Is Quantum Theory Exact? The endeavor for the theory beyond standard quantum mechanics – Frascati 28 – 30 April 2014

Collapse Models: introduction and overview

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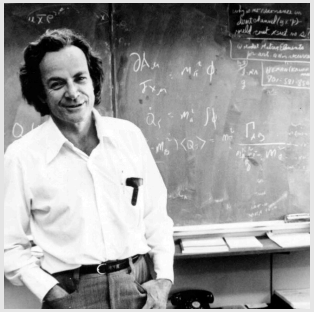
Shut up and calculate?



Does this mean that my observations become real only when I observe an observer observing something as it happens? This is a horrible viewpoint. Do you seriously entertain the thought that without observer there is no reality? Which observer? Any observer? Is a fly an observer? Is a star an observer? Was there no reality before 109 B.C. before life began? Or are you the observer? Then there is no reality to the world after you are dead? I know a number of otherwise respectable physicists who have bought life insurance. By what philosophy will the universe without man be understood?

It would seem that the theory is exclusively concerned about "results of measurement", and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of "measurer"? Was the wavefunction of the world waiting to jump for thousands of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system [...] with a Ph.D.? If the theory is to apply to anything but highly idealized laboratory operations, are we not obliged to admit that more or less "measurement-like" processes are going on more or less all the time, more or less everywhere? Do we not have jumping then all the time?

The Copenhagen interpretation assumes a mysterious division between the microscopic world governed by quantum mechanics and a macroscopic world of apparatus and observers that obeys classical physics. During measurement the state vector of the microscopic system collapses in a probabilistic way to one of a number of classical states, in a way that is unexplained, and cannot be described by the time-dependent Schrödinger equation [...] Faced with these perplexities, one is led to consider the possibility that quantum mechanics needs correction

Beyond measurements and observers

It is clear that measurements on microscopic systems are unavoidably invasive, because micro-systems are small

Therefore measurements do not reveal the properties the system possessed before the measurement. They are the result of the interaction between the system and the apparatus

Nonetheless, Copenhagen's dogma according to which it is not possible, or does not make sense, to talk about the properties a systems possesses independently of measurements, does not make sense. Worse than this, this attitude has blocked scientific research

Research in quantum foundations – in spite of Copenhagen – proved (at least) two important points:

- It is possible to formulate a "quantum theory without observers"
- Deeper understanding of Nature is unraveled (nonlocality …)

Which quantum theory without observers?

Answering this question corresponds to answering the following questions: what is the role of the wave function?

Option 1: The wave function is only a tool for computing probabilities. Reality lies somewhere else (Einstein’s idea). Particles are not really described by the wave function. They are described, for example, by points moving in space ➔ Bohmian mechanics

- Non locality and Bell inequalities
- The wave function is “real” (M. Pussey, J. Batterr & T. Rudolph, *Nat. Phys. 8, 475 (2012)*)

Option 2: The wave function does describe physical reality (Schrödinger’s idea). Particles are waves (wave packets). Collapse is real ➔ Collapse models

- No-faster-than-light signaling poses severe constraints on the form of collapse
- It is possible to modify the Schrödinger equation. Experimental research is very active

Collapse models

1986: GianCarlo Ghiardi, Alberto Rimini, Tullio Weber (GRW)
1990: GianCarlo Ghirardi, Philip Pearle, Alberto Rimini (CSL)

Idea: The wave function directly describes matter. Matter has a wavy nature. When measured, the wave function collapses. Collapses occur more or less all the time, more or less everywhere. They are a property of Nature. Measurements amplify them, because apparatuses are big.

- Modify the Schrödinger equation, to include the collapse
- Negligible effect on the dynamics of micro systems
- Effective collapse for macro objects ➔ amplification mechanics

Important: Their predictions differ from standard quantum predictions. Contrary to all other alternatives, **they can be tested experimentally**.

