Spontaneous wave function collapse models and the limits of quantum mechanics

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- Collapse models – some general features
- The CSL model
- Possible extensions
- Phenomenology – lower and upper bounds
- Open problems

Collapse Models

Idea: To modify the Schrödinger equation in order to induce the collapse of the wave function dynamically. **The wave function is coupled nonlinearly to a random noise.**

There are several constraints to be obeyed.

1. Quantum coherence must be preserved for microscopic and mesoscopic systems.
2. Macroscopic objects must behave classical-like -> their wave function must be always well localized in space.
3. In measurement processes, they must explain uniqueness of outcomes.
4. They must reproduce the Born probability rule.
5. They must be nonlocal (violation of Bell's inequalities), but at the same time they must not allow for superluminal signaling.

The CSL Model

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

GRW hitting model + Pearle's gambler's ruin game

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

Quantum Hamiltonian

NEW TERMS → **New Physics**

- $N(\mathbf{x}) = a^\dagger(\mathbf{x})a(\mathbf{x})$ particle density operator, $\langle N(\mathbf{x})\rangle_t = \langle\psi_t|N(\mathbf{x})|\psi_t\rangle$

→ **nonlinearity**

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

→ **stochasticity**

$r_C = 1/\sqrt{\alpha} \sim 10^{-5}$ cm correlation length of the noise

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

Mass proportional CSL model: $\lambda \longrightarrow \lambda\left(\frac{m}{m_N}\right)^2$, $m_N =$ nucleon mass

Possible extensions

	Markovian models (white noise) **All frequencies appear with the same weight**	**non-Markovian models (colored noise)** **The noise can have an arbitrary spectrum**
Models without dissipation (q-coupling) **Only the noise acts on the wave function**	**GRW / CSL** **QMUPL** L. Diosi, *Phys. Rev. A* 40, 1165 (1989).	**non-Markovian CSL** P. Pearle, in *Perspective in Quantum Reality* (1996) S.L. Adler and A. Bassi, *Journ. Phys. A* 41, 395308 (2008). arXiv: 0807.2846 **non-Markovian QMUPL** A. Bassi and L. Ferialdi, *arXiv: 0901.1254*
Models with dissipation ([q+ip]-coupling) **Noise and wave function act on each other**	**Thermal QMUPL model** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083	? **The "true" model?**

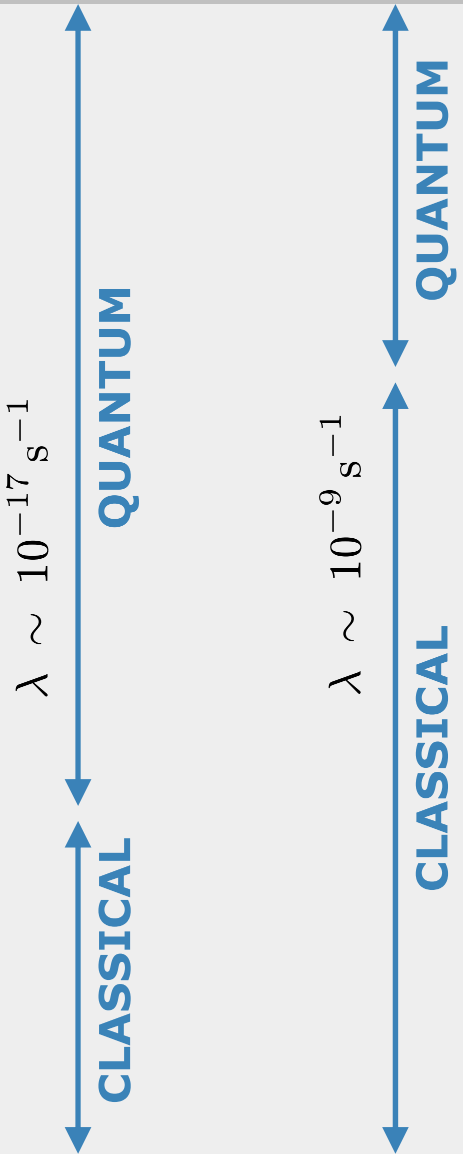
Importance of collapse models

1. **Collapse models as a solution of the measurement problem of Quantum Mechanics.** These models offer a paradox-free description of quantum measurements (and not only).

2. **Collapse models as a rival theory of Quantum Mechanics.** This is necessary in order to give a quantitative meaning to experiments testing quantum mechanics. They are alternative theory, which makes different predictions, to which these experiments can be compared.

3. **Collapse models as phenomenological models of an underlying pre-quantum theory.** If quantum mechanics is not exact, and spontaneous collapse-type effects are seen in experiments, these model may offer a direction to look for a new theory.

