On the measurement problem, decoherence and the language of Quantum Mechanics.

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Partly based on paper to appear in quant-ph server.

Main Points and Outline

- Some background, what is the "measurement problem" in QM?
- On strong objectivity, realism, Copenhagen, Beables vs Observables...
- Decoherence and the emergence of classical properties. How to understand it, and does it "solve" the "problem"?
- If there is no collapse of ψ why isn't everything deterministic?
- And Born rule? Zurek's envariance and its interpretation. (Very briefly, more in paper.)
- Strongly objective decoherence from Quantum Cosmology? (In paper but not today)

Some background

The QM "measurement problem" has a long history and seems to be extremely difficult to resolve.

Much due to interpretational issues (experimental predictions same).

To some part, problems already in classical physics: Is there a satisfactory derivation of the second law of thermodynamics and increase of entropy?

Eg Boltzmann's H-theorem? Boltzmann vs Zermelo: unsettled even after 100 years.

In QM problem much more pronounced: superposition principle, indeterminacy, kinematical non-separability.

Early debates/Ideas: Einstein vs Bohr (realism vs Copenhagen/Operationalism), Von Neumann's formulation, London and Bauer, Schrodinger's cat, Wigner (Mind and matter), EPR...

Tell me briefly what the “problem” is please

Von Neumann’s ideal measurement:

System S: $|\psi^0\rangle_S = a|\psi^A\rangle_S + b|\psi^B\rangle_S \quad |a|^2 + |b|^2 = 1$

Apparatus A: $|\xi^0\rangle_A$

Pointer State, “ready” to go

S+A initial: $|\psi^0\rangle_S|\xi^0\rangle_A = (a|\psi^A\rangle_S + b|\psi^B\rangle_S)|\xi^0\rangle_A$

System + Apparatus interact via Hamiltonian $\hat{H}_{SA}$ so that:

$$\hat{\mathcal{U}}_{SA}|\psi^0\rangle_S|\xi^0\rangle_A = a|\psi^A\rangle_S|\xi^A\rangle_A + b|\psi^B\rangle_S|\xi^B\rangle_A$$

Pointer position “A”

Pointer position “B”

But what is the outcome? No definite Apparatus state. Contrary to experience...

Cf Schrodinger’s kitty

In orthodox QM we simply declare the collapse to take place at some point. After measurement we then have a mixture rather than a pure state.

Orthodox/Textbook QM

Two different mechanisms at play:
1- Internal, dynamical, Unitary evolution represented by exact mathematical formulation.
2- "Collapse" of ψ induced by "measurement" via external "observers". No precise mathematical formulation.

Truly: The physicist said "Let there be measurement". And there was measurement.

The theory is fundamentally about the results of 'measurements' and therefore presupposes in addition to the 'system' (object) a 'measurer' (subject). Now must this subject include a person? Or was there already some such subject-object distinction before the appearance of life in the universe?

Quote from Bell

What qualifies as "measurement", and what/who as "observer"? (Need a PhD?)
What processes in the universe are subject to dynamical Unitary evolution, where and when do "collapses" occur? Are the jumps instantaneous? Is the collapse only associated with our knowledge about the outcome of the experiment? Etc...

But...Why Care!?

Since no predictive difference in different interpretations, why not just "Shut up and calculate"..? But is everything really fine?

Another quote from Bell:
(Speakable and Unspeakable in Quantum Mechanics)

... What is much more likely is that the new way of seeing things will involve an imaginative leap that will astonish us. In any case it seems that the quantum description will be superseded. In this it is like all theories made by man. But to an unusual extent its ultimate fate is apparent in its internal structure. It carries in itself the seeds of its destruction.

And one from Everett:
(The Many Worlds Interpretation of Quantum Mechanics)

It is now clear that the interpretation of quantum mechanics with which we began is untenable if we are to consider a universe containing more than one observer: We must therefore seek a suitable modification of this scheme, or an entirely different system of interpretation.

Some Terminology (i.e. fancy talk mind you)

A descriptive statement of nature "strongly objective" if (see also D'Espagnat, Veiled Reality):

it can be considered as having a truth value in virtue of a reality existing independently of us, so that things can be said to posses certain qualities without any reference to measurements or to them being "observable" or not.

Cf 2 Statements:

1: The particle has a spin component along the positive z-axis.

↑

"Strongly objective"

2: Upon measurement, the particle will be observed to posses a spin component along the positive z-axis.

