Title: Phenomenology of spontaneous wave-function collapse models

Date: May 27, 2013 02:00 PM

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Abstract: Models of spontaneous wave function collapse make predictions, which are different from those of standard quantum mechanics. Indeed, these models can be considered as a rival theory, against which the standard theory can be tested, in pretty much the same way in which parametrized post-Newtonian gravitational theories are rival theories of general relativity. The predictions of collapse models almost coincide with those of standard quantum mechanics at the microscopic level, as these models have to account for the microscopic world, as we know it. Departures become significant when the size of the system increases. However, for larger systems environmental influences become more and more difficult to eliminate. This is the reason why it is tricky to test collapse models experimentally, and so far no decisive test has been performed. We will review the main phenomenological properties of collapse models, in particular the so-called amplification mechanics, as well as the main models, which are debated in the literature (GRW, CSL, QMUPL, DP). We will review the lower bounds on the collapse parameter, and more importantly the upper bounds set by available experimental data. This data come both from experimental tests on earth, and from cosmological observations.


The Quantum Landscape: Generalization of Quantum Theory and
Experimental Tests - Perimeter Institute (May 27-31, 2013)
Phenomenology of wave
function collapse models
Angelo Bassi - University of Trieste & INFN - Italy

"Collapses occur more or less all the time, more or less everywhere" (J.S. Bell)

The Schrödinger equation is linear ➔ superposition principle

Approved!

What?

Collapse models ➔ no macroscopic superpositions

Approved!

OR

Approved!

Collapse models

GRW MODEL: G.C. Ghirardi, A. Rimini and T. Weber, *Phys. Rev. D* 340, 470 (1986)

CSL MODEL: P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

REVIEW: A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003)

REVIEW: A. Bassi, K. Lochan, S. Satin, T.P. Singh and H. Ulbricht, *Rev. Mod. Phys.* 85, 471 (2013)

Also: Diosi, Gisin, Adler, Wiseman, Tumulka, Dowker, Bedingham …

Question: Which form for the collapse equation?

Answer: The form of the collapse equation is "uniquely identified" by general requirements

N. Gisin & I.C. Percival, *J. Phys. A 25, 5677 (1992)*

H.M. Wiseman & L. Diosi, *Chem. Phys. 268, 91 (2001)*

S.L. Adler & T.A. Brun, *J. Phys. A 34, 1 (2001)*

S. Weinberg, *Phys. Rev. A 85, 062116 (2012). See also: Ann. Phys. 194, 336 (1989); Phys. Rev. Lett. 62, 485 (1989)*

A. Bassi, D. Duerr & G. Hinrichs, ArXiv:1303:4284 (2013)

Uniqueness of collapse equation – Setup

Definition: Two **mixtures** $\{p_i; |\psi_i\rangle\}$ and $\{q_i; |\phi_i\rangle\}$ are **equivalent** iff:

$$\sum_i p_i |\psi_i\rangle\langle\psi_i| = \sum_i q_i |\phi_i\rangle\langle\phi_i|.$$

Let us consider a **generic evolution for the state-vector:**

$$|\psi_0\rangle \xrightarrow{\mathrm{E_t}} |\psi_t\rangle$$

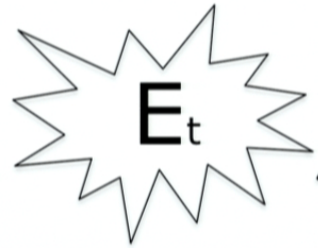
E_t could be non-linear, stochastic … anything

IMPORTANT: Such a dynamics, in general, does not imply a well-defined dynamics for the density matrix. Equivalent ensembles can evolve in non-equivalent ensembles

Therefore, in general, the density matrix formalism loses its meaning in this context

