

Black holes, information and decoherence

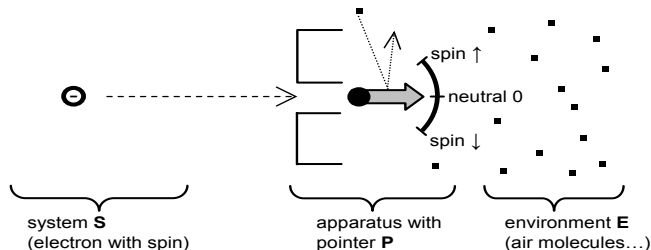
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- Phys.Rev.D79:124037, 2009 ; arXiv:0903.2258
with **David Reeb**

Quantum mechanics and decoherence



- $|+z\rangle|P_0\rangle|E_0\rangle \xrightarrow{U} |+z\rangle|P_\uparrow\rangle|E_1\rangle$
- $|-z\rangle|P_0\rangle|E_0\rangle \xrightarrow{U} |-z\rangle|P_\downarrow\rangle|E_2\rangle$
- **What if $|+x\rangle = (|+z\rangle + |-z\rangle) / \sqrt{2}$ initially ?**
 $|+x\rangle|P_0\rangle|E_0\rangle \xrightarrow{U^{\text{linear}}} (|+z\rangle|P_\uparrow\rangle|E_1\rangle + |-z\rangle|P_\downarrow\rangle|E_2\rangle) / \sqrt{2}$

Many-Worlds: both branches real and realized (“unitarity”)

Copenhagen: one branch picked out, 50% chance (“collapse”)

Copenhagen or Many-Worlds ?

Measurement, operator \mathcal{O}

Copenhagen: $\rho_C = \begin{pmatrix} 1/2 & 0 \\ 0 & 1/2 \end{pmatrix}$ in $|+z\rangle|P_\uparrow\rangle, |-z\rangle|P_\downarrow\rangle$ basis

Many-Worlds: $\psi = \frac{1}{\sqrt{2}} (|+z\rangle|P_\uparrow\rangle|E_1\rangle + |-z\rangle|P_\downarrow\rangle|E_2\rangle)$

$$\rightarrow \rho_{MW} = |\psi\rangle\langle\psi| = \begin{pmatrix} 1/2 & \langle E_1|E_2\rangle \\ \langle E_2|E_1\rangle & 1/2 \end{pmatrix}$$

Can an observer **outside** this system tell the difference between the two possibilities? (**mixed vs pure?**)

$$\text{Tr}(\rho_C \mathcal{O}) \neq \text{Tr}(\rho_{MW} \mathcal{O})$$

but: $\langle E_1|E_2\rangle \sim \frac{1}{\exp(N)}$ (or orthogonal)

\rightarrow **“Environmental Decoherence”** ($N \sim 10^{23}$)

Copenhagen or Many-Worlds ?

Does this question belong in the domain of physics or philosophy?

J. Bell: “For all *practical* purposes (FAPP), the process of decoherence leads to Copenhagen interpretation”

R. Omnés: Apparatus with accuracy to decide $\rho_C \leftrightarrow \psi_{MW}$ needs e^N atoms (only 10^{80} protons in universe!) \rightarrow *in principle* undecidable

We will argue that black hole information experiments are **as hard or harder** than determining whether Copenhagen collapse occurs. Essentially, because one has to decide whether **pure to mixed evolution** happens.

Warning: slightly off-topic!

Does anyone believe that the usual QM probabilities (the Born rule) arise naturally in Many Worlds?

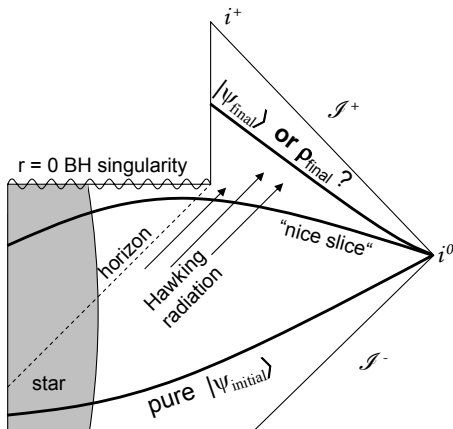
If so, please see me sometime to discuss!

On the origin of probability in quantum mechanics

Buniy, Hsu and Zee

Phys.Lett.B640:219-223,2006 ; hep-th/0606062

Black hole information puzzle



- start from pure $|\psi_{\text{initial}}\rangle$
- form black hole & Hawking evaporation
- a) trace over horizon (Hawking 1976)
- b) no cloning of information on nice slice
- state on final slice: *pure or mixed?*
- *final state independent of initial state?*
- evolution *unitary?*

- Hawking, no-cloning: **mixed**
 - string theory, AdS/CFT: **pure & unitary**
- } (empirically) **decidable?**

Hawking suggested that black holes cause pure states to evolve to mixed states.

But, FAPP, decoherence does the same thing (or at least appears to).

To test Hawking's proposal one has to go *beyond* FAPP and *beyond* decoherence.

Such experimental capability would allow fundamental tests of quantum measurement and of specific interpretations.

Experiments on black hole information are *at least* as hard as tests of collapse vs many worlds.

Varieties of black hole information experiments

Most ambitious: test purity, linearity, unitarity

- Pure initial states $|a\rangle$ mapped to *pure* final states $|b\rangle$?
- Linearity preserved: $\alpha|a\rangle + |a'\rangle \rightarrow \alpha|b\rangle + |b'\rangle$?
- Mapping unitary: $|b\rangle = U|a\rangle$ with $UU^\dagger = \mathbb{1}$?

