Non-quantum Effect and Test of Spontaneous Collapse Models in Mechanical Oscillators

Lajos Diósi

Wigner Center, Budapest

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Mechanical Schrödinger Cats, Catness

Microscopic mass distribution matters: $f(r) = \sum_k m_k \delta(r - x_k)$.
$f_1(r), f_2(r)$, *catness* $\|f_1 - f_2\|^2$ is to be chosen later.

$$|\mathrm{Cat}\rangle = \frac{|f_1\rangle + |f_2\rangle}{\sqrt{2}}$$

Collapse: $$|\mathrm{Cat}\rangle\langle\mathrm{Cat}| \Longrightarrow \frac{1}{2}|f_1\rangle\langle f_1| + \frac{1}{2}|f_2\rangle\langle f_2|$$

- immediate if we measure f suddenly
- gradual if we monitor $f(r,t)$ with finite resolution.
- spontaneous and gradual at rate $\sim \|f_1 - f_2\|^2$ — in new QM

Spontaneous Collapse Models (demystified):

- $f(r,t)$ is being monitored, with resolution encoded in $\|f_1 - f_2\|$
- Devices are hidden, hence outcome signal is not accessible
- The only testable effect is the back-action of hidden monitors

DP and CSL

Finite spatial resolution $\sigma\rangle 0$ against divergence:

$$f(r) = \sum_k m_k g_\sigma(r - x_k)$$

- DP: very fine microscopic resolution $\sigma = 10^{-12}cm$
- CSL: loose, almost macroscopic resolution $\sigma = 10^{-5}cm$

Resolution of (hidden) monitoring f:

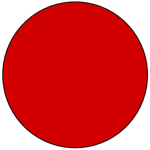
- DP: weak, proportional to the Newton constant G
- CSL: strong, proportional to a 'new' constant $\lambda \approx 10^{-9}Hz$

Fine spatial resolution with small G in DP, poor spatial resolution with large λ in CSL: similar collapse effects for bulk d.o.f., with characteristic differences...

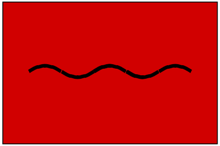
What is monitored spontaneously about a bulk?

DP: all bulk coordinates, like c.o.m., solid angle, acoustics

position, angle



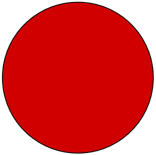
position, angle



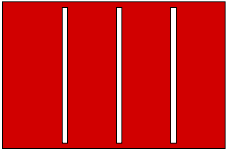
internal macroscopic modes

CSL: location of surfaces and nothing else

position, angle



position, ~~angle~~



horizontal position 4x stronger

Mechanical oscillator under spontaneous collapse (hidden monitoring)

1D oscillation, extended object, mass m, frequency Ω, c.o.m.: $\hat{x}, \hat{p}$

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\Omega^2\hat{x}^2 \tag{1}$$

Dynamics of c.o.m. state $\hat{\rho}$, under spontaneous (hidden) monitoring:

$$\frac{d\hat{\rho}}{dt} = \frac{-i}{\hbar}[\hat{H}, \hat{\rho}] - \frac{D_{\mathrm{sp}}}{\hbar^2}[\hat{x}, [\hat{x}, \hat{\rho}]]. \tag{2}$$

D_{sp} depends on DP/CSL, on geometry/structure of the mass.
Back-action, two equivalent interpretations:

- x-decoherence (quantum) — suggests quantum interference tests
- p-diffusion (classical) — allows classical non-interferometric tests

Spontaneous collapse yields spontaneous heating

Full classical Fokker-Planck:

$$\frac{d\rho}{dt} = \{H,\rho\} + \eta\frac{\partial}{\partial p}p\rho + \eta m k_B T\frac{\partial^2}{\partial p^2}\rho + D_{\mathrm{sp}}\frac{\partial^2}{\partial p^2}\rho, \tag{3}$$

damping rate η, environmental temperature T.
With $D_{\mathrm{sp}}=0$, equilibrium at T: $\rho_{\mathrm{eq}} = \mathcal{N}\exp(-H/k_B T)$.
With $D_{\mathrm{sp}} \rangle 0$, equilibrium at $T + \Delta T_{\mathrm{sp}}$,

$$\Delta T_{\mathrm{sp}} = \frac{D_{\mathrm{sp}}}{\eta m k_B} = \frac{D_{\mathrm{sp}}}{m k_B}\tau \tag{4}$$