Uniqueness of collapse equation – Gisin's argument

N. Gisin, *Helv. Phys. Acta* 62, 363 (1989)



INITIALLY ENGANGLED STATE

$$|V\rangle = \sum_i \sqrt{d_i}|\psi_i\rangle \otimes |\alpha_i\rangle = \sum_i \sqrt{p_i}|\phi_i\rangle \otimes |\beta_i\rangle$$

ALICE MEASURES EITHER A OR B

$$A = \sum_i \alpha_i |\alpha_i\rangle\langle\alpha_i| \qquad B = \sum_i \beta_i |\beta_i\rangle\langle\beta_i|$$

BOB RECEIVES TWO EQUIVALENT ENSEMBLES

$$\rho_A = \sum_i d_i |\psi_i\rangle\langle\psi_i| \quad \textbf{OR} \quad \rho_B = \sum_i p_i |\phi_i\rangle\langle\phi_i|$$

IF THE EQUIVALENCE RELATION IS NOT PRESERVED

$$\rho_A \neq \rho_B$$

THEN FASTER-THEN-LIGHT COMMUNICATION

Consequence 1: existence of map for ρ

The no superluminal condition implies that **initially equivalent mixtures remain equivalent**

Then E_t defines a map on the density matrices

$$\rho_0 = \begin{cases} \sum_i p_i |\psi_i\rangle\langle\psi_i| \\ \sum_i q_i |\phi_i\rangle\langle\phi_i| \end{cases} \xrightarrow{T_t} \rho_t = \begin{cases} \sum_i p_i |\psi_{i,t}\rangle\langle\psi_{i,t}| \\ \sum_i q_i |\phi_{i,t}\rangle\langle\phi_{i,t}| \end{cases}$$

$$\sum_i q_i |\phi_i\rangle\langle\phi_i| \xrightarrow{E_t} \sum_i q_i |\phi_{i,t}\rangle\langle\phi_{i,t}|$$

Consequence 2: linearity of the map for ρ

The map T_t is **linear**

$$\rho_{1,0} = \sum_i p_i |a_i\rangle\langle a_i| \qquad \rho_{2,0} = \sum_i q_i |b_i\rangle\langle b_i|$$

$$\rho_0 = \lambda\rho_{1,0} + (1-\lambda)\rho_{2,0}$$

Then

$$\begin{aligned} T_t[\rho_0] &= \sum_i [\lambda p_i |E_t(a_i)\rangle\langle E_t(a_i)| + (1-\lambda) q_i |E_t(b_i)\rangle\langle E_t(b_i)|] \\ &= \lambda T_t\left[\sum_i p_i |E_t(a_i)\rangle\langle E_t(a_i)|\right] + (1-\lambda) T_t\left[\sum_i q_i |E_t(b_i)\rangle\langle E_t(b_i)|\right] \\ &= \lambda T_t[\rho_{1,0}] + (1-\lambda) T_t[\rho_{2,0}] \end{aligned}$$

Consequence 3: Lindblad theorem

LINDBLAD THEOREM: A **linear** evolution of the Quantum-Dynamical Semi-group (➔ **Markovian** dynamics), which satisfies **complete positivity** is of the Lindbald type:

$$\frac{\mathrm{d}\rho_t}{\mathrm{d}t} = -i[H, \rho_t] + \sum_{k=1}^{n} \left(L_k \rho_t L_k^\dagger - \frac{1}{2} L_k^\dagger L_k \rho_t - \frac{1}{2} \rho_t L_k^\dagger L_k \right)$$

The mathematical question

Given a nonlinear and stochastic evolution for the state-vector (on the unit sphere)

$$\mathrm{d}\psi_t = A(\psi_t)\mathrm{d}t + \sum_{k=1}^{N} B_k(\psi_t)\mathrm{d}W_{k,t},$$

Where $A(\psi)$ and $B_k(\psi)$ are unspecified nonlinear operators, find the conditions under which it generates a Lindblad type of equation

$$\frac{\mathrm{d}\rho_t}{\mathrm{d}t} = -i[H,\rho_t] + \sum_{k=1}^{n}\left(L_k\rho_t L_k^\dagger - \frac{1}{2}L_k^\dagger L_k\rho_t - \frac{1}{2}\rho_t L_k^\dagger L_k\right)$$

