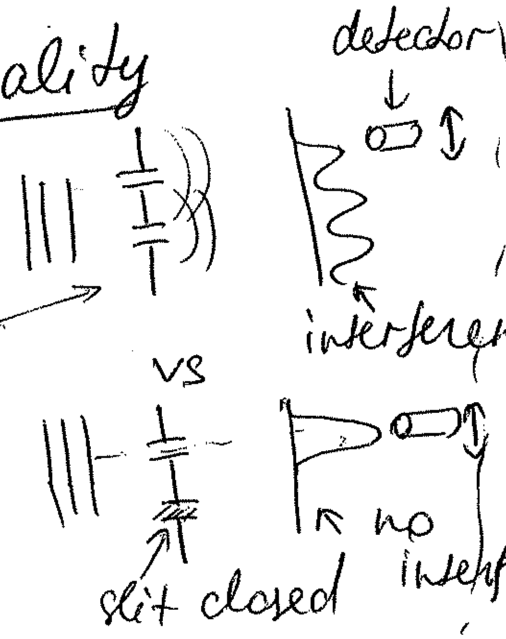
nonlocality

Ex. 1

double-slit



⟹ The detector sees different signals depending on whether the second slit is open or closed

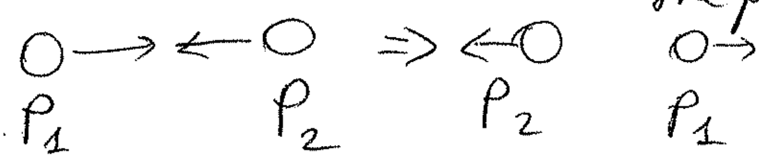
⟹

<u>nonlocal interaction</u>! ⇒ (why would a particle passing through a slit care about the presence or absence of another slit?) ⇒ particles separated in space can have <u>correlated properties</u>

<u>Ex. 2</u> Bohm's Gedankenexperiment ⇒ consider a pair of spin-$\frac{1}{2}$ particles with total spin $S=0$ (and each in $\ell = 0$ state, i.e. 0 angular orbital momentum)

<u>Note</u>: pairs like these can be created by the scattering of a beam of low-energy protons from (H)-gas

Let's say, this pair interacts during some time (e.g. during the scattering event) and then move the particles far apart:



When protons are apart, we measure S_{z_1} and get $+\frac{\hbar}{2}$. Then, since total $S=0$

(S_{z_1}: z-component of spin of particle 1)

⇓

S_{z_2} must be $-\frac{\hbar}{2}$.

⇓

therefore, a second measurement (on particle 2) is not necessary: S_{z_2}-value can be deduced from the measured S_{z_1}. <u>Problem</u>: how can noninteracting particles far apart affect each other? ⟹

QM: in such a state ("entangled state"), particles are not independent of each other. * ← more on p. 6

⇓

Einstein, Podolsky, Rosen (EPR) paradox
(Phys. Rev. 47, 777 (1935))

⇓ ⟹ subjective theories

The Copenhagen interpretation
(N. Bohr & collegues)

⇓

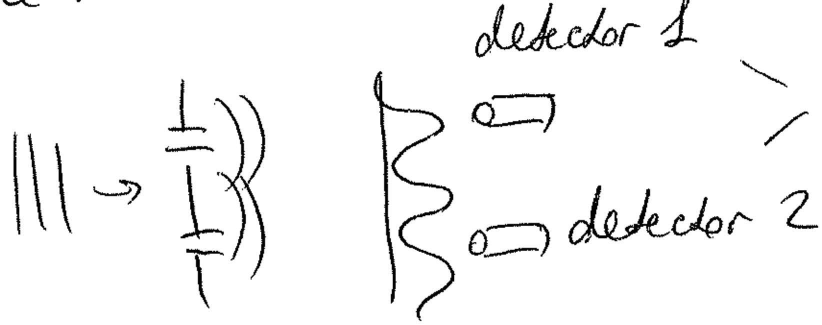
Idea: impossibility of separating the QM system from the measuring apparatus

Hidden-variable theories

⇓

Bell's theorem

Ex.



since the arrangement of measuring devices is different

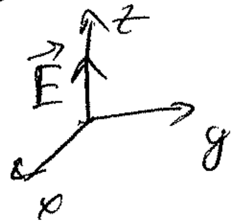
⇓

these are different QM systems!