→ requires preparation of all initial states and exact measurement of final states, **including macroscopic superpositions.**

Varieties of black hole information experiments

Test purity vs decohered mixed state

- e.g. form BH with $|+z\rangle$, $|-z\rangle$ and $(|+z\rangle + |-z\rangle)/\sqrt{2}$
- as before in QM, requires precision $\sim \exp(-N) \sim \exp(-S)$
- precision of apparatus with N' degrees of freedom: $\sim 1/N'$

→ need huge apparatus: $N' \sim \exp(S)$ degrees of freedom

Maldacena (hep-th/0106112) proposes that 2-point functions of local operators in an AdS background can distinguish between unitary evolution and information destruction. The precision required is also $\sim \exp(-S)$.

Perhaps one could study **small black holes** with $S \sim 100$?

But quantum corrections to semiclassical description used to deduce information paradox are only suppressed by powers of $1/S$; much larger than $\exp(-S)$.

Sharpness of paradox less than accuracy of measurement tests?

Purity vs decoherence

Alternative to exponential precision: carefully engineered, non-local measurement operator.

Coleman-Hepp model of measurement:

$$\begin{aligned} |\Psi_1\rangle &= |1\rangle \otimes |E_1\rangle = |+\rangle \otimes |+++ \cdots +\rangle \\ |\Psi_2\rangle &= |2\rangle \otimes |E_2\rangle = |-\rangle \otimes |--- \cdots -\rangle, \end{aligned} \quad (1)$$

Design an operator M for which $\langle \Psi_1 | M | \Psi_2 \rangle$ is large: we simply take the tensor product operator

$$M = \bigotimes_i \sigma_x^i, \quad (2)$$

where $\sigma_x^i |\pm\rangle = |\mp\rangle$ measures the spin of environmental qubit i in the x -direction.

More realistically,

$$|\Psi\rangle \rightarrow |\Psi'\rangle = U(c_1|\Psi_1\rangle + c_2|\Psi_2\rangle) , \quad (3)$$

so desired measurement operator becomes

$$\hat{\rho}_M \rightarrow \hat{\rho}'_M = U\hat{\rho}_M U^\dagger . \quad (4)$$

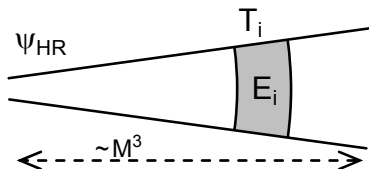
But note M is non-local if the environmental state develops correlations between degrees of freedom in different locations.

Basic dichotomy: need either *exponential sensitivity* or *non-local probe*. (And, generically, probe has to be precisely tuned.)

Hawking mixed state vs typical pure state

(a) Hawking mixed state ρ_* (adiabatic evaporation with piecewise constant temperature T)

(b) “typical” pure state $\psi \in \mathcal{H}_R \subset \mathcal{H}$:



- $\psi \in \mathcal{H}_R$ has similar energy distribution as Hawking's prediction
- such that $\rho_* = \mathbb{1}_{\mathcal{H}_R} / \dim \mathcal{H}_R$

Decide between (a) and (b) by a measurement on small subsystem S :
 $M \ll \text{size}(S) \ll M^3$, $\dim \mathcal{H}_S \ll M^2$.

Hawking mixed state vs typical pure state

One can show that measurements done on a small subsystem S of the typical pure state $\psi \in \mathcal{H}_R$ yield almost **the same outcomes** (up to exponentially small deviations) as measurements on the maximally mixed (Hawking) state $\rho_* = \mathbb{1}_{\mathcal{H}_R}/\dim \mathcal{H}_R$.

Intuition: typical pure states are maximally entangled; trace over complement of subspace S leads to almost same density matrix ρ_S .

Provides **quantum basis** for foundations of statistical mechanics!
(Replaces ergodic hypotheses.)

Hawking mixed state vs typical pure state

Recent theorem in quantum statistical mechanics (Popescu et al.), concerning measurements on a subsystem S :

If $\rho_* = \mathbb{1}_{\mathcal{H}_R}/d_R$ with $d_R = \dim \mathcal{H}_R \sim e^{M^2}$:

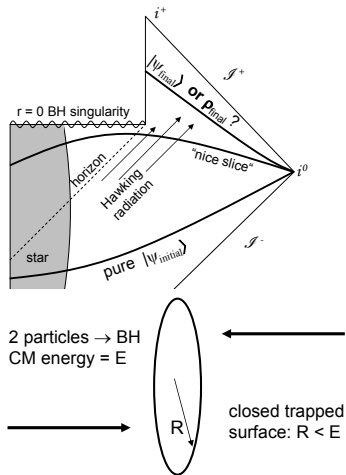
then only the fraction $\exp(-d_R^{1/3})$ of the states $\psi \in \mathcal{H}_R$ can be distinguished from ρ_* by measurements on subsystem S , if measurement precision is worse than $d_R^{-1/3} \sim e^{-M^2}$.

I.e. one *almost surely* cannot distinguish ψ from Hawking's ρ_* experimentally.

This is even true if one could measure the (pure) state of S exactly, and not only particle excitations in S (as our particle detectors).

The precision necessary could decide Decoherence vs. Copenhagen

Decoherence and semiclassical spacetime



- Hawking's calculation and no-cloning theorem rely on **classical** background (BH) spacetime
- **What if the black hole never formed?**
 \rightarrow branches where infalling particles "miss" each other:
$$\psi \rightarrow \psi' = \psi_{\text{BH}} + \psi_{\text{miss}}$$
- Can these branches restore unitarity?

- Black hole information experiments are **at least as hard as** experiments which test decoherence vs fundamental wavefunction collapse.
- If the latter is considered a question of philosophy, so might the question of pure vs mixed state after evaporation.
- Role of branches in quantum gravity with different classical (or non-classical) geometries?

Thank you!