$\tau = 1/\eta = Q/\Omega$: relaxation (ring-down) time of oscillator
Validity of classical (non-quantum) treatment:

$$k_B \Delta T_{\mathrm{sp}} \gg \hbar\Omega. \tag{5}$$

Spontaneous heating $\Delta T_{\rm sp}$ in DP and CSL

$$\Delta T_{\rm sp} = \frac{D_{\rm sp}}{mk_B}\tau \approx \begin{cases} \tau[s] \times 10^{-5}K; & \text{DP} \quad \cancel{m}, \cancel{shape} \\ \frac{\varrho[g/cm^3]}{d[cm]}\tau[s] \times 10^{-6}K; & \text{CSL} \quad \cancel{m} \end{cases}$$

$\Delta T_{\rm sp}$ for *DP*:

Q

Ω		10^2	10^3	10^4	10^5	10^6
	10^5Hz	$[10^{-8}$K$]$	$[10^{-7}$K$]$	$[10^{-6}$K$]$	10^{-5}K	10^{-4}K
	10^4Hz	$[10^{-7}$K$]$	10^{-6}K	10^{-5}K	10^{-4}K	10^{-3}K
	10^3Hz	10^{-6}K	10^{-5}K	10^{-4}K	10^{-3}K	$\mathbf{10^{-2}}$K
	10^2Hz	10^{-5}K	10^{-4}K	10^{-3}K	$\mathbf{10^{-2}}$K	$\mathbf{10^{-1}}$K
	10Hz	10^{-4}K	10^{-3}K	$\mathbf{10^{-2}}$K	$\mathbf{10^{-1}}$K	**1**K
	1Hz	10^{-3}K	$\mathbf{10^{-2}}$K	$\mathbf{10^{-1}}$K	**1**K	**10**K

Data in [brackets] are not in the classical domain $k_B\Delta T_{\rm sp} \gg \hbar\Omega$.
Data in **boldface** are above the millikelvin range!

Detecting $\Delta T_{\rm sp}$: just classical thermometry?

In soft $\Omega = 1Hz - 1kHz$ oscillators of long ring-down time $\tau = 1h - 1month$, DP and CSL predict spontaneous heating

$$\Delta T_{\rm sp} = 1mK - 10K.$$

$\Delta T_{\rm sp}$ is non-quantum, large enough to be detected by a classical 'thermometer' of resolution $\delta T \lesssim \Delta T_{\rm sp}$.
Paradoxical: Construction of the oscillator, preparation of the equilibrium state, precise mK-thermometry may need quantum optomechanics.
Does 'Standard Quantum Limit' constrain δT? No, for two reasons:

- The effect $\Delta T_{\rm sp}$ is classical!
- SQL constrains stationary sensing. We go the other way ...

Preparation and detection separated

Effect $\Delta T_{\rm sp} \gg \hbar\Omega/k_B$ is classical, experiment might be fully classical. It won't, because of extreme technical demands.

- Constructing soft high-Q mechnical oscillator
  - micro mass, e.g.: $5mg$ Matsumoto et al. $(\Delta T_{\rm sp} = 6.4K)$
  - heavy mass, e.g.: $40kg$ Advanced LIGO $(\Delta T_{\rm sp} = 0.16K?)$
- Preparing equilibrium state over hours—weeks
  - at room temperature $T \approx 300K$
  - at active cooling $T \lesssim \Delta T_{\rm sp}$
- Switch on detection of spontaneous heating
  - by spectral 'thermometry'
  - by state tomography

Summary and implications for DP/CSL

- spontaneous collapse = hidden monitoring
- spontaneous decoherence = spontaneous p-diffusion (classical)
- spontaneous heating $\Delta T_{\mathrm{sp}} = const. \times$ring-down time
- DP/CSL: $\Delta T_{\mathrm{sp}} = 1mK - 10K$ if ring-down time is 1h-1month
- preparation and detection (tomography) separated
- very close feasibility

If predicted ΔT_{sp} won't yet be seen, DP/CSL won't yet be rejected!
Just current optimistic parametrization would have to be updated:
DP parameters: (σ, G) where σ may be larger than $10^{-12}cm$.
CSL parameters: (σ, λ) where λ may be smaller than $10^{-9}Hz$.

Diosi, PRL114, 050403 (2015)
Matsumoto,Michimura,Hayase,Aso,Tsubono, arXiv:1312.5031
Advanced LIGO, arxiv:1411.4547