A part of Copenhagen interpretation is the idea of <u>complementarity</u>: some observables form complementary pairs, which can't be measured simultaneously (x, p, L_x, L_z, ...). For example, an attempt to determine x, p_x at the same time would be "as senseless as to ask where linearly polarized light is left-handedly or right-handedly polarized".

<u>Recall</u>: $$\vec{E} = E\hat{z} = \frac{\hat{z}+i\hat{x}}{2}E + \frac{\hat{z}-i\hat{x}}{2}E$$

$\vec{E}$ ← linearly polariza(tion)



right- and left-handed components

<u>Problem</u>: how to treat measuring apparatus ⇓ wave function? smth else?

So, is there a way to preserve determinism and locality? ⇒ "alternative QM" ⇒ "hidden-variable" theories:

<u>Idea</u>: consider QM as a statistical theory in a sense that it deals with probabilities of events, which are fixed by non-observable properties

In other words, the reason we can get different outcomes as a result of a measurement is that there are hidden variables, which can't be measured at the same time with the "main" observable we are trying to measure, and these variables "drive" our measurement to different values.

Until 1964 : metaphysical debates leading to predictions that could not be verified experimentally

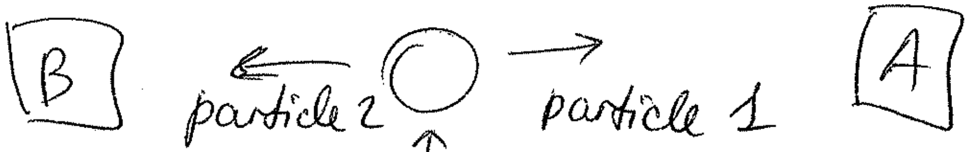
Then ⇒ J. Bell : produced a "testable" inequality that is a direct consequence of every local deterministic hidden-variable theory

Sakurai 3.9 (3.10 in gray edition)

clearly showed discrepancy between QM predictions and any hidden-variable theory

Until now ⇒ violation of a Bell inequality (= applicability of QM and non-applicability of hidden-variable theories) has been shown in a variety of experiments, using photons, neutrons, ions, etc.

Science 301, 621 (2003)
Nature 446, 871 (2007)



$S=0$

$\frac{1}{\sqrt{2}}(|+-\rangle - |-+\rangle)$

from Sakurai 3.9 (3.10 in gray)

B:

1) measure S_z and get $S_z = -\frac{\hbar}{2}$ ⟸⟹ **A:** 1) measure S_z and get $S_z = +\frac{\hbar}{2}$

<u>or</u>

B: 2) if we measured S_x, we would find $S_x = -\frac{\hbar}{2}$, but if we can measure only $S_z \to \pm\frac{\hbar}{2}$ with equal probability! ⟸ **A:** 2) measure S_x and get $S_x = +\frac{\hbar}{2}$

<u>or</u>

B: 3) equal probability to measure $S_z = \pm\frac{\hbar}{2}$ ⟸ **A:** 3) no measurement at all

⇓

Outcome of measurement B depends on what A does! (even with a large distance between A & B and no means of communication!)

⇓

<u>QM explanation</u>: "a measurement on what appears to be a part of the system is to be regarded as a measurement on the whole system"

Subjective theories

- E. P. Wigner: wave function collapse (during the measurement) actually happens when the information arrives at our brain

  Assumption: the human mind is of a different nature than the physical material world

  Problem: minds of different people reach the same conclusions concerning the results of physical experimen

- E. Everett: idea of irreversible change in the universe

  Universe doesn't end in one of the various possible states as a result of a measurement, but all possible results really take place. So, the universe splits up into a number of different non-interacting universes, and we see only one branch of this universes. Every time the measurement occurs, the universe splits

  Problem: concept is uneconomical; idea of an infinite number of universes can't be proven, since individual universes don't interact

<u>Bottom line</u>: QM has been extraordinarily successful in predicting energy spectra, transition probabilities, cross-sections, etc.

<u>But</u>

it <u>keeps evolving</u> as we look for deeper insight into our world & ourselves.