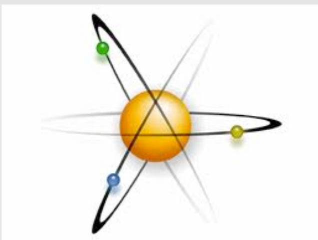
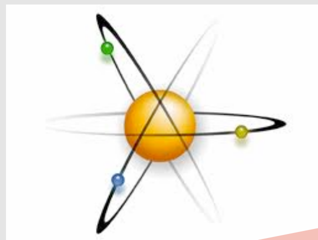
Questioning Fundamental Physical Principles
CERN – 6-9 May 2014

Recent Developments in Collapse Models

Angelo Bassi - University of Trieste & INFN - Italy

The measurement problem of quantum mechanics

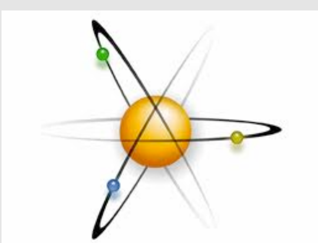
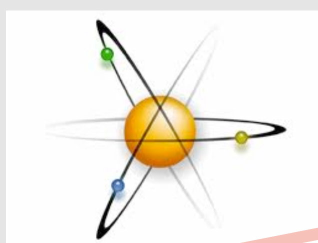
The Schrödinger equation is linear ➔ superposition principle

 + 

Approved!

What?

But in real life

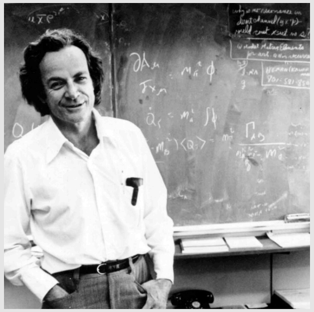
 + 

Approved!

OR

Of course!

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 10^9 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

Collapse models

A. Bassi and G.C. Ghirardi, *Phys. Rept.* 379, 257 (2003) A. Bassi *et al., Rev. Mod. Phys.* 85, 471 (2013)

The general structure is

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

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

New physical effects

Which kind of operators?

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

NOTE: The Born rule comes out automatically

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 $\longrightarrow$ **New Physics**

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

choice of the operators

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

nonlinearity

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

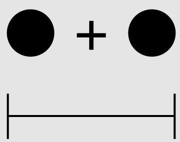
stochasticity

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

two parameters

Collapse rate

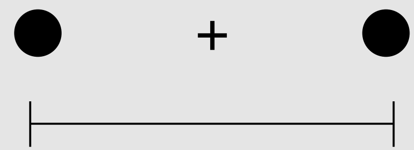
Small superpositions



$\ll r_C$

Collapse NOT effective

Large superpositions



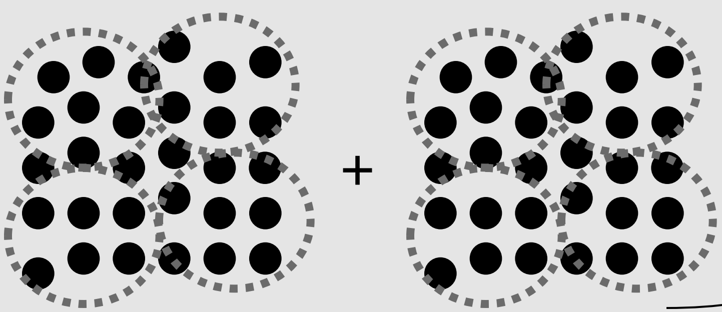
$\geq r_C$

Collapse effective

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

n = number of particles within r_C

N = number of such clusters



Amplification mechanics

Few particles

no collapse

quantum behavior

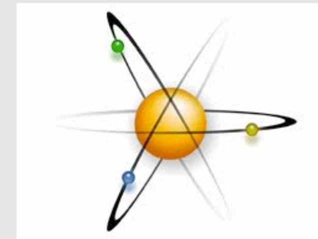
Many particles

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)

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

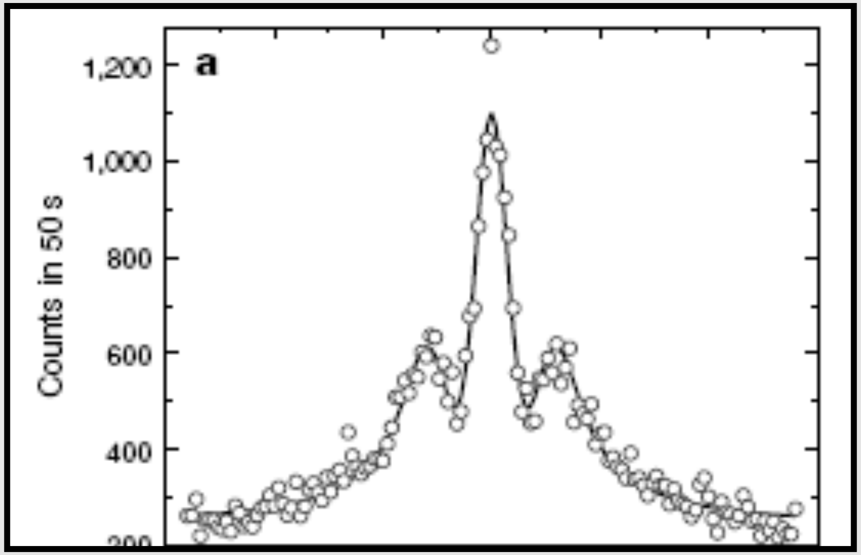
Increasing size of the system

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?

