Realistic quantum field theory from dynamical collapse models

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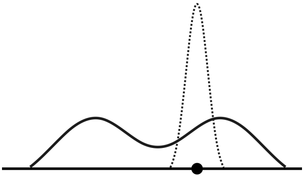

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Objective: provide a new perspective on collapse models to

- extend them to QFT almost trivially
- make them interpretations rather than modifications of quantum mechanics

& say some simple yet not always so well known things about collapse models along the way

I – Introduction:

What are collapse models, what problem do they attempt to solve, and how do they work?

Collapse models

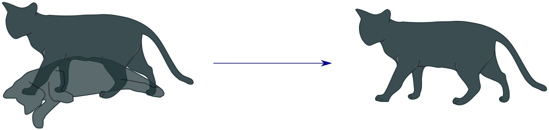
Naive definition

Collapse models are an attempt to solve the measurement problem of quantum mechanics through an *ad hoc*, non-linear, and stochastic modification of the Schrödinger equation.

$$\partial_t |\psi_t\rangle = -iH|\psi_t\rangle + \varepsilon\, f_\xi(|\psi_t\rangle)$$

A few names:

Pearle, Ghirardi, Rimini, Weber, Diósi, Adler, Gisin, Tumulka, Bedingham, Penrose, Percival, Bassi, Ferialdi, Weinberg ...



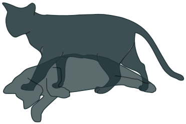
Decoherence

$$\rho = \begin{pmatrix} p & u \\ u^* & 1-p \end{pmatrix} \xrightarrow[\text{decoherence}]{} \begin{pmatrix} p & 0 \\ 0 & 1-p \end{pmatrix}$$

Decoherence :

- Gives a "for all practical purposes" (FAPP) understanding of measurement
- Does not solve the measurement problem without further inputs

Decoherence explains why the dead and live cats do not interfere, but does not (alone) explain why we pick just one.



A toy qubit collapse model

The simplest collapse model ever – inspired from continuous measurement theory:

Toy model

$|\psi_t\rangle \in \mathbb{C}^2$, and collapse in the σ_z basis

$$\partial_t|\psi_t\rangle = \left\{\sqrt{\gamma}\,(\sigma_z - \langle\sigma_z\rangle_t)\,\eta_t - \frac{\gamma}{2}\,(\sigma_z - \langle\sigma_z\rangle_t)^2\right\}|\psi_t\rangle$$

where η_t is white noise (in Itô convention) and γ is a rate.

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where η_t is white noise (in Itô convention) and γ is a rate.

The phase u in the σ_z basis is killed exponentially quickly:

$$\partial u_t = -\frac{\gamma}{8} u_t + \frac{\sqrt{\gamma}}{2}(2p_t - 1)\,\eta_t$$

This is **decoherence**.

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The population $p_t = |\langle 0|\psi_t\rangle|^2$ is decoupled and obeys:

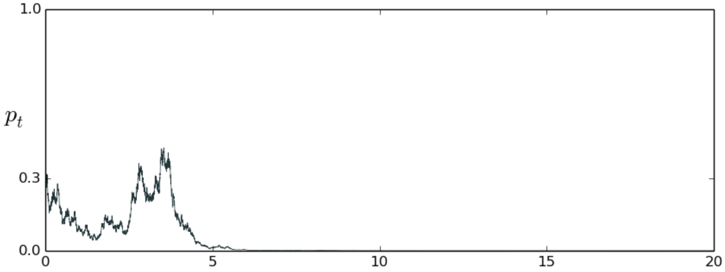
$$\partial p_t = \sqrt{\gamma}\,p_t(1 - p_t)\,\eta_t$$

This is **collapse**

A toy qubit collapse model

If $|\psi_0\rangle = \sqrt{p}|0\rangle + \sqrt{1-p}|1\rangle$, the collapse evolution gives:

$$\partial p_t = \sqrt{\gamma}\, p_t(1 - p_t)\, w_t$$



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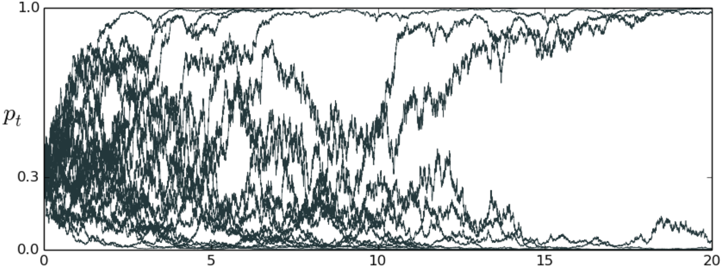

A toy qubit collapse model

Many-body generalization :

- N qubits
- Each qubit collapses at rate $\gamma \ll 1$
- Start in generalized GHZ state

$$|\psi_0\rangle = p\,|0\rangle \otimes \cdots \otimes |0\rangle + \sqrt{1-p}\,|1\rangle \otimes \cdots \otimes |1\rangle$$

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Amplification

The probability p_t obeys:

$$\partial_t p_t = \sqrt{N\gamma}\, p_t(1-p_t)\,\tilde{\eta}_t$$

hence $\gamma \longrightarrow N\gamma$.

The GRW model

GRW model for N spinless particles

- Standard linear evolution between jumps

$$\partial_t|\psi_t\rangle = -iH|\psi_t\rangle$$

- Jump hitting particle k in x_f at a rate λ

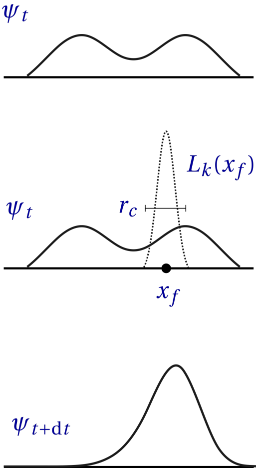
$$|\psi_t\rangle \to \frac{\hat{L}_k(x_f)|\psi_t\rangle}{\|\hat{L}_k(x_f)|\psi_t\rangle\|}$$

with

$$\mathbb{P}(x_f) = \|\hat{L}_k(x_f)|\psi_t\rangle\|^2$$

and

$$\hat{L}_k(x_f) = \frac{1}{(\pi r_c^2)^{3/2}} \mathrm{e}^{(\hat{x}_k - x_f)^2/(2r_c^2)}$$



Ghirardi, G. C., Rimini, A., & Weber, T. (1986) Phys. Rev. D, **34**(2), 470.

The GRW model

The new parameters λ and r_c can be fixed in such a way that:

Weak collapse

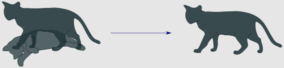
A single particle *extremely rarely* collapses in the position basis

- Microscopic dynamics unchanged

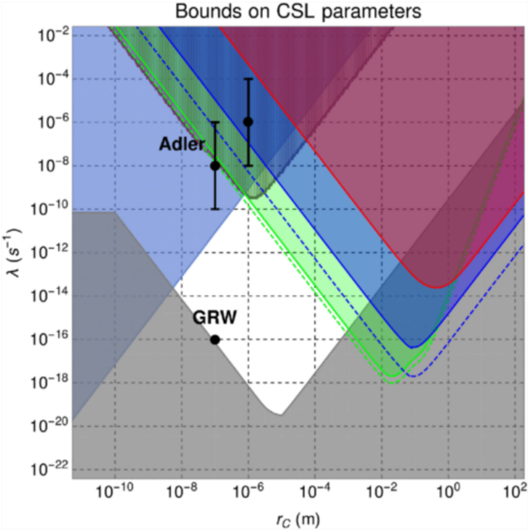
Amplification

The effective collapse rate is renormalized for macroscopic superpositions:

- Macroscopic superpositions almost instantly collapse



Parameter diagram



M. Carlesso, A. Bassi, P. Falferi, and A. Vinante,
Phys. Rev. D **94**, 124036 (2016)

II – Collapse models in general:
What behavior can be expected from collapse models in general?

General collapse model

- **Starting point:** a Markovian stochastic Schrödinger equation (SSE)

$$\partial_t|\psi_t\rangle = -iH|\psi_t\rangle + \varepsilon\, f(|\psi_t\rangle, \eta_t)$$

that tends to collapse states in some basis for $H = 0$.

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- **Constraints**: to preserve Born rule and avoid faster-than-light signaling

$$\partial_t\rho_t = \mathcal{L}(\rho_t)$$

  where $\mathcal{L}$ is a Lindblad (super)operator.

General collapse model – in questions

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   $\Longrightarrow$ **yes** – don't forget the objective, solving the measurement problem. Not all unravelings work, e.g.:

   $$\partial_t|\psi_t\rangle = i\gamma\sigma_z\eta_t|\psi_t\rangle$$

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   $\Longrightarrow$ **no** – the Lindblad equation can be dilated into a unitary evolution with a **Markovian** bath
   $\Longrightarrow$ **yes** – collapse models make predictions different from those of the Standard Model

III – Generalizing collapse models further:
What generalizations are possible? Can collapse models be made relativistic? What about QFT?

Attempts at relativistic collapse models

Constructing relativistic collapse models is **difficult**

- "Sharp " collapse models are divergent
- "Smeared" collapse models seem to necessarily break Lorentz invariance

There exists elaborate proposals [Tumulka, Pearle, Bedingham, Sudarsky], which require some level of **non-Markovianity**. But empirical content then hard to extract.

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Challenge

Can one construct "simple" relativistic collapse models with a transparent empirical content?

General – non Markovian – collapse model

- **Starting point:** a Markovian stochastic Schrödinger equation (SSE)

$$\partial_t|\psi_t\rangle = -iH|\psi_t\rangle + \varepsilon\, f(|\psi\rangle, \eta)$$

that tends to collapse states in some basis for $H = 0$.

- **Empirical content**: collapse noise unobservable directly, hence empirical content (apart collapse) lies in $\rho_t = \mathbb{E}\left[\,|\psi_t\rangle\langle\psi_t|\,\right]$

- **Constraints**: to preserve Born rule and avoid faster-than-light signaling

$$\rho_t = \Phi_t \cdot \rho_0$$

where Φ_t is a trace-preserving completely positive map.

As before, the empirical content could be reproduced by a non-Markovian bath.

IV – A proposal

Recollecting previous results to make collapse models symmetric and invisible

Reversing the reasoning

The old way

1. Work hard to find a stochastic Schrödinger equation

$$\partial_t |\psi_t\rangle = \cdots$$

with some free parameters

2. Notice the empirical content lies in:

$$\rho_t = \mathbb{E}\left[\, |\psi_t\rangle\langle\psi_t| \,\right]$$

where $\rho_t = \Phi_t \cdot \rho_0$

3. Notice that it could be dilated into a pure (albeit quite unnatural) evolution on a bigger space $\mathscr{H} \otimes \mathscr{H}_{\text{aux}}$

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The proposal

1. Start from an interacting theory (e.g. QED, Yukawa) $\mathscr{H} = \mathscr{H}_f \otimes \mathscr{H}_b$

2. Trace out one of the two sectors

$$\rho_t^f = \text{tr}_b \left