Lower bounds



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

QUANTUM

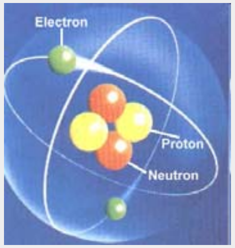
CLASSICAL

$\lambda \sim 10^{-9} \mathrm{s}^{-1}$

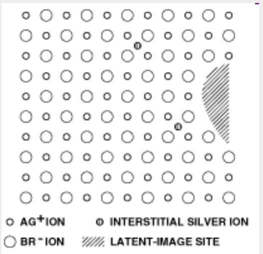
QUANTUM

CLASSICAL

Microscopic world
(few particles)

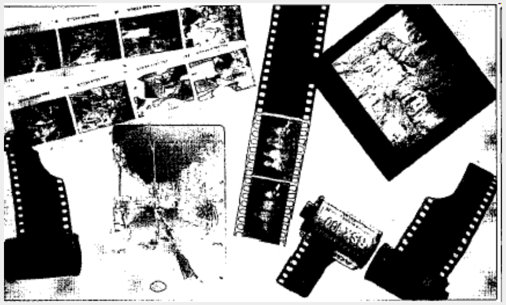


Latent image formation
(~ 5-6000 nucleons)



$$\begin{aligned}\gamma + AgBr &\to Ag^+ + Br^- \\ &\to Ag^+ + Br + e^- \quad (e^- \text{ trapped by a grain}) \\ &\to Ag + Br \quad (Ag \text{ trapped by a grain})\end{aligned}$$

Macroscopic world
(10^{23} particles)

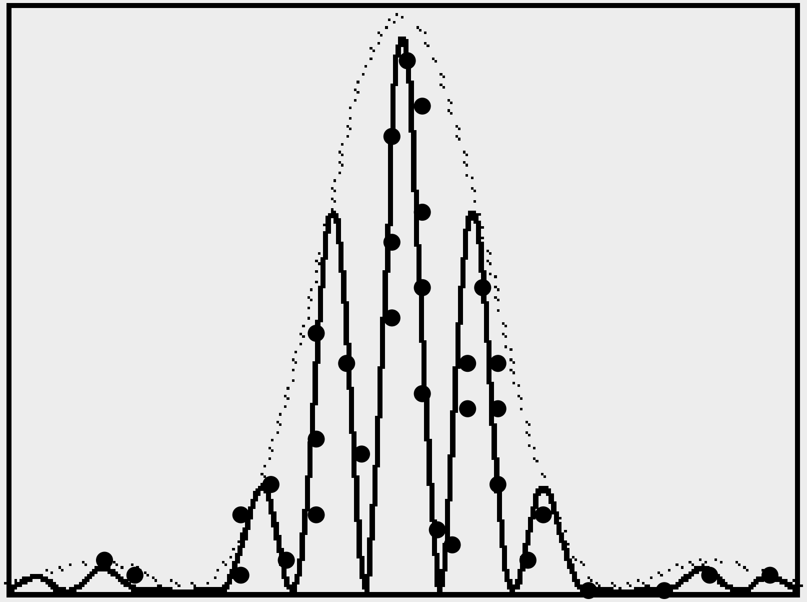


Upper bounds 1.a

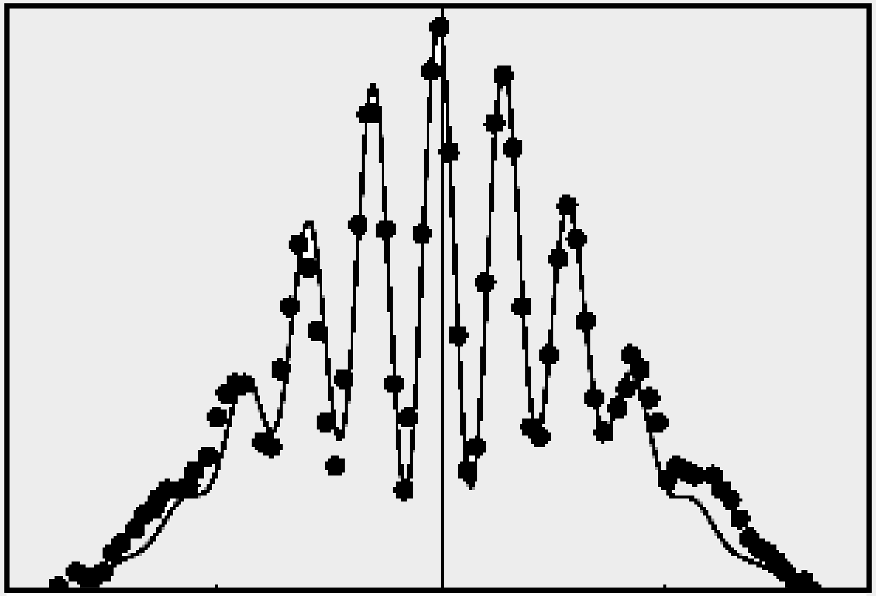
Destruction of quantum interference

The nonlinear terms work against the superposition principle.