↑

"Weakly objective": Explicitly refers to measurements or observations

Observables vs Beables

Bell's definition of beables: The beables of the theory are those elements which might correspond to elements of reality, to things which exist. Their existence does not depend on 'observation'. Indeed observation and observers must be made out of beables.

Einstein, Podolsky, Rosen also defined "elements of physical reality" in their classic paper and gave operational definition.

In orthodox QM, no beables but rather observables. Observer-free phenomena meaningless.

Orthodox QM therefore does clash with realism. But there are ontological, objective formulations of QM:

De Broglie/Bohm's pilot wave, dynamical collapse theories etc.

However, any strongly objective realist formulation of QM must be highly non-local and also contextual. Naive realism all but dead.

Bell
Clauser-Horne

Kochen-Specker

The Copenhagen Interpretation: Bohr

For Bohr no measurement problem: Every event about which we can meaningfully speak in physics must be described in classical terms.

No properties of *S* exist without *A*. i.e. only *S*+*A* is meaningful. *A* always classical.

The description of nature is a description of communicable, collective human experience which necessarily is conveyed in classical terms. If we cannot talk about "it" then it does not exist.

Smells almost Kantian, or Berkeleyian

The measurement process not to be described entirely as a dynamical process involving the system and the apparatus. Therefore no "cat"-problem.

States in Classical and Quantum World

What is the "state"? $|\psi\rangle = \sum_k a_k |\psi_k\rangle$

Abstract symbol that facilitates, via certain rules of manipulation, the computation of the outcome of measurements performed upon the given system.

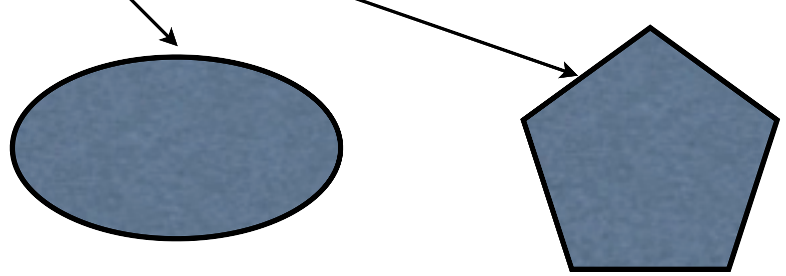
No ontological commitment

These are pure states. Restrictive already classical physics.

→ Points in (p,q) phase space

Eg, No temperature for pure states. Hamiltonian dynamics: pure $\longrightarrow$ pure. How do you approach equilibrium? Increase of entropy? Need pure $\longrightarrow$ mixture.

Use Gibbs ensemble to generalize state concept. Set of states form convex set. Pure states are the extremal elements of this set.



$$x, y \in S \rightarrow tx + (1-t)y \in S, t \in [0,1]$$

Density Operators

Self-adjoint operator with unit trace: $\mathrm{Tr}\hat{\rho} = 1.$

For non-degenerate spectrum: $\hat{\rho} = \sum_{k=1}^{\infty} w_k |\psi_k\rangle\langle\psi_k|$ ➡ $\sum_{k=1}^{\infty} w_k = 1$

Set of all density operators convex set. Technically belongs to $\mathcal{L}(\mathcal{H})$: Liouville space

↑ Ordinary Hilbert space

Mathematical formulation more or less same as for pure states. So generalize state concept by considering all density operators.

Important for measurement problem!

Pure states: $\hat{\rho}^2 = \hat{\rho}$

Ensemble interpretation: The w_k represent insufficient knowledge of the true state of the system. Ignorance of observer leads to probabilities.

We reject this interpretation

From pure states to mixtures?

For general description take all states to be equally "real", i.e. all $\hat{\rho}$ in convex set of states at same footing ontologically.

The ensemble and the state one and same thing. Natural then to discuss evolution from pure states to "mixtures". Crucial for measurement process.

In statistical thermodynamics one can define the temperature even for a single particle, and discuss approach to equilibrium and Maxwell distribution using Gibbs ensemble.

Hamiltonian dynamics cannot take you from pure to mixture. Eg Von Neumann entropy

$S_{vn} = -\mathrm{Tr}\,(\hat{\rho}\ln\hat{\rho})$ invariant under unitary $\hat{\mathcal{U}}$.

In classical mechanics: Liouville theorem + Poincare theorem, no irreversibility.

