

Collapse Models and the limits of Quantum Mechanics

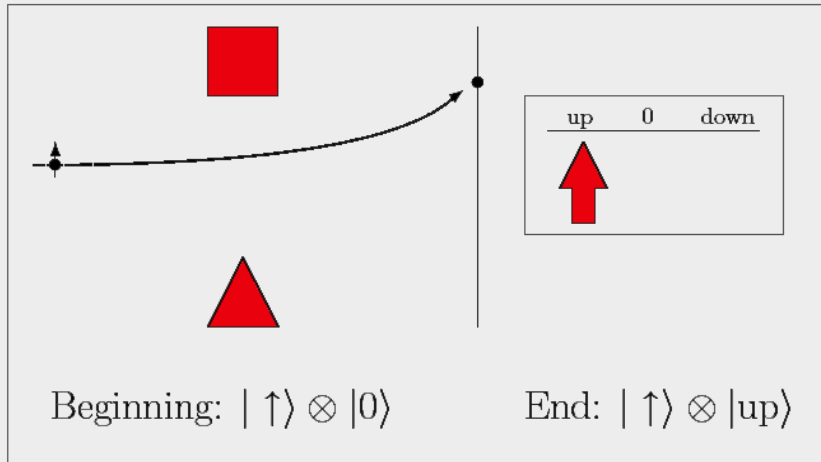
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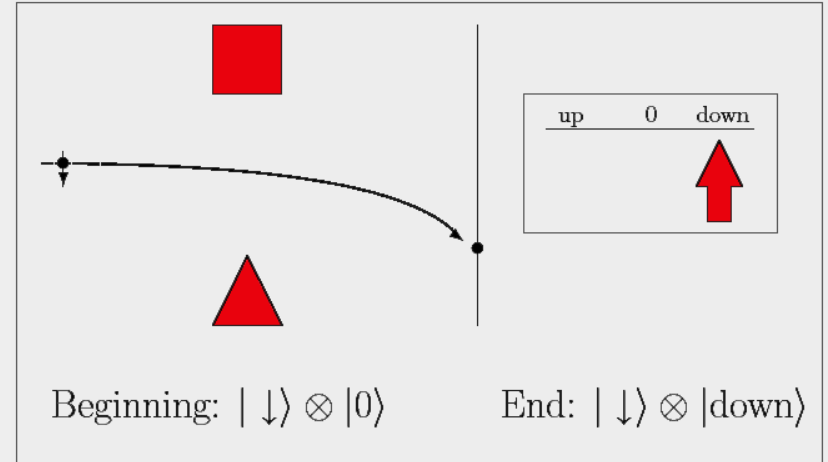
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The measurement problem



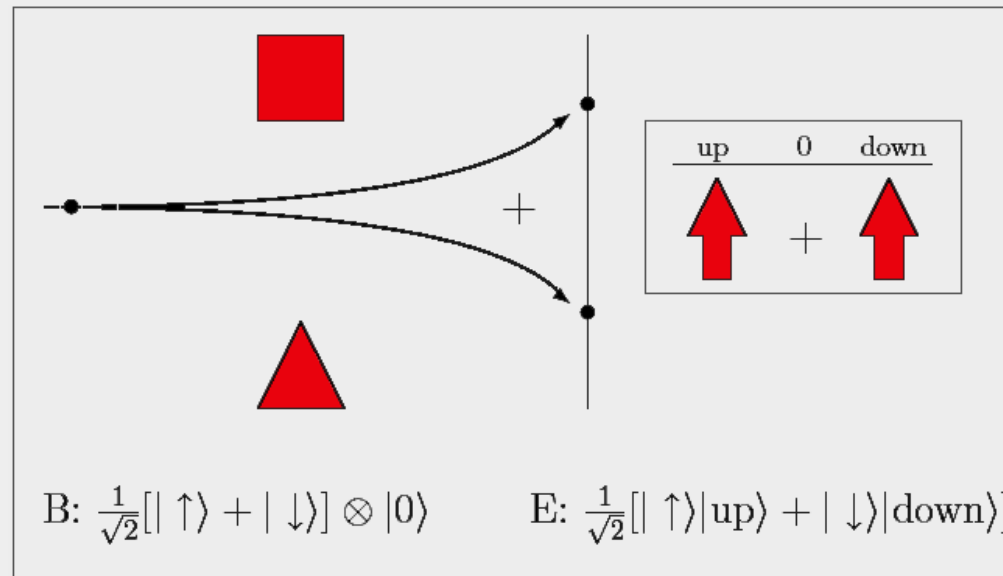
**FIRST
MEASUREMENT**



**SECOND
MEASUREMENT**

If quantum mechanics is universal

use the **linearity** of the Schrödinger equation



Problem: how do we interpret superpositions of different macroscopic states?

The “official” solution

postulate of wave packet reduction

“... A **measurement** always causes the system to jump into an eigenstate of the dynamical variable that is being measured ...”

(P.A.M. Dirac: “Quantum Mechanics”, Oxford University Press, 1930)

“We therefore have two fundamentally different types of interactions which can occur in a system ... first, the arbitrary changes by **measurements** ...”