For the statistical operator $\rho_t \equiv \mathbb{E}[|\psi_t\rangle\langle\psi_t|]$


The structure is completely
complex coefficients of the N×N
CAUTION

Answer

Assume that I, L_1, ... L_n are linearly independent. Then the stochastic Schrödinger equation leads to the Lindblad equation if and only if $N \geq n$ and

$$A(\psi) = -iH - \frac{1}{2}\sum_{k=1}^{N}\left(L_k^\dagger L_k - 2\ell_{k,t}^{(\psi)} L_k^{(\psi)} + |\ell_{k,t}^{(\psi)}|^2\right)$$

$$B_k(\psi) = L_k^{(\psi)} - \ell_{k,t}^{(\psi)}, \qquad \ell_{k,t}^{(\psi)} = \frac{1}{2}\langle \psi_t, (L_k^{(\psi)\dagger} + L_k^{(\psi)})\psi_t \rangle$$

Modulo unimportant phase factors. Here L_{n+1}, ... L_N are zero and the operators $L_k^{(\psi)}$ and their "adjoints" are defined as follows

$$L_k^{(\psi)} := \sum_{j=1}^{N} u_{kj}(\psi)\, L_j, \qquad L_k^{(\psi)\dagger} := \sum_{j=1}^{N} u_{kj}^*(\psi)\, L_j^\dagger$$

The structure is completely defined, the only degrees of freedom being the complex coefficients of the N×N unitary matrix $u_{kj}(\psi)$.

Which models?

The general structure is

$$d|\psi\rangle_t \;=\; \left[-\frac{i}{\hbar}H\,dt \;+\; \sqrt{\lambda}(A - \langle A\rangle_t)dW_t - \frac{\lambda}{2}(A - \langle A\rangle_t)^2 dt\right]|\psi\rangle_t$$

$$\langle A\rangle_t \;=\; \langle\psi_t|A|\psi_t\rangle$$

Which kind of operators?

Reasonable assumption: the collapse operators – which identify the "preferred basis", should be **connected to position**

NOTE: The Born rule comes out automatically

Space-collapse models

	White noise models	Colored noise models
	All frequencies appear with the same weight	The noise can have an arbitrary spectrum
Infinite temperature models No dissipative effects	**GRW / CSL** G.C. Ghirardi, A. Rimini, T. Weber , *Phys. Rev. D* 34, 470 (1986) G.C. Ghirardi, P. Pearle, A. Rimini, *Phis. Rev. A* 42, 78 (1990) **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989)	**Non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler & A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **Non-Markovian QMUPL** A. Bassi & L. Ferialdi, *PRL* 103, 050403 (2009)
Finite temperature models Dissipation and thermalization	**Dissipative QMUPL model** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083	**Non-Markovian & dissipative QMUPL** (L. Ferialdi, A. Bassi, PRL 108, 170404 (2012))

CSL model

P. Pearle, *Phys. Rev. A* 39, 2277 (1989). G.C. Ghirardi, P. Pearle and A. Rimini, *Phys. Rev. A* 42, 78 (1990)

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H dt + \sqrt{\lambda} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t) dW_t(\mathbf{x}) - \frac{\lambda}{2} \int d^3x (N(\mathbf{x}) - \langle N(\mathbf{x})\rangle_t)^2 dt \right] |\psi_t\rangle$$

System's Hamiltonian

NEW COLLAPSE TERMS ➡ **New Physics**

$N(\mathbf{x}) = a^\dagger(\mathbf{x}) a(\mathbf{x})$ particle density operator

choice of the preferred basis

$\langle N(\mathbf{x})\rangle_t = \langle \psi_t | N(\mathbf{x}) | \psi_t \rangle$

nonlinearity

$W_t(\mathbf{x}) = \text{noise} \quad \mathbb{E}[W_t(\mathbf{x})] = 0, \quad \mathbb{E}[W_t(\mathbf{x}) W_s(\mathbf{y})] = \delta(t-s) e^{-(\alpha/4)(\mathbf{x}-\mathbf{y})^2}$ **stochasticity**