Approach to equilibrium, increase of entropy?

Decoherence I

(Zurek, Zeh and Joos)

All systems correlated with "environment" via dynamical interactions. Systems have no "absolute" states, but only "relative" states (Everett).

Radical departure from classical physics

System+Apparatus+Environment: $\mathcal{SAE}$, so relevant state: $\hat{\rho}_{\mathcal{S}A\mathcal{E}}$

Hamiltonians: $\hat{H}_{\mathcal{S}A}$ and $\hat{H}_{A\mathcal{E}}$ ← Pointer states determined by this piece

Only those states that are eigenstates of $\hat{H}_{A\mathcal{E}}$ will "survive" the ubiquitous interactions with $\mathcal{E}$

Let $\hat{H}_{A\mathcal{E}} = \sum_{k=1}^{N} \hat{H}_{A\mathcal{E}_k}$

$$\hat{H}_{A\mathcal{E}_k} = g_k(|\xi_+\rangle\langle\xi_+| - |\xi_-\rangle\langle\xi_-|) \otimes (|e_+^k\rangle\langle e_+^k| - |e_-^k\rangle\langle e_-^k|) \otimes \prod_{j\neq k}^{N} \otimes I_j$$

pointer states "up" and "down" — environment "up" and "down"

Decoherence II

What makes a certain dynamical quantity an "observable" is the fact that it can form dynamical correlations with $\mathcal{E}$.

"Observables" tend to rapidly form correlations with much bigger environment.

But much of these correlations indefinitely lost to local observers/systems. Hence: Only density operator to be used for the description of the SA system is the one obtained by taking the trace over $\mathcal{E}$.

$$\hat{\rho}_{SA} = \mathrm{Tr}_{\mathcal{E}}\, \hat{\rho}_{SA\mathcal{E}}$$
$$\approx |a|^2 |\psi_+\rangle|\xi_+\rangle\langle\psi_+|\langle\xi_+| + |b|^2 |\psi_-\rangle|\xi_-\rangle\langle\psi_-|\langle\xi_-|$$

Mixture

Non diagonal terms vanish very rapidly. So interference effects between different pointer states lost.

For position measurements: $\mathrm{Tr}_{\mathcal{E}}\hat{\rho} = \int dx\, dx'\, \psi(x)\psi^*(x')f(x,x')|x\rangle\langle x'|$

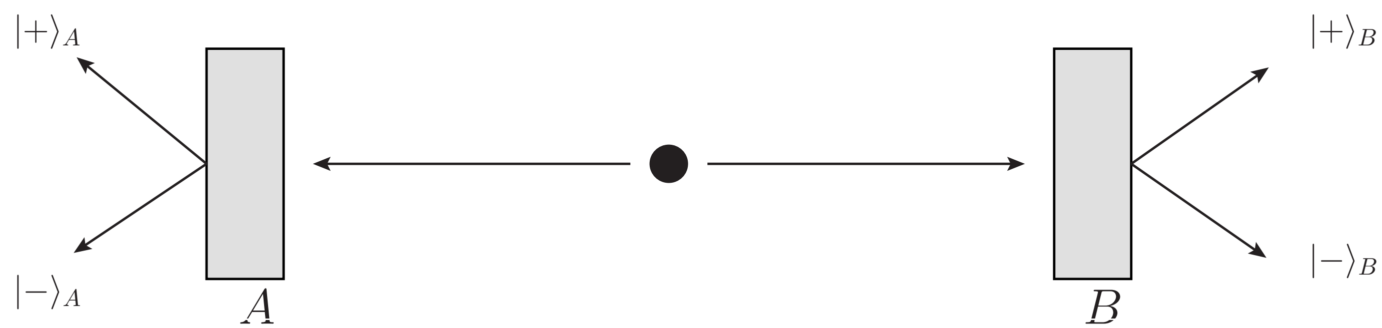
Squeezed along diagonal

Decoherence and "Improper" mixtures

But do we "really" get rid off interference terms? A "demon" could in principle still detect them.

If ensemble interpretation, then reduced $\hat{\rho}$ only an "improper" mixture.