Collapse models

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)	**White noise models** All frequencies appear with the same weight	**Colored noise models** 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** A. Bassi, E. Ippoliti and B. Vacchini, *J. Phys. A* 38, 8017 (2005). ArXiv: quant-ph/0506083 **Dissipative GRW & CSL** A. Smirne, B. Vacchini & A. Bassi (*in progress*)	**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**

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

choice of the preferred basis

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

nonlinearity

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

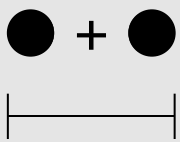
stochasticity

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

two parameters

Collapse rate

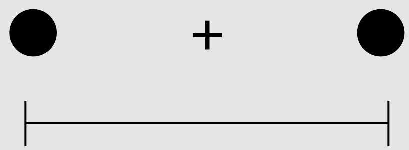
Small superpositions



$\ll r_C$

Collapse NOT effective

Large superpositions

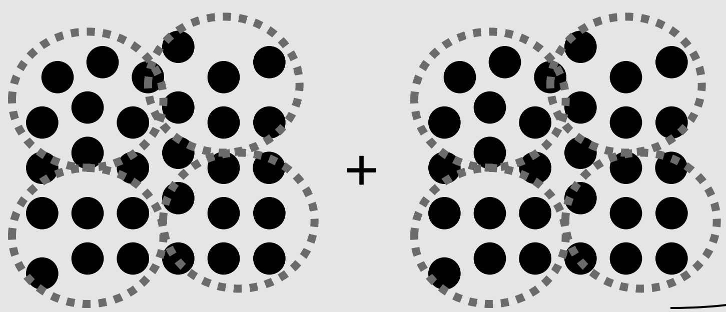


$\geq r_C$

Collapse effective

↓

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



n = number of particles within r_C

N = number of such clusters

Amplification mechanics

Few particles

no collapse

quantum behavior

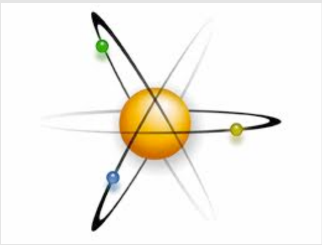
Many particles

Fast collapse

classical behavior

Which values for λ and r_c?

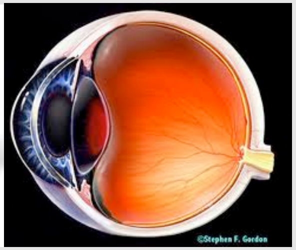
Microscopic world
(few particles)



$$\lambda \sim 10^{-8\pm 2}\mathrm{s}^{-1}$$

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)

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

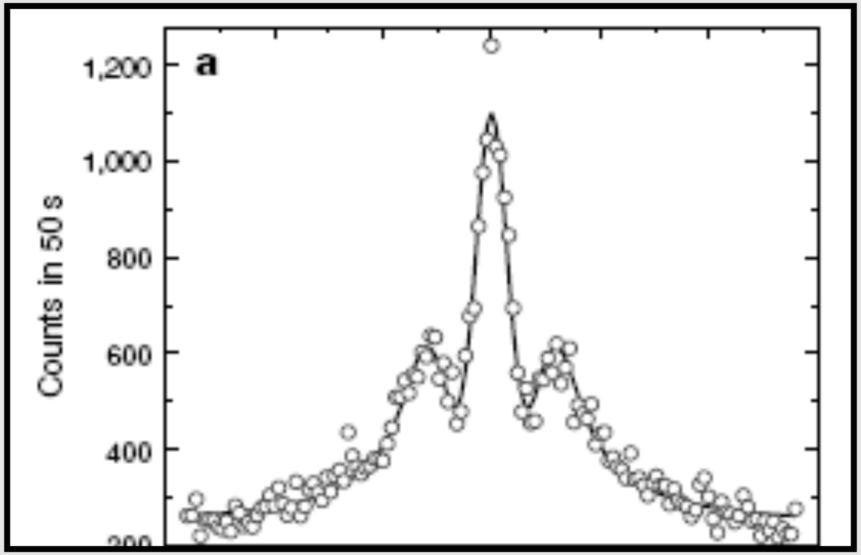
Increasing size of the system

Constraints from Experiments

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)**
  S. Eibenberger *et al.* PCCP 15, 14696 (2013)



C_{60} diffraction experiment

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

Future experiments: ~10^6 AMU
K. Hornberger *et al.*, Rev. Mod. Phys. 84, 157 (2012)
P. Haslinger *et al.*, Nature Phys. 9, 144 (2013)

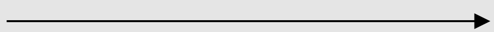
Outer space for higher masses?