$\lambda =$ collapse strength $\qquad r_C = 1/\sqrt{\alpha} =$ correlation length

two parameters

Collapse rate

Small superpositions

● + ●

$\ll r_C$

Collapse NOT effective

Large superpositions

● + ●

$\geq r_C$

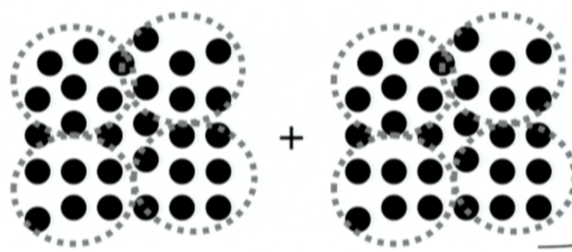
Collapse effective

↓

$$\boxed{\Gamma = \lambda n^2 N}$$

n = number of particles within r_C

N = number of such clusters



Amplification mechanics

Few particles

no collapse

quantum behavior

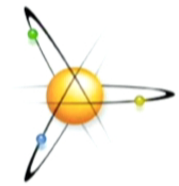
Many particles

Fast collapse

classical behavior

Which values for λ and r_c?

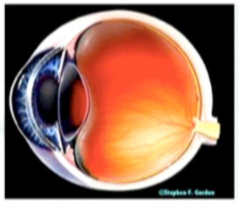
Microscopic world
(few particles)



$$\lambda \sim 10^{-8\pm2}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (Adler - 2007)

Mesoscopic world
Latent image formation
+
perception in the eye
(~ 10^4 - 10^5 particles)



S.L. Adler, JPA 40, 2935 (2007)

A. Bassi, D.A. Deckert & L. Ferialdi, EPL 92, 50006 (2010)

$$\lambda \sim 10^{-17}\mathrm{s}^{-1}$$

QUANTUM – CLASSICAL TRANSITION (GRW - 1986)

Macroscopic world
(> 10^{13} particles)

G.C. Ghirardi, A. Rimini and T. Weber, PRD 34, 470 (1986)

$$r_C = 1/\sqrt{\alpha} \ \sim \ 10^{-5}\mathrm{cm}$$

Increasing size of the system

Constraints from Experiments

Collapse effects are tiny, but scale with the size of the system

Two main strategies

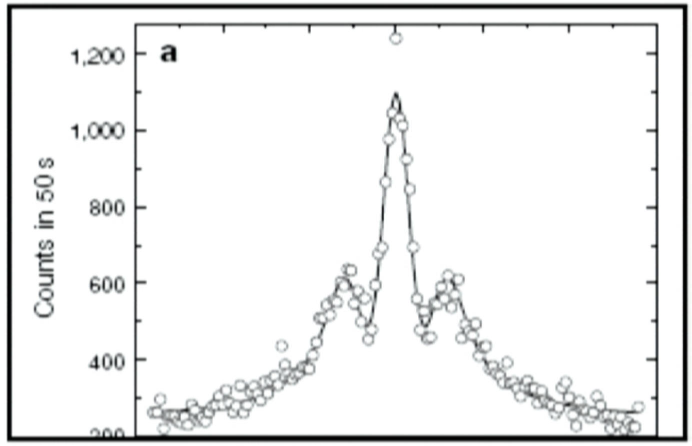
1. **High precision laboratory experiments** (mainly interference experiments)

2. **Cosmological observations** (small deviations from the standard quantum dynamics imply different histories for the universe)

Matter-wave interferometry

Diffraction of macro-molecules:

- **C_{60} (720 AMU)**
  M. Arndt et al, *Nature* 401, 680 (1999)
- **C_{70} (840 AMU)**
  L. Hackermüller et al, *Nature* 427, 711 (2004)
- **$C_{30}H_{12}F_{30}N_2O_4$ (1,030 AMU)**
  S. Gerlich et al, *Nature Physics* 3, 711 (2007)
- **Larger Molecules (10,000 AMU)**
  Arndt group (2013)



C_{60} diffraction experiment

The experimental bounds are some 2 orders of magnitude higher than Adler's proposed value (therefore some 10-11 orders of magnitude away from GRW's proposed value)

Future experiments: ~10^6 AMU
S. Gerlich et al, *Nature Physics* 3, 711 (2007)
S. Nimmrichter, *PRA* 83, 043621 (2011)

Outer space for higher masses?

ALSO:
Micro-mirrors, nano-spheres
Marshall, W., et al., *Phys. Rev. Lett.* 91, 130401 (2003)
Romero-Isart, O., et al., *Phys. Rev. A* 83, 013803 (2011)

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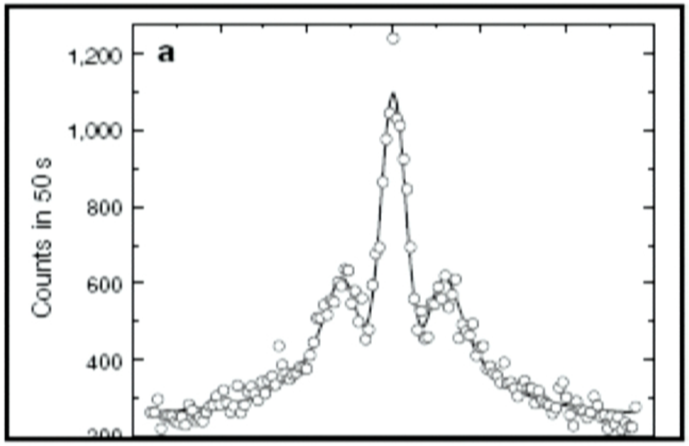

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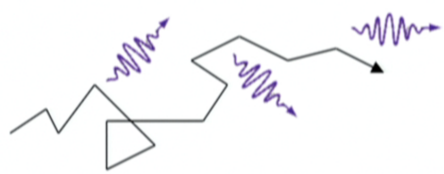
Spontaneous photon emission

FREE PARTICLE

1. Quantum mechanics

2. Collapse models



$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

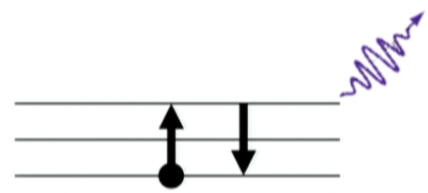
Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

S.L. Adler, A. Bassi & S. Donadi, ArXiv 1011.3941. JPA, to appear.

BOUND STATE

1. Quantum mechanics

2. Collapse models



$$\frac{d\Gamma_k}{dk} = 2\left[1 - \frac{1}{(1+(ka_0/2)^2)^2}\right]\frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

S.L. Adler, F. Ramazanoglu, *J. Phys. A* 40, 13395 (2007)

Spontaneous photon emission: weak GRW value for λ

Comparison with experimental data

↓

Original CSL models (with the **weak** value for λ) is ruled out!

Mass-proportional model (noise having a gravitational origin?)

$$\lambda \to \lambda \left(\frac{m}{m_N} \right)^2$$

then:

$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k} \to \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m_N^2 c^3 k}$$

→ **Compatibility is restored (with respect to GRW's proposed value for λ)**

TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

Energy (keV)	Expt. upper bound (counts/keV/kg/day)	Theory (counts/keV/kg/day)
11	0.049	0.071
101	0.031	0.0073
201	0.030	0.0037
301	0.024	0.0028
401	0.017	0.0019
501	0.014	0.0015

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Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

Spontaneous photon emission: Adler's strong value for λ

What about the stronger value for λ (Adler)?