Eg let $|\psi\rangle = \frac{1}{\sqrt{2}}(|+\rangle_A|-\rangle_B - |-\rangle_A|+\rangle_B)$



Mixture (same for B)

Local density op for A: $\hat{\rho}_A = \mathrm{Tr}_B|\psi\rangle\langle\psi| = \frac{1}{2}(|+\rangle_{AA}\langle+| + |-\rangle_{AA}\langle-|).$

But AB ensemble not really mixture. Eg interference terms important for $\hat{S}_x^A \otimes \hat{S}_x^B$

Hence "improper"

So what does that mean?

Reduced $\hat{\rho}$ just "improper"? So do macroscopic bodies occupy "definite states"? Is the cat dead or alive?

Eg what about "observable" $\hat{S}_x^S \otimes \hat{S}_x^A \otimes \prod_{k=1}^{N} \otimes \hat{S}_x^k$? Still "measurement problem"?

My take: Proper mixtures an illusion and ensemble interpretation not valid. $\hat{\rho}$ ***is*** the state itself. Not a mixture of definite states, but itself ***is*** the state.

So what if we include $\mathcal{E}$ in system? Well then consider $\mathcal{E}' \supset \mathcal{E}$ But what if we include $\mathcal{E}'$ as well...?

What if we expanded our formalism to include all microscopic DOF and their unitary dynamics ..? Well then no trace anymore!

So the demon does not know what the trace is!

But then no longer same questions. No questions about Schrodinger's cat and no question about classical world and experience of local observers in this world!

Not acceptable for strong objectivist!

But why Born rule? And why probabilities?

Decoherence works with density operators. Thus Born rule already assumed. But why?

Fundamentally everything is deterministic: $\psi(t) = \hat{\mathcal{U}}(t, t_0)\psi(t_0)$

$$\hat{\rho}(t) = \hat{\mathcal{U}}(t, t_0)\hat{\rho}(t_0)\hat{\mathcal{U}}^\dagger(t, t_0)$$

So how come Born? If no collapse then why do we observe a probabilistic world?
And what are probabilities anyway?

Everett simply declared existence of probability measure for each branch of wave-function. But no real justification/derivation.

$$\psi(t) = \sum_k a_k(t)\phi_k$$

$$p_k = |a_k|^2$$

Why?

On the nature of probabilities

Meaning of probabilities still widely discussed, many different camps:

Classical (Laplace): Ignorance interpretation . Probabilities can be determined a priori by an examination of the space of possibilities.

Many criticisms, Bertrand's paradoxes

Logical interpretation (Keynes, Carnap): Probability as a branch of logic. Construction of formal languages.

Bayesian subjectivist (Ramsey, de Finetti): Probability as degree of rational belief. Betting strategies and Dutch Book etc.

Hard to see connection to physics

Frequentist interpretation (von Mises): Probabilities arise as limiting frequencies of actual events. Natural connection to science. Claims objectivity but requires infinite ensembles. So subjective in the end...

Also finite frequentism but plagued with many problems.

More on probabilities.

Propensity Interpretation (Popper): Probability p of an outcome of a certain type is a propensity of a repeatable experiment to produce outcomes of that type with limiting relative frequency p.

Almost frequentist, so same critique

Also, why? Where does that propensity come from?

