Spontaneous wavefunction collapse: grounded in the familiar

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Quantum Measurement 1932-

Quantum Monitoring 1988-

Spontaneous Quantum Measurements/Monitorings: Why?

Is the moon there ... ?

Spontaneous Quantum Monitoring

Ghirardi-Rimini-Weber(-Bell) 1986-

Continuous Spontaneous Localization 1990-

Gravity-Related Spontaneous Collapse 1987-

Penrose vs D, D versus Penrose

Summary and More Things to Talk About

When standard collapse is testable, when it is not

Standard Von Neumann position measurement

Quantum Measurement 1932- von Neumann

Observable $\hat{x}$, measurement precision (unsharpness) σ.
Irreversible, alters energy/momentum of the measured system.

Selective measurement – **Collapse** – nonlinear,stochastic

$$\Psi \longrightarrow \text{DEVICE} \longrightarrow \Psi|_x = \mathcal{N} \exp\left(\frac{(x-\hat{x})^2}{4\sigma^2}\right)\Psi$$

Random outcome x, probability:

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\Psi^\dagger \exp\left(\frac{(x-\hat{x})^2}{2\sigma^2}\right)\Psi$$

Non-selective measurement – **Decoherence** – linear,deterministic

$$\Psi\Psi^\dagger \longrightarrow \text{DEVICE} \longrightarrow \int p(x)\Psi|_x\Psi|_x^\dagger dx$$

$$\hat{\rho} \longrightarrow \text{DEVICE} \longrightarrow \mathcal{M}_{CP}\hat{\rho}$$

Quantum Monitoring 1988- D,Belavkin,Wiseman-Milburn

Monitoring = time-continuous measurement

E.g.: Measurements at unsharpness $\sigma \to \infty$, repeated at rate $\lambda \to \infty$, constant $\gamma = \lambda/\sigma^2$ is the strength of monitoring.

Irreversible, alters energy/momentum of the monitored system.

Selective monitoring – **Dynamical Collapse** –
Nonlinear Stochastic Schrödinger Eq. (**NLSSE**) for $\Psi|_{\{x\}}$:

$$\frac{d\Psi|_{\{x\}}}{dt} = -\frac{i}{\hbar}\hat{H}\Psi|_{\{x\}} - \frac{\gamma}{8}(\hat{x} - \langle\hat{x}\rangle)^2\Psi|_{\{x\}} + \frac{\sqrt{\gamma}}{2}(\hat{x} - \langle\hat{x}\rangle)\Psi|_{\{x\}} w_t$$

Random outcome (signal) $x_t = \langle\hat{x}\rangle_t + w_t/\sqrt{\gamma}$

Non-selective monitoring – **Dynamical Decoherence** –
Linear, deterministic Master Eq. (**ME**) for $\hat{\rho} = \langle\Psi|_{\{x\}}\Psi|^\dagger_{\{x\}}\rangle_{stoch}$:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{\gamma}{8}[\hat{x}, [\hat{x}, \hat{\rho}]]$$

Spontanous Measurements/Monitorings: Why?

Standard Quantum Measurements/Monitorings

- are the unique mechansim of classical data emergence
- assume measuring devices, which is
  - necessary and confirmed in micro-systems
  - annoying in macro-systems.

That's why we choose the simplest idea, and assume Spontaneous Quantum Measurements/Monitorings

- weak and ignorable in micro-systems
- amplified and dominant in macro-systems

Spontaneous Measurements/Monitorings retain the math of standard M's/M's, explain the emergence of classicality in macroscopic d.o.f., at the price:
tiny irreversibility and non-conservation of energy/momentum.

Is the moon there ... ?

Is the moon there when nobody looks? [Mermin 1985]
Two quotations:

Pascual Jordan: "Observations not only disturb what has to be measured, they produce it....We compel [the electron] to assume a definite position.... We ourselves produce the results of measurements."

Abraham Pais: "I recall that during one walk Einstein suddenly stopped, turned to me and asked whether I really believed that the moon exists only when I look at it."

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Spontaneous Quantum Monitoring

Concept: Spontaneous (deviceless) Measurements universally present every time and everywhere, parametrized so that their effect is ingnorable for microscopic degrees of freedom, is amplifying on the mezoscales, and becomes dominant on macroscales.