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)

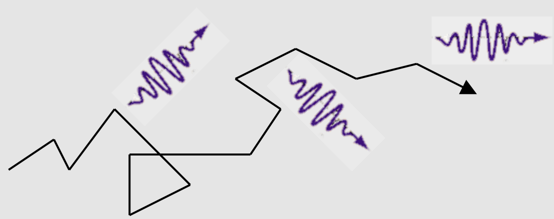
Spontaneous photon emission

FREE PARTICLE

1. Quantum mechanics

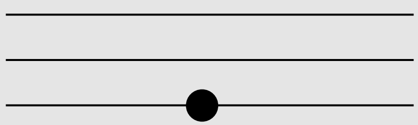


2. Collapse models

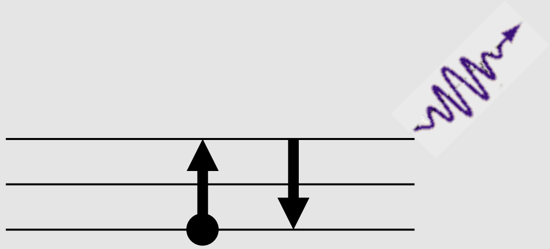


BOUND STATE

1. Quantum mechanics



2. Collapse models



1. One needs to introduce mass proportionality in the model
2. Adler’s value for λ is ruled out by 2 orders of magnitude, unless the noise spectrum has a cut off

The emission rate (CSL, perturbation theory)

$$\frac{d\Gamma_k}{dk} = \frac{\lambda \hbar e^2}{4\pi^2 \epsilon_0 c^3 m_0^2 r_C^2 k} \left[\tilde{f}(0) + \tilde{f}(\omega_k) \right]$$

$\tilde{f}(\omega)$ = Fourier transform of the correlation function of the noise

Q. Fu, Phys. Rev. A 56, 1806 (1997)
Formula without "factor 2", for a free particle, according to the CSL model (perturbation expansion)

S.L. Adler and F.M. Ramazanoˇglu, J. Phys. A 40, 13395 (2007)
Formula confirmed and generalized to hydrogenic atoms (CSL model, perturbation expansion)

A. Bassi and D. Duerr, J. Phys. A 42, 485302 (2009)
Formula with the *"factor 2", for a free particle, according to the QMUPL model (exact)*

S.L. Adler, A. Bassi and S. Donadi, J. Phys. A 46, 245304 (2013)
The "factor 2" is unphysical, it vanishes with more realistic assumptions (perturbative approach, CSL)

A. Bassi and S. Donadi, Phys. Lett. A 378, 761-765 (2014)
The "factor 2" is unphysical (exact calculations, QMUPL model)

S. Donadi, D.-A. Deckert and A. Bassi, Annals of Physics 340, 70-86 (2014)
The "factor 2" vanishes, when e.m. field treated exactly (CSL, perturbation expansion only for noise)

The correct (perturbative) result

S. Donadi and A. Bassi (in preparation)

The message so far

1. To derive the right formula, one cannot stop to first order perturbation theory in the e.m. field

2. Only special cases can be treated to higher perturbative order (the number of Feynman diagrams rapidly becomes unmanageable)

Solution

Higher order terms in the e.m. field can be easily taken care of, by considering complex shifts in the energy levels: $\Delta E \longrightarrow \Delta E + i\hbar\Gamma$

