# IQM

Both "QM" and Relativity changed our way to understand the world!

However, there is nowhere a course such as the "interpretation of special relativity". The fact is that there is no ambiguity there.

On the contrary, QM contains some peculiarities, especially in the so-called "standard" or Kopenhagen interpretation.

- Causality

- Linear evolution of the underline eqs but non-linearity of the measurement

- Role of the observer

. . . . .
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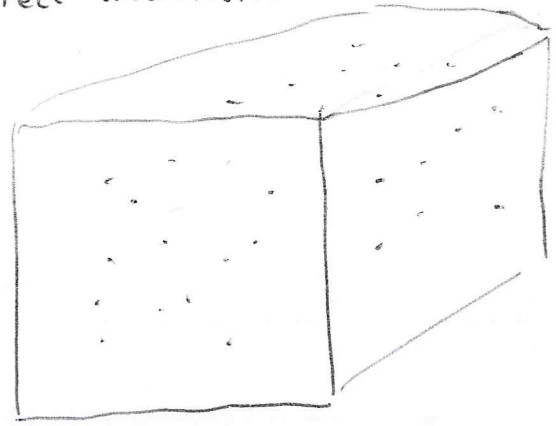
As we shall see, more interpretations of QM - all in agreement with the experiments - are possible and legitimate. The question why only one is presented at universities is related to the historical evolution of QM and to the role of important physicists, such as Bohr and Einstein.

In order to discuss and introduce the various subjects it is good to pick up a certain example: the neutron "n".

"n" is unstable : $n \mapsto p + e^- + \bar{\nu}_e$

Half life time ~ 10 min.

Correct treatment



Box with $N_0$ neutrons at $t=0$.

How many neutrons at $t>0$?

$$N(t) = N_0 e^{-t/\Upsilon}$$

$\Upsilon$ is a parameter: mean life time.

$$\left( N(t=\Upsilon) = \frac{N_0}{e} \right)$$

$$N(t=t_{1/2}) = \frac{N_0}{2}$$

$t_{1/2} = (\ln 2)\cdot\Upsilon \simeq 0.69\,\Upsilon$

For the neutron:

$t = t_{1/2} = 10$ m, 14 sec

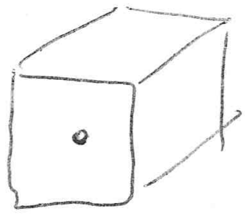
$\Upsilon =$ 14 min, 56 sec.

Where does the exp come from? Is it general?

Actually NO! The exp is an approximation!

This leads also to the so-called "Quantum Zeno effect"...

Let us now consider only 1 neutron.



In QM states are represented by kets $|S\rangle$.

- At $t=0$:

$$|S, t=0\rangle = |n\rangle$$ (100% sure that we have a neutron)

- For $t \mapsto \infty$

$$|S, t\mapsto\infty\rangle = |p\rangle$$ (100% sure to have a proton)

- For - say - $t = t_{1/2}$

$$|S, t=t_{1/2}\rangle = \sqrt{\frac{1}{2}}\,|p\rangle + \sqrt{\frac{1}{2}}\,|n\rangle$$

the system is in a superposition of a proton and a neutron and the same time.

First issue of QM: Can $|S\rangle$ be both? is this correct?

What does it happen if we "measure" the system at $t = t_{1/2}$ ?

$$|S, t = t_{1/2}\rangle = \sqrt{\tfrac{1}{2}}\,|m\rangle + \sqrt{\tfrac{1}{2}}\,|p\rangle$$

⇓

**Measurement at $t_{1/2}$**

↙ $\left(\sqrt{\tfrac{1}{2}}\right)^2 = 0.5$ we find m → For $t \gtrsim t_{1/2}$ $|m\rangle$

↘ $\left(\sqrt{\tfrac{1}{2}}\right)^2 = 0{,}5$ we find p → For $t \gtrsim t_{1/2}$ $|p\rangle$

→ Probability!

we can't say, before doing the measurement, if it will be $|m\rangle$ or $|p\rangle$! No way!

Nonlinearity

When doing the measurement $|S, t = t_{1/2}\rangle$ collapses either to $|p\rangle$ or to $|m\rangle$ instantaneously

... ad: What is a measurement?