Choice of monitored observables, of parametrization, do matter!

model	monitored observables	effective rate of monitoring	spatial resolution
GRW 1986	particle positions $\hat{x}_\alpha$	$\lambda = 10^{-17}/sec$ collapse rate	$\sigma = 10^{-5} cm$ localization length
DP 1987	mass density field $\hat{\mu}(x)$	$G/\hbar$	$\sigma > 10^{-9} cm$ short length cutoff
CSL 1990	mass density field $\hat{\mu}(x)$	$\gamma \propto \lambda\sigma^3/m_0^2$ $\lambda < 10^{-12}/\mathrm{sec}$	$\sigma = 10^{-5} cm$ localization length

Ghirardi-Rimini-Weber(-Bell) 1986-

Position $\hat{x}_\alpha$ of each elementary particle is spontaneously measured at rate $\lambda = 10^{-17}/s$ and precision $\sigma = 10^{-5}cm$:

$$\Psi \longrightarrow \mathcal{N} \exp\left(\frac{(x_\alpha - \hat{x}_\alpha)^2}{4\sigma^2}\right)\Psi$$

Random outcome x_α, probability:

$$p_\alpha(x_\alpha) = \frac{1}{\sqrt{2\pi\sigma^2}}\Psi^\dagger \exp\left(\frac{(x_\alpha - \hat{x}_\alpha)^2}{2\sigma^2}\right)\Psi$$

No effect on microscopic d.o.f. but on massive d.o.f., e.g., the c.o.m. $\hat{x}_{cm}$ of $N = 10^{23}$ particles, when the effective collapse rate becomes $10^8/s$.

Rigid body c.o.m. Dynamic Decoherence ME:

$$\frac{d\hat{\rho}_{cm}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}_{cm}] - \frac{N\lambda}{8\sigma^2}[\hat{x}_{cm}, [\hat{x}_{cm}, \hat{\rho}_{cm}]], \qquad (\text{if } \Delta x_{cm} \ll \sigma)$$

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Continuous Spontaneous Localization 1990- G-R-Pearle

Smeared spatial mass density distribution:

$$\hat{\mu}_\sigma(x) = \sum_\alpha m_\alpha G_\sigma(x - \hat{x}_\alpha).$$

Spontaneously monitored at (effective) rate $\gamma_{CSL} = (2\sqrt{\pi}\sigma)^3\lambda$.

Selective monitoring – Dynamical Collapse – NLSSE:

$$\frac{d\Psi}{dt} = -\frac{i}{\hbar}\hat{H}\Psi - \frac{\gamma_{CSL}}{2m_0^2}\int \left(\hat{\mu}_\sigma(x) - \langle\hat{\mu}_\sigma(x)\rangle\right)^2 d^3x\Psi$$

$$+\frac{\sqrt{\gamma_{CSL}}}{m_0}\int \left(\hat{\mu}_\sigma(x) - \langle\hat{\mu}_\sigma(x)\rangle\right)\Psi w_t(x) d^3x$$

Measured signal: $\mu_t(x) = \langle\hat{\mu}_\sigma(x)\rangle_t + \frac{1}{2}\frac{m_0}{\sqrt{\gamma_{SCL}}} w_t(x)$

Nonselective monitoring – Dynamical Decoherence – ME:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{\gamma_{CSL}}{2m_{AMU}^2}\int [\hat{\mu}_\sigma(x), [\hat{\mu}_\sigma(x), \hat{\rho}]] d^3x$$

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Gravity-Related Spontaneous Collapse 1987- D,Penrose

Smeared spatial mass density $\hat{\mu}_\sigma(x)$ is spontaneously monitored by $1/r$-correlated spontaneous measurements at (effective) rate $G/\hbar$.