(J. von Neumann: “Mathematical Foundations of Quantum Mechanics”, Princeton University Press, 1932)

$$\frac{1}{\sqrt{2}} [|\uparrow\rangle \otimes |\text{up}\rangle + |\downarrow\rangle \otimes |\text{down}\rangle]$$



$$50\% \quad |\uparrow\rangle \otimes |\text{up}\rangle$$

$$50\% \quad |\downarrow\rangle \otimes |\text{down}\rangle$$

The problem is still there

problems with the postulate of wave packet reduction

1. Two “fundamentally different” types of interactions.
 - A) **Schrödinger equation**: linear, deterministic, reversible.
 - B) **Wave packet reduction**: non-linear, stochastic, irreversible.
2. When does wave packet reduction apply, in place of the Schrödinger evolution?



MEASUREMENT PROBLEM

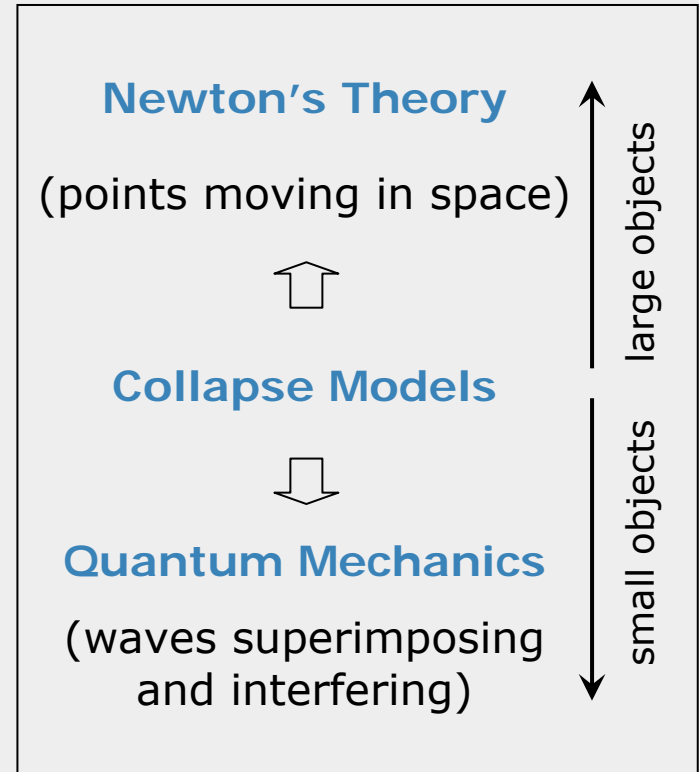
«It would seem that the theory is exclusively concerned about ‘results of measurements’, and has nothing to say about anything else. What exactly qualifies some physical systems to play the role of ‘measurer’? Was the wave function of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system ... with a Ph.D.?» “Against Measurement”, Physics Today – August 1990.



Collapse Models

The **idea** is to **modify the Schrödinger equation**, in order to include the process of wave function collapse into the dynamics. In particular:

1. For **microscopic systems**, the wave function must behave like Schrödinger's wave function: it must **diffuse, superimpose, interfere, ...**
2. For **macroscopic objects**, the wave function must be always well localized in space and behave like **a point moving according to Newton's laws**.
3. In a measurement situation, one recovers **quantum probabilities** and the **postulate of w.p. reduction**.



It is not clear at all, beforehand, that such a program can be fulfilled!

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

How should one modify the Schrödinger equation?

1. The modification must be **nonlinear**, since we want to avoid the superposition of different macroscopic terms at the macroscopic level.
#Gisin: non-linear deterministic modifications do faster-than-light.
2. The modification must be **stochastic**, since these models must recover quantum indeterminism.
#Stochasticity must be able to:
 - i) circumvent Gisin's theory;
 - ii) reproduce quantum probabilities.
3. There must be an **amplification mechanism**: the modification must be quite **irrelevant on microscopic scales**, and quite **strong on macroscopic scales**, so that at the micro-level the new equation is a Schrödinger-type equation, while at the macro level it is a Newton-type equation.

Most important collapse models

GRW model

(Ghirardi-Rimini-Weber model)

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

Discrete jump processes. Works only for distinguishable particles.

CSL model

(Continuous Spontaneous Localizations)

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

Continuous version of GRW model. Works with identical particles.

QMUPL model

(Quantum Mechanics with Universal Position Localization)

L. Diosi, *Phys. Rev. A* 40, 1165 (1989).

Simplified model but realistic. Very useful for mathematical analysis

The dynamics of Collapse Models

QMUPL model - The a wave function of a system of **N** constituents evolves according to the following stochastic differential equation (SDE)

$$d|\psi_t\rangle = \left[\underbrace{-\frac{i}{\hbar} H_{\text{TOT}} dt}_{\text{Quantum Hamiltonian}} + \underbrace{\sum_{n=1}^N \sqrt{\lambda_n} (q_n - \langle q_n \rangle_t) dW_t^{(n)} - \frac{1}{2} \sum_{n=1}^N \lambda_n (q_n - \langle q_n \rangle_t)^2 dt}_{\text{NEW TERMS}} \right] |\psi_t\rangle$$



New Physics

W_n = Brownian motion, q_n = position operator, $\langle q_n \rangle_t = \langle \psi_t | q_n | \psi_t \rangle$

$\lambda_n \equiv \frac{m_n}{m_0} \lambda_0$ m_0 = nucleon mass

The new physics

Destruction of quantum interference

The nonlinear terms work against the superposition principle.