Experimental data rule out such a possibility by 2 orders of magnitude!
There is a natural way to restore compatibility:

Colored noise collapse models

For theses models, the formula for the emission rate changes as follows:

$$\left.\frac{d\Gamma_k}{dk}\right|_{\text{colored}} = \gamma(\omega_k)\left.\frac{d\Gamma_k}{dk}\right|_{\text{white}}$$

γ = Fourier transform of the correlation function of the noise

S.L. Adler, F. Ramazanoglu, *J. Phys. A* 40, 13395 (2007)

Cutoff at frequencies ~ 10^{18} s^{-1} sufficient for compatibility with known data

S.L. Adler, F. Ramazanoglu, ibid.

Cutoff at frequencies c/r_C ~ 10^{15} s^{-1}

A. Bassi and G.C. Ghirardi, *Phys. Rep.* 379, 257 (2003)

BUT the story is not over!

Energy non-conservation

The stochastic terms induce a random motion of particles.

The noise pumps energy into the system.

For one nucleon (GRW's value)

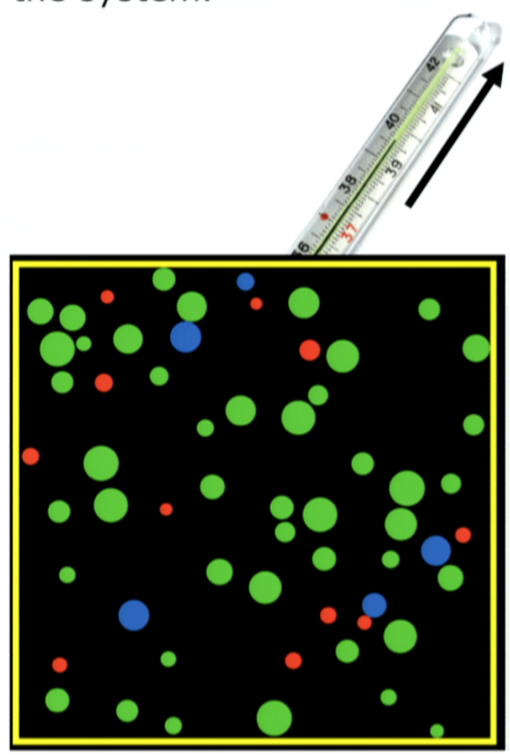
$$\frac{dE}{dt} = \frac{\lambda\alpha\hbar^2}{4m} \simeq 10^{-25}\text{eV s}^{-1}$$

→ 1 eV increase in 10^{18} yr

For a gas (GRW's value)

Temperature increase 10^{-15} K/yr

G.C. Ghirardi, A. Rimini, T. Weber, *Phys. Rev. D* 34, 470 (1986)



Energy non-conservation

Cosmological observations

The smart thing to do is to look at large structures in the universe.

The larger the system, the bigger the spontaneous-collapse effect.

So far, cosmological data are compatible with collapse models.

Energy non-conservation is very model dependent

Cosmological data	Distance (orders of magnitude) from GRW value for λ	Distance (orders of magnitude) from Adler's value for λ
Dissociation of cosmic hydrogen	17	9
Heating of the Intergalactic medium (IGM)	8	0
Heating of protons in the universe	12	4
Heating of Interstellar dust grains	15	7

S.L. Adler, *Jour. Phys. A* 40, 2935 (2007), arXiv:quant-ph/0605072

Inflation, cosmic seeds & collapses

Can collapse models explain the emergence of the seeds of cosmic structure?

How does the inflationary history of the universe change, if collapses occur?