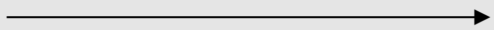
ALSO:
Micro-mirrors, nano-spheres
Marshall, W., et al., *Phys. Rev. Lett.* 91, 130401 (2003)
Romero-Isart, O., et al., *Phys. Rev. A* 83, 013803 (2011)

Spontaneous photon emission

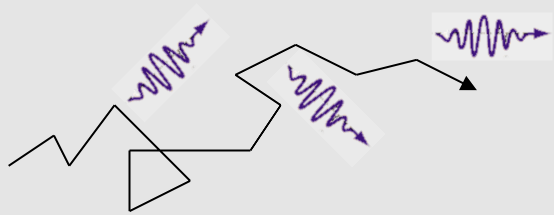
S. Donadi, D.-A. Deckert, A. Bassi, *Ann. Phys.* 340, 70 (2014) and references therein

FREE PARTICLE

1. Quantum mechanics

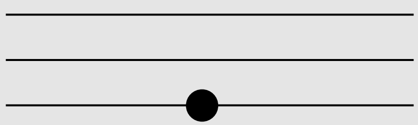


2. Collapse models

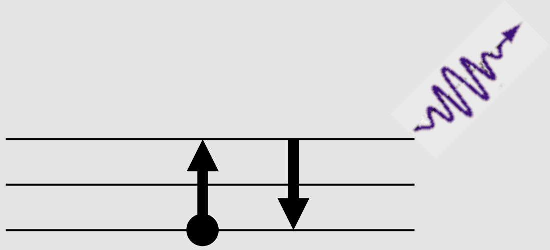


BOUND STATE

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

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

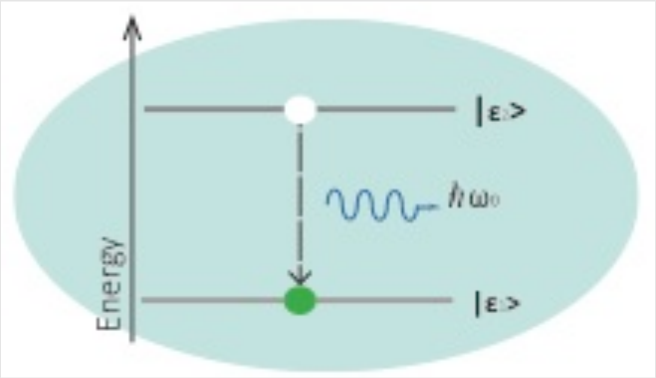
S.L. Adler and A. Bassi, *Science* 325, 275 (2009)

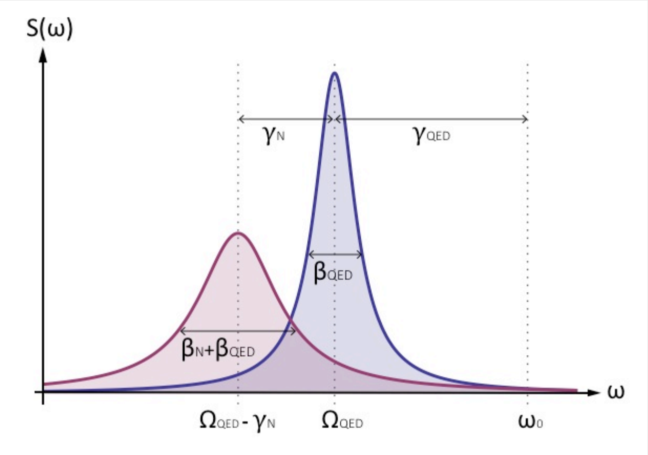
Collaboration with C. Curceanu

Collaboration with M. Arndt & H. Ulbricht

Testing collapse in the frequency domain

M. Bahrami, A. Bassi, H. Ulbricht, *PRA* **89,** 032127 (2014). M. Bahrami, M. Paternostro, A. Bassi, H. Ulbricht, Phys. Rev. Lett. to appear





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	$\frac{3\Lambda}{4}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{32\omega_0}\left(\frac{\mu\, x_0}{m_0\, r_C}\right)^4$
$\mu = 1\,$amu and $\omega_0 = 10^{10}$Hz	5.3×10^{-13}	6.2×10^{-36}
$\mu = 10^7\,$amu and $\omega_0 = 1.7 \times 10^8$Hz	3.1×10^{-4}	1.3×10^{-16}
Double-well	$\frac{\Lambda}{8}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^2$	$\frac{\Lambda^2}{128\,\omega_0}\left(\frac{\mu\, q_0}{m_0\, r_C}\right)^4$
$\mu = m_e = 5.5 \times 10^{-4}\,$amu and $q_0 = 1$Å	4.2×10^{-23}	$10^{-57} - 10^{-55}$
$\mu = 1\,$amu and $q_0 = 1$Å	1.4×10^{-16}	$10^{-44} - 10^{-42}$
$\mu = 10^7\,$amu and $q_0 = 1$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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- Graduate students: M. Carlesso, M. Caiaffa, L. Cimbaro

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