Result

$$\frac{d\Gamma}{dk} = \sum_{\lambda} \int d\Omega_k \frac{\gamma}{\hbar^2} \sum_{f} \left| \sum_{n} \frac{\langle f \left| R_k \right| n \rangle \langle n \left| N_i \right| i \rangle}{\left[i \left(\triangle_{fn} + \omega_k \right) - \Gamma_n \right]} - \frac{\langle f \left| N_i \right| n \rangle \langle n \left| R_k \right| i \rangle}{\left[i \left(\triangle_{ni} + \omega_k \right) + \Gamma_n \right]} \right|^2 \tilde{f} \left(\triangle_{fi} + \omega_k \right)$$

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 ➔ for dissipative models, everything will change

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

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

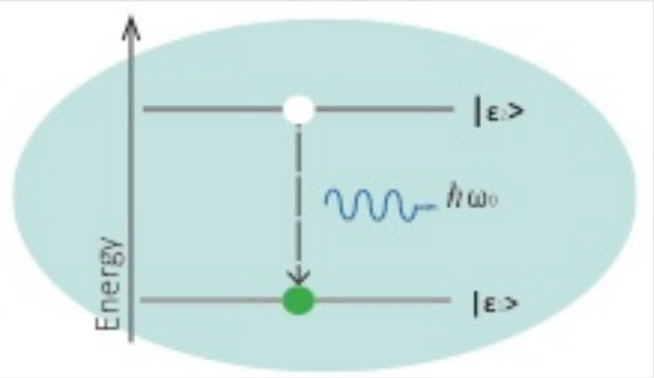
S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

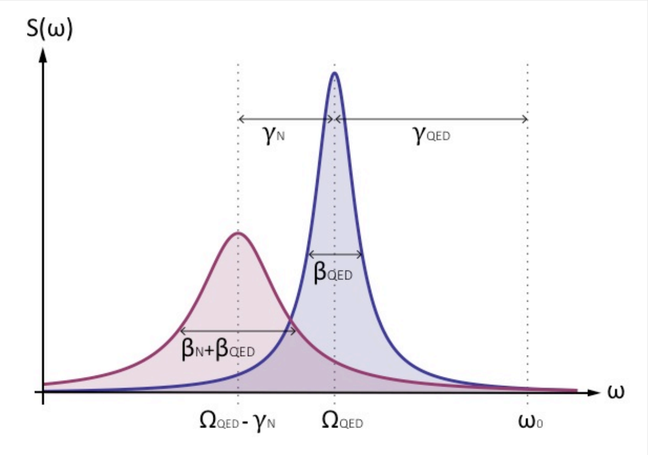
Collaboration with C. Curceanu

Collaboration with H. Ulbricht & M. Arndt

Testing collapse in the frequency domain

M. Bahrami, A. Bassi and H. Ulbricht, *Phys. Rev. A* **89,** 032127 (2014)





The noise responsible for the collapse of the wave function, generates an extra Lamb shift and broadening. Lamb shift is negligible, while broadening can be measured

System	$\beta_{\rm N}$ (Hz)	$\gamma_{\rm N}$ (Hz)
Hydrogen-like Atoms	$10^{-20} - 10^{-18}$	$\sim 10^{-53}$
Harmonic oscillator	$\frac{3\Lambda}{4}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{32\omega_0}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^4$
$\mu = 1\,\text{amu and}\ \omega_0 = 10^{10}\text{Hz}$	5.3×10^{-13}	6.2×10^{-36}
$\mu = 10^7\,\text{amu and}\ \omega_0 = 1.7 \times 10^8\text{Hz}$	3.1×10^{-4}	1.3×10^{-16}
Double-well	$\frac{\Lambda}{8}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{128\,\omega_0}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^4$
$\mu = m_e = 5.5 \times 10^{-4}\,\text{amu and}\ q_0 = 1\text{Å}$	4.2×10^{-23}	$10^{-57} - 10^{-55}$
$\mu = 1\,\text{amu and}\ q_0 = 1\text{Å}$	1.4×10^{-16}	$10^{-44} - 10^{-42}$
$\mu = 10^7\,\text{amu and}\ q_0 = 1\text{Å}$	0.014	$10^{-16} - 10^{-18}$

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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THE GROUP

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