In interference experiments, one should see a reduction of interference fringes



Prediction of quantum mechanics
(no environmental noise)



Prediction of collapse models
(no environmental noise)

Upper bounds 1.b

Destruction of quantum interference

Diffraction of macro-molecules:

- **C_{60} (720 AMU)**

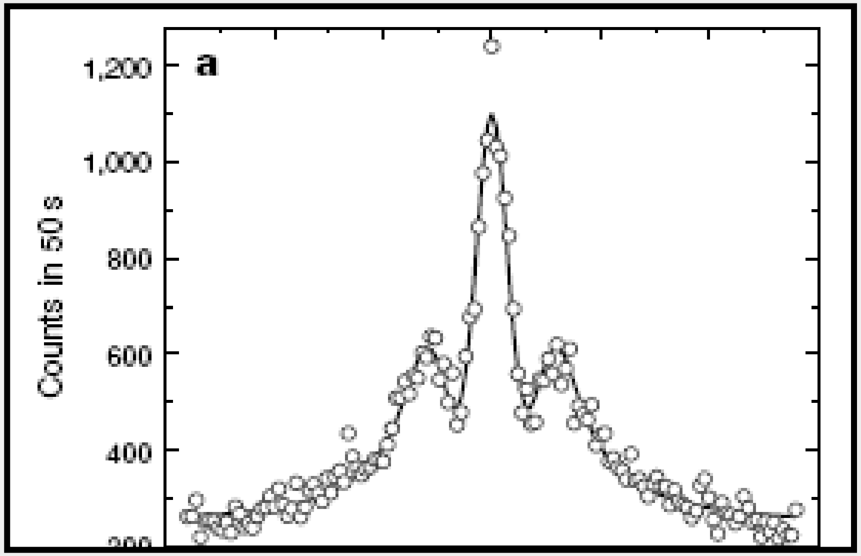
  M. Arndt et al, *Nature* 401, 680 (1999)

- **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)



C_{60} diffraction experiment

Future experiments

They include much larger molecules (~11,000 a.m.u., possibly up to **1,000,000 a.m.u.**). A three orders of magnitude increase in the number of particles would become interesting

	Distance (orders of magnitude) from the standard CSL value	Distance (orders of magnitude) from the enhanced value
Diffraction of macro-molecules	**13**	**5**

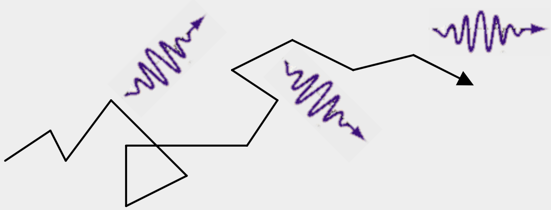
Upper bounds 2.a

Spontaneous emission of radiation

FREE PARTICLE

1. Quantum mechanics

2. Collapse models

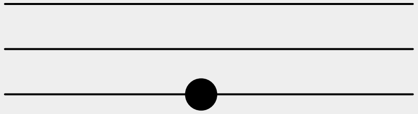


$$\frac{d\Gamma_k}{dk} = \frac{e^2 \lambda \hbar}{2\pi^2 \epsilon_0 m^2 c^3 k}$$

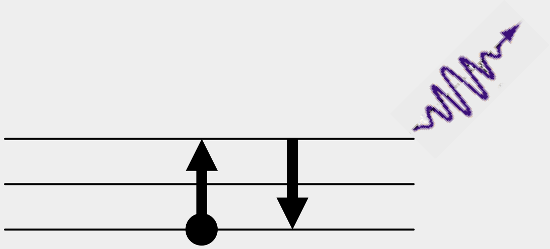
Q. Fu, *Phys. Rev. A* 56, 1806 (1997)

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)

Upper bounds 2.b

Spontaneous emission of radiation

Comparison with experimental data

➡

The original GRW and CSL models are ruled out!