Selective monitoring – Dynamical Collapse – NLSSE:

$$\frac{d\Psi}{dt} = -\frac{i}{\hbar}\hat{H}\Psi - \frac{G}{2\hbar}\int [\hat{\mu}_\sigma(x) - \langle\hat{\mu}_\sigma(x)] \, [\hat{\mu}_\sigma(y) - \langle\hat{\mu}_\sigma(y)\rangle] \frac{d^3x d^3y}{|x-y|}\Psi$$

$$+\sqrt{G/\hbar}\int \left(\hat{\mu}_\sigma(x) - \langle\hat{\mu}_\sigma(x)\rangle\right)\Psi w_t(x) d^3x$$

Measured signal: $\mu_t(x) = \langle\hat{\mu}_\sigma(x)\rangle_t + \frac{1}{2}\sqrt{\hbar/G}\, w_t(x)$

Nonselective monitoring – Dynamical Decoherence – ME:

$$\frac{d\hat{\rho}}{dt} = -\frac{i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{G}{2\hbar}\int\int [\hat{\mu}_\sigma(x), [\hat{\mu}_\sigma(y), \hat{\rho}]] \frac{d^3x d^3y}{|x-y|}$$

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Penrose vs D, D versus Penrose

Penrose	D
Incompatibility between Quantum Theory and	
General Relativity	Newtonian Gravity
Ultimate uncertainty of	
time-translation Killing vector	Newton potential Φ
Measure of uncertainty:	
no GR covariant form	simple non-relativistic form:
	$\int \lvert\nabla\delta\Phi\rvert^2 dV$
No dynamical eqs.	NLSE and ME

Decay rate of macroscopic superposition $|M;Left\rangle + |M;Right\rangle$:

postulated	Derived from ME

$$\tau_{DP}^{-1} = \Delta E_G / \hbar$$

$$\Delta E_G = 2U_G(LR) - U_G(LL) - U_G(RR)$$

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Summary and More Things to Talk About

Nature arranges extreme weak (otherwise standard) quantum measurements of particle positions (GRW) or of mass configuration (DP,CSL) everywhere and -time in the Universe, while measuring DEVICEs are kept hidden from our eyes and physics. The following 'spontaneous' collapse/decoherence yields a unified theory of the micro- and macroworld, without resorting on the device-related standard quantum measurement postulate.

- Experiments: two ways to go
  - Gran Sasso Experiment* (correct and silly reactions)
- Relativity? Non-Markovianity? Dissipativity?
- Is collapse (NLSE) testable, or just decoherence (ME) is?
- DP,Tilloy-D,Oppenheim: A healthier semiclassical gravity
- Hybrid classical-quantum ME = equivalent formalism
- ...

* 2021 Donadi-Piscicchia-Curceanu-D-Laubenstein-Bassi

When standard collapse is testable, when it is not

Ideal measurement

$$|1\rangle, |2\rangle, \dots \ \text{(BASIS)}$$

$$|\Psi\rangle \longrightarrow \text{DEVICE} \longrightarrow |n\rangle \ \text{(COLLAPSE)}$$

$$n \ \text{(OUTCOME)}$$

$$p_n = |\langle n|\Psi\rangle|^2 \ \text{(OUTCOME PROBABILITY)}$$

Average over n:

$$|\Psi\rangle \longrightarrow \text{DEVICE} \longrightarrow \hat{\rho} = \sum p_n |n\rangle\langle n| \ \text{(DECOHERENCE)}$$

COLLAPSE, i.e.: the post-measurement statevector, is testable if the OUTCOME is known. Otherwise it is not testable. Only the DECOHERENCE, i.e.: the post-measurement density matrix is testable.

Standard Von Neumann position measurement

$\Psi(x) \longrightarrow$ DEVICE $\longrightarrow \Psi_{\mathbf{x}}(x)$ localized randomly at $\mathbf{x}$ ($\mathbf{x}$: OUTCOME)

SELECTIVE measurement ($\mathbf{x}$ available): Ψ COLLAPSES

COLLAPSE mathematics, stochastic

$$\Psi(x) \longrightarrow \Psi_{\mathbf{x}}(x) = \frac{1}{\sqrt{p(\mathbf{x})}} \exp\left(-\frac{(x-\mathbf{x})^2}{4\sigma^2}\right) \Psi(x)$$

NONSELECTIVE measurement ($\mathbf{x}$ avaraged out): Ψ only DECOHERES

DECOHERENCE mathematics, deterministic

$$\Psi(x)\Psi^*(y) \longrightarrow \exp\left(-\frac{(x-y)^2}{8\sigma^2}\right) \Psi(x)\Psi^*(y)$$

SELECTIVE contains NONSELECTIVE but not the other way around.