Testing Spontaneous Wavefunction Collapse Models on Classical 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 C[ontinuous] S[pontaneous] L[ocalization]

Spatial resolution $\sigma\rangle 0$ is finite (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 $\sigma = 10^{-5} cm$

Spatio-temporal resolution of (hidden) monitoring f:

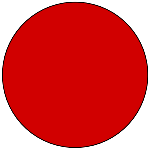
- DP: weak, proportional to the Newton constant G
- CSL: strong, $\propto \lambda \approx 10^{-9} Hz/$amu, new universal constant!

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...

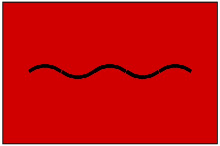
What is monitored spontaneously about a bulk?

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

position, angle



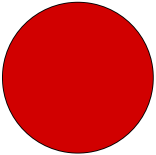
position, angle



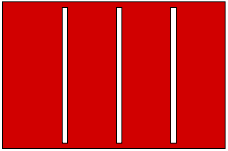
internal macroscopic modes

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) — interference tests
- **p-diffusion (classical) — non-interferometric tests**

Digression: interferometric tests 2003

Very demanding!

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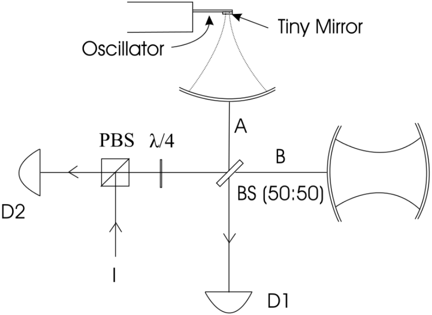
Towards Quantum Superpositions of a Mirror

William Marshall,[1,2] Christoph Simon,[1] Roger Penrose,[3,4] and Dik Bouwmeester[1,2]



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 ΔT_{sp} in DP and CSL

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

ΔT_{sp} for *DP*:

				Q		
		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
Ω	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 $k_B\Delta T_{\mathrm{sp}} \gg \hbar\Omega$.

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 opto-, magneto-, electro- ... mechanics

Preparation and detection separated

Effect $\Delta T_{\mathrm{sp}} \gg \hbar\Omega/k_B$ 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. $(\Delta T_{\mathrm{sp}} = 6.4K)$
  - heavy mass, e.g.: $40kg$ Advanced LIGO $(\Delta T_{\mathrm{sp}} = 0.16K?)$
- Preparing equilibrium state over hours—weeks
  - at room temperature $T \approx 300K$
  - at active cooling $T \lesssim \Delta T_{\mathrm{sp}}$
- Switch on detection of spontaneous heating
  - by spectral 'thermometry'
  - by state tomography

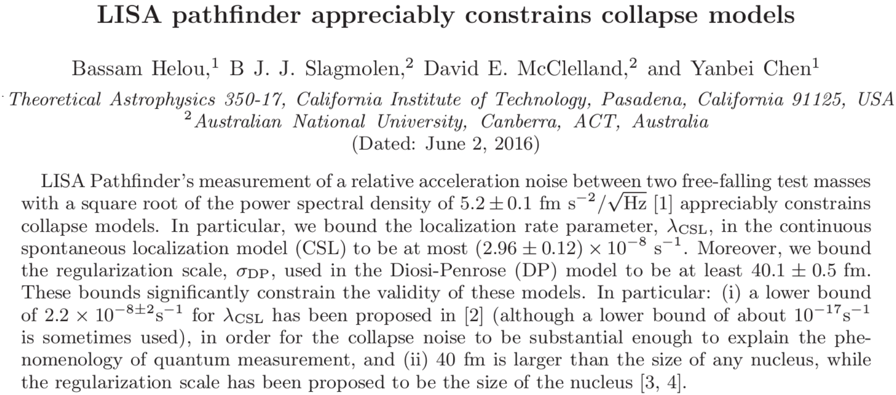
Summary and implications for DP/CSL

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

If predicted $\Delta T_{\rm sp}$ 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

Epilogue



LISA pathfinder appreciably constrains collapse models

Bassam Helou,[1] B J. J. Slagmolen,[2] David E. McClelland,[2] and Yanbei Chen[1]
[1]*Theoretical Astrophysics 350-17, California Institute of Technology, Pasadena, California 91125, USA*
[2]*Australian National University, Canberra, ACT, Australia*

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LISA Pathfinder's measurement of a relative acceleration noise between two free-falling test masses with a square root of the power spectral density of 5.2 ± 0.1 fm $\mathrm{s}^{-2}/\sqrt{\mathrm{Hz}}$ [1] appreciably constrains collapse models. In particular, we bound the localization rate parameter, λ_{CSL}, in the continuous spontaneous localization model (CSL) to be at most $(2.96 \pm 0.12) \times 10^{-8}\ \mathrm{s}^{-1}$. Moreover, we bound the regularization scale, σ_{DP}, used in the Diosi-Penrose (DP) model to be at least 40.1 ± 0.5 fm. These bounds significantly constrain the validity of these models. In particular: (i) a lower bound of $2.2 \times 10^{-8\pm2}\mathrm{s}^{-1}$ for λ_{CSL} has been proposed in [2] (although a lower bound of about $10^{-17}\mathrm{s}^{-1}$ is sometimes used), in order for the collapse noise to be substantial enough to explain the phenomenology of quantum measurement, and (ii) 40 fm is larger than the size of any nucleus, while the regularization scale has been proposed to be the size of the nucleus [3, 4].