General, for each t:

$$|S, t\rangle = e^{-t/2\gamma}\,|m\rangle + \sqrt{1 - e^{-t/2\gamma}}\,|p\rangle$$

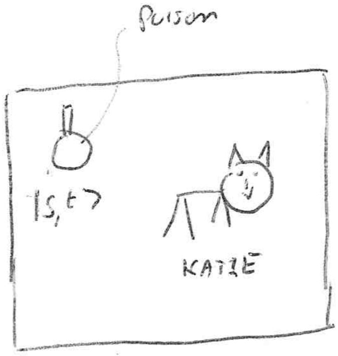
$\left(e^{-t/2\gamma}\right)^2 = e^{-t/\gamma}$ is the prob. to find $|m\rangle$ when doing a measur. at t.

$1 - e^{-t/\gamma}$ " " " " " $|p\rangle$ " " " " "

"almost 1"

⇝ what is the measurement?

Schrödinger was also puzzled about this point. He then thought about the following exp: Put a cat in a box in which there is a device killing the cat when the decay $n \leftrightarrow p$ takes place.




We open the box and watch inside after $t = t_{1/2}$.

According to QM:

$$|\text{FULL-SYSTEM (Particle + cat)}\rangle = \sqrt{\frac{1}{2}}\,|n\rangle|K\text{-}L\rangle + \sqrt{\frac{1}{2}}\,|p\rangle|K\text{-}T\rangle$$

Then, the cat is "living" and "dead" at the same time.

Or can the cat perform an experiment?

What can do that? only a man? A machine? Or is a cat enough? or a bacterium?

This all sounds meaningless...

but it shows which confusion emerged when QM was developed.

Solution 1: Hidden Variables

The description of QM is not complete. There are some variables which are not taken into account.

(Non-completeness: "similar" to thermodynamics ... where probabilities arise from the partial knowledge of the system)

At a certain "t" the cat is 'dead' or 'alive', but not both things.

⇝ Bohmian Mechanics: QM with trajectories ....
perfectly in agreement with QM.

One may also ask "why in course it is not presented as the standard interpretation?"

Answers:
- → Historical
- ... but also
- → trajectories cannot be "seen"

The Bohmian mechanics is deterministic.

- Constraints on hidden variables: Bells inequalities.

They show that theories with hidden variables are nonlocal. However, it is not true (as often stated) that they disprove such theories
(... confusion in QM ptorrow ...)

## Solution 2: "Everett" or Multiverse

Accept fully 'QM': the cat is always 'dead' and 'alive' at the same time.

No collapse of the wf.

$$|system\rangle = \underbrace{\underbrace{\sqrt{\tfrac{1}{2}}\,|m\rangle|K-L\rangle}_{\text{world "1"}} + \underbrace{\sqrt{\tfrac{1}{2}}\,|p\rangle|K-T\rangle}_{\text{"world "2""}}}_{\text{Multiverse}}$$

"Crazy", but consistent with QM... one can show that the probabilities in a certain "world" emerge.

$$|system_{\text{with observer}}\rangle = \sqrt{\tfrac{1}{2}}\,|m\rangle|K-L\rangle\underbrace{|O-G\rangle}_{\text{happy}} + \sqrt{\tfrac{1}{2}}\,|p\rangle|K-T\rangle\underbrace{|O-U\rangle}_{\text{unhappy}}$$

'Decoherence' shows that each world will evolve independently. So, in each world there is after the separation no effect from the others.

"ACHTUNG": it is often said that decoherence solves the problems of QM... this is not true... the cat is still alive and dead at a certain "t".

... in both cases there was no collapse → Bohm: cat either dead or alive
→ Everett: cat dead and alive

Solution 3: G-R-W theories

there is indeed the collapse.

There are nonlinear terms in the equations which generate it.

Before the measurement: $|system\rangle = \sqrt{\frac{1}{2}}\,|m\rangle|K\text{-}L\rangle + \sqrt{\frac{1}{2}}\,|p\rangle|K\text{-}T\rangle$

After " " " Either $|p\rangle$ or $|m\rangle$ ... caused by nonlinearities (in some cases 'chaotic')

Non linearities: "small" for small system, but "large" for macroscopic system!

There are measurable differences from QM!

They will be tested in the future.

## Entanglement :

Two particles... one is "n" and one is "p".

$$|system\rangle = \sqrt{\tfrac{1}{2}}\ |n-L\rangle|p-R\rangle + \sqrt{\tfrac{1}{2}}\ |n-R\rangle|p-L\rangle$$

Teilchen 2 — Teilchen "1"

if 1 is n then 2 is p and viceversa.

Entanglement. A measur. 'here' tell me something which is far away.

Example of the socks → it is not the same. Local determinism is dead.

Basis of Q-bit, quantum computers, ... and of many beer- and wine-based discussions of QM!