- A. Perez, H. Sahlmann and D. Sudarsky, Class. Quant. Grav. 23, 2317 (2006)
- A. De Unanue and D. Sudarsky, Phys. Rev. D 78, 043510 (2008)
- A. Diez-Tejedor, G. Leon and D. Sudarsky, Gen. Rel. Grav. 44, 2965 (2012)
- S. J. Landau, C. G. Scoccola and D. Sudarsky, Phys. Rev. D 85, 123001 (2012)
- J. Martin, V. Vennin and P. Peter, arXiv:1207.2086.
- P. Canate, P. Pearle and D. Sudarsky, arXiv:1211.3463.
- Suratna Das, Kinjalk Lochan, Satyabrata Sahu and T. P. Singh, arXiv:1304.5094

Upper bounds on λ. Summary

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
Matter-wave interference experiments	2	Dissociation of cosmic hydrogen	9
Decay of supercurrents (SQUIDs)	6	Heating of Intergalactic medium (IGM)	0
Spontaneous X-ray emission from Ge	-2	Heating of protons in the universe	4
Proton decay	10	Heating of Interstellar dust grains	7

S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

Present day technology allows for meaningful tests

One has to be careful in reading the table

Laboratory experiments	Distance (orders of magnitude) from Adler's value for λ	Cosmological data	Distance (orders of magnitude) from Adler's value for λ
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Proton decay	10	Heating of Interstellar dust grains	7

It depends on the type of noise

STILL THE BEST

(and people are investing money)

?

They all assume that no dissipative effects take place.

Quantum oscillating systems

M. Bahrami, S. Donadi, L. Ferialdi, A. Bassi, C. Curceanu, A. Di Domenico, B. Hiesmayr, *Nature Sci. Reports (2013)*

Some systems which naturally oscillate: neutrinos, kaons, chiral molecules

They offer natural tests for collapse models CSL predictions:

NEUTRINOS	cosmogenic	solar	laboratory
E (eV)	19^{19}	10^{6}	10^{10}
t (s)	3×10^{18}	5×10^{2}	2×10^{-2}
Λt	2×10^{-55}	4×10^{-45}	2×10^{-57}

J. Christian, *Phys. Rev. Lett.* 95, 160403 (2005)

Damping rate (how interference terms are suppressed): $\mathbf{e^{-\Lambda t}}$

MESONS	K-mesons	B-mesons	B_s-mesons	D-mesons
Λ (Hz)	1.5×10^{-38}	1.4×10^{-34}	1.7×10^{-31}	3.2×10^{-37}

CHIRAL MOLECULES	SOR_1R	SOR_2R	SOR_3R	SOR_4R
m (amu)	154	216	316	340
Λ (Hz)	$10^{-9.2}$	$10^{-9.1}$	$10^{-8.6}$	$10^{-8.3}$

Gravity induced collapse?

Quantum fields + gravity (semi-classical limit) + non-relativistic limit

Schrödinger-Newton equation:

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left(-\frac{\hbar^2}{2m}\frac{\partial^2}{\partial x^2} - Gm^2\int\frac{|\psi(y,t)|^2}{|x-y|}dy\right)\psi(x,t)$$

D. Giulini and A. Grossardt, *Class. Quantum Grav.* 29, 215010 (2012) and references therein

Nonlinear deterministic equation. It collapses the wave function in space (in which precise sense?), but allows for superluminal signaling

Diosi-Penrose model

$$\frac{d}{dt}\hat{\rho} = -\frac{i}{\hbar}[\hat{H},\hat{\rho}] - \frac{\mathrm{G}}{2\hbar}\int\int\frac{d\mathbf{r}\,d\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|}[\hat{f}(\mathbf{r}),[\hat{f}(\mathbf{r}'),\hat{\rho}]] \qquad \hat{f}(\mathbf{r}) = \frac{M}{V}\theta(R-|\hat{\mathbf{q}}-\mathbf{r}|)$$

L. Diosi, *J. Phys. A* 21, 2885 (1988); *Phys. Lett. A* 129, 419 (1988). R. Penrose, *Gen. Rel. Grav*. 28, 581 (1996)

Good collapse equation. However it diverges. A (large) cutoff is needed

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