However, in a **mass-proportional** model (noise having a gravitational origin?), one assumes

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

which implies, for example:

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

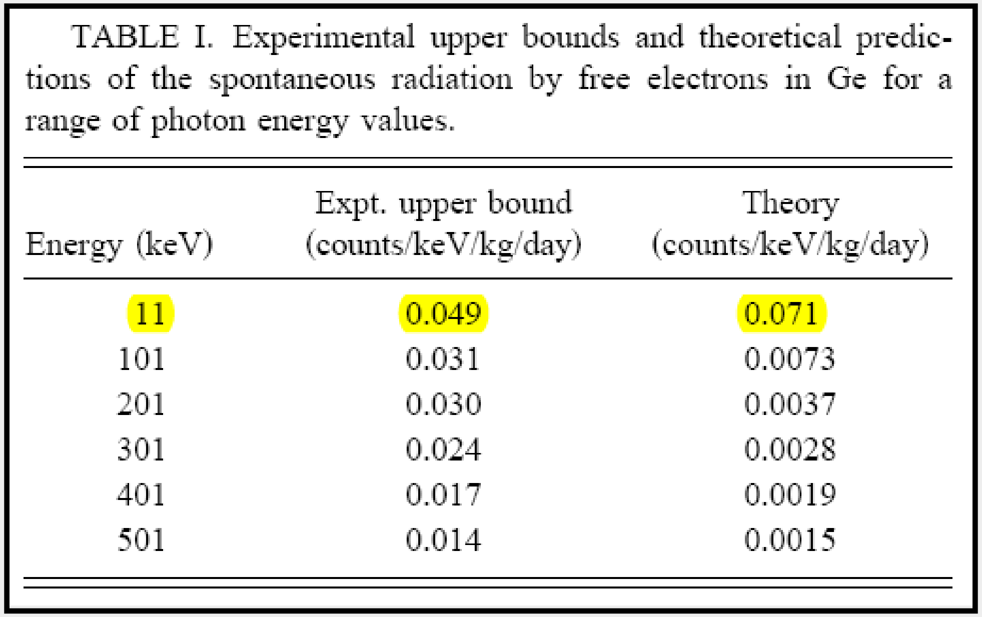


TABLE I. Experimental upper bounds and theoretical predictions of the spontaneous radiation by free electrons in Ge for a range of photon energy values.

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

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

➡ **Compatibility is restored**

Upper bounds 2.c

Spontaneous emission of radiation

Current upper bound on the *mass proportional CSL model*, coming from spontaneous X-ray emission

So far, this is the strongest known upper bound.

If one takes non-white noises into account (non-Markovian dynamics)

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

	Distance (orders of magnitude) from the standard CSL value	Distance (orders of magnitude) from the enhanced value
Spontaneous X-ray emission from Ge	**6**	**-2**

γ is the 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 $c\alpha^{1/2}$ ~ 10^{15} s^{-1}

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

Upper bounds on the parameter λ

Laboratory experiments	Distance (in orders of magnitude) from standard CSL value	Cosmological data	Distance (in orders of magnitude) from standard CSL value
Fullerene diffraction experiments	**13**	Dissociation of cosmic hydrogen	**17**
Decay of supercurrents (SQUIDs)	**14**	Heating of Intergalactic medium (IGM)	**8**
Spontaneous X-ray emission from Ge	**6**	Heating of protons in the universe	**12**
Proton decay	**18**	Heating of Interstellar dust grains	**15**

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

Note. Reducing the numbers by about 8 orders of magnitude gives the distance of each bound from the enhanced value of λ obtained if one assumes that latent image formation constitutes measurement. This value is excluded by the upper bound coming from the spontaneous X-ray emission from Ge. Compatibility is restored when non-Markovian effects are taken into account.

A dedicated experiment

Spontaneous X-ray emission from Ge offers the strongest upper bound.

This suggests that a **dedicated experiment** which tests collapse models, thus the superposition principle of Quantum Mechanics, should look in this direction.

Main difficulty: one needs to isolate the experimental setup very well.

Solution: underground experiment.

Collaboration with the INFN-LNF laboratories in Frascati, which have also underground facilities (Gran Sasso).

Open questions

1. Collapse models assume the existence of a **random field filling space.** What is the origin of such a field? Does it have a **gravitational** nature? Can it be connected e.g. to **dark energy/matter?**

   (S.L. Adler and A. Bassi: *J. Phys. A* 41, 395308, 2008)

2. The coupling between the random field and the wave function is **anti-Hermitian**: what is the origin of this non-standard coupling? Could it be cosmological?

3. Collapse models appear as **phenomenological models of an underlying pre-quantum theory**: what does this theory look like?

   (Adler, "Quantum Theory as an Emergent Phenomenon", C.U.P. 2004)

4. What are the most promising **experiments**, which can detect possible violations of quantum mechanics, as predicted by collapse models?

   (*Sience*, 1st July issue, 2005)