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

Energy non-conservation

The stochastic terms induce a random motion of particles.

The noise pumps energy into the system.

Spontaneous emission of radiation

The random terms cause particles to fluctuate

Charge particles will emit radiation

Lower bounds on the parameters

With reference to the **QMUPL model**

$$d|\psi_t\rangle = \left[-\frac{i}{\hbar} H_{\text{TOT}} dt + \sum_{n=1}^N \sqrt{\lambda_n} (q_n - \langle q_n \rangle_t) dW_t^{(n)} - \frac{1}{2} \sum_{n=1}^N \lambda_n (q_n - \langle q_n \rangle_t)^2 dt \right] |\psi_t\rangle$$

$$\lambda_n \equiv \frac{m_n}{m_0} \lambda_0 \quad m_0 = \text{nucleon mass}$$

There is one new parameter, which sets the strength of the collapse process. This means that it also sets the **micro-macro threshold**, i.e. the scale at which systems start behaving classically.

GRW choice: $\lambda_{\text{GRW}} = \lambda_0 = 10^{-2} \text{m}^{-2} \text{sec}^{-1}$

Only systems with an Avogadro's number of constituents are rapidly localized

Adler's choice: $\lambda_{\text{Adler}} = 10^{9 \pm 1} \lambda_0$

The collapse should occur already during the process of latent image formation

Upper bounds on the parameters

So far, the phenomenological analysis on collapse models sets the following upper bounds.

FULLERENE DIFFRACTION	DECAY OF SUPERCURRENTS	RADIATION FREE ELECTR.	11KeV PHOTONS FROM Ge	PROTON DECAY
$5 \times 10^{12} \lambda_0$	$10^{14} \lambda_0$	$10^{12} \lambda_0$	$3 \times 10^6 \lambda_0$	$10^{18} \lambda_0$

HYDROGEN DISSOCIATION	HEATING OF PROTONS	IGM	INTER-STAR DUST GRAINS	
$4 \times 10^{17} \lambda_0$	$10^{12} \lambda_0$	$10^{8 \pm 1} \lambda_0$	$10^{15} \lambda_0$	

S.L. Adler, *Journ. Phys. A* 40, 2935 (2007).

Note: Adler's value is not compatible with data from photon emission from Ge. This discrepancy can be overcome by considering non-markovian models

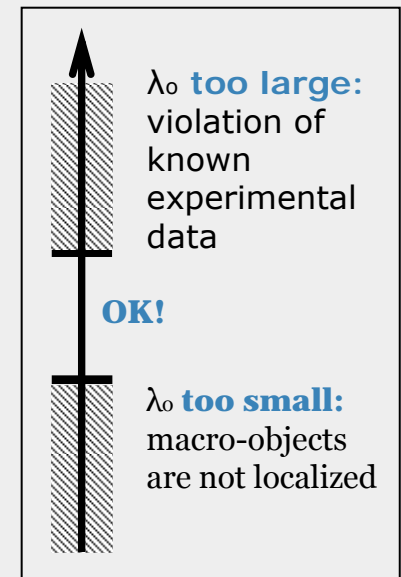
Present status

1. Collapse Models work perfectly well at the **non relativistic level**:
 - a. They agree with standard quantum mechanics within the limits of present-day technology.
 - b. They reduce to classical mechanics for macroscopic systems.
 - c. They consistently describe measurements done on quantum systems, explaining both the Born probability rule and the postulate of wave function collapse.
2. They have been successfully generalized to systems of **identical particles** (non relativistic quantum field theories).

There are still many **open questions** and problems to be solved, at different level of research: mathematical and theoretical physics, phenomenology and experimental physics.

Open questions: phenomenology

1. The analysis of experiment data which sets the **upper bounds** for the collapse parameters is only at the beginning. Much more work needs to be done!
2. What is the most reasonable **lower bound**? As we have seen, there is a difference of 9 orders of magnitude between the GRW value and Adler's value for the collapse parameter
3. How do the upper and lower bounds modified change for **different types of models** (with non-white noises and/or with dissipative effects)?



Open questions: experiments

Which are the most promising experimental situations to look at, in order to detect possible violations of quantum mechanics, as predicted by collapse models?

This is not easy to answer, as the analysis is only at the beginning.

The previous table of upper bounds suggests that the best candidates are not interference experiments (with macro-molecules), but most likely experiments on the spontaneous emission of radiation from charged particles.

A feasibility study of a dedicated experiment of this kind is the goal of the recent collaboration between Trieste (G.C. Ghirardi, A. Bassi) and LNF – Frascati (C. Petrascu, M. Poli Lener).