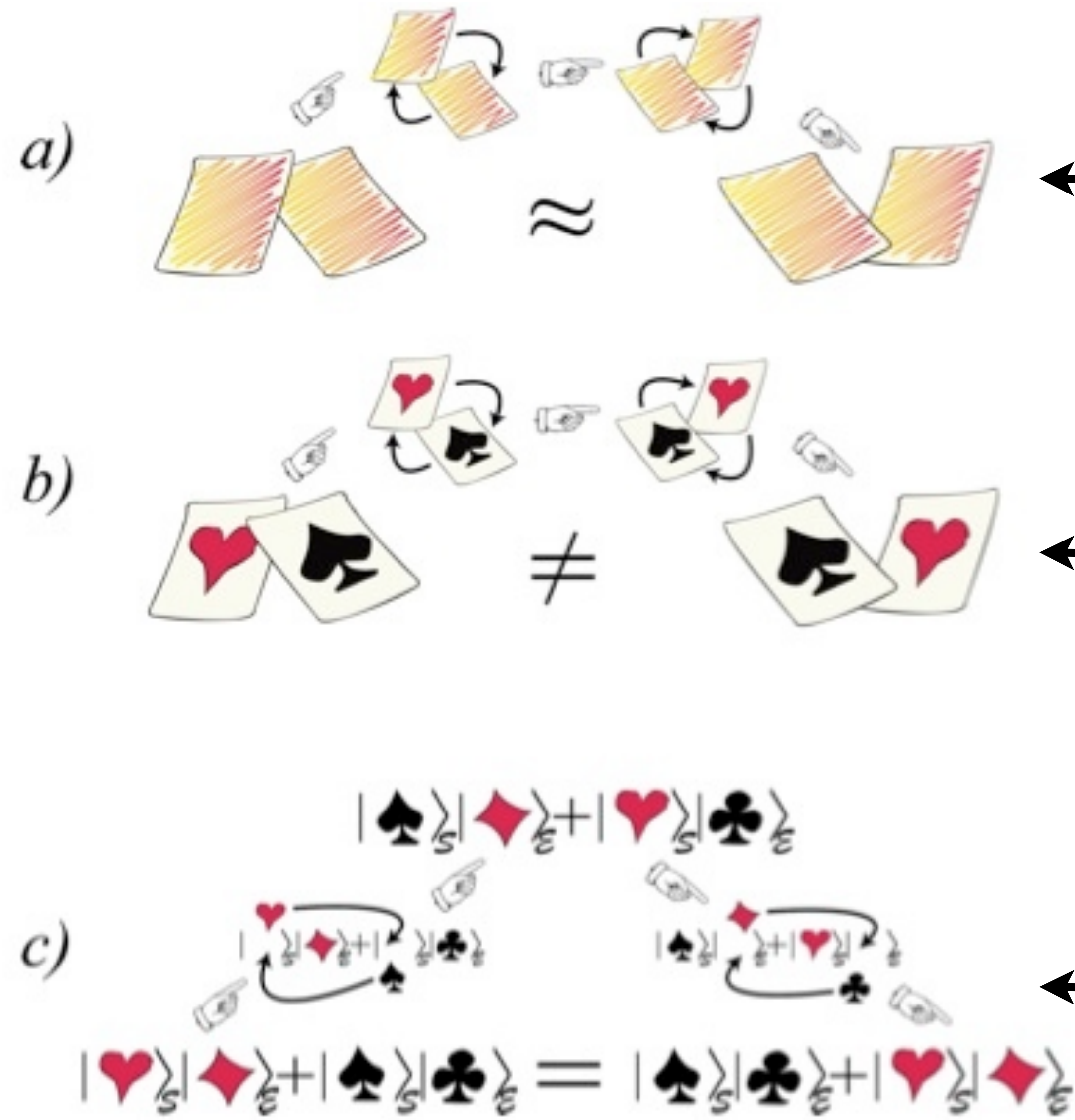
Best system interpretation (Lewis): Laws of nature are the theorems of the best systematization of the universe. And those "best" theorems may be probabilistic.

Eg Probabilities may purely arise from initial conditions, if they improve description.

Bohm's pilot-wave an example. But what is "best" not completely objective.

Seems still not like a real explanation. Also, if from initial conditions we need to assume our universe is "typical" and not "freak".

Origin of probabilities in QM?



Laplace: subjective ignorance leads to probabilities. Each card occupies definite state but we are indifferent to swaps

↑ Keynes

fundamentally nothing probabilistic, perfect knowledge implies no probabilities. Not indifferent to swaps. The demon knows it all!

In QM we are indifferent to swaps that can be reversed by swapping environment. So we are indifferent to S being heart or spade even though we have perfect knowledge (no hidden variables) of SE state.

From Zurek, PHYSICAL REVIEW A **71**, 052105 2005

Epilogue

Despite enormous empirical success, no real "understanding" of QM. Maybe there will never be...

"Shut up and calculate" a healthy and recommended attitude. But it has its limits!
As Bell said: We might be astonished by the next leap.

I think it is well due to update textbooks on QM to discuss problems with collapse of ψ .
Collapse has no place in basic formulation.

Decoherence provides a very well answer for emergence of classical properties. But cannot be understood in strongly objective language.

So I still go for a world made of observables rather than beables, and a weakly objective description of nature. Bell and Einstein would strongly disagree!

Philosophically, however, some sort of realism still most "reasonable" option.

Let’s close with a Zen poem

Life is like a cloud of mist
Emerging from a mountain cave
And death
A floating moon
In its celestial course
If you think too much
About the meaning they may have
You'll be bound forever
Like an ass to a stake.

Thanks for today!!

And much thanks to Hannes for invitation
And to Anna Stasto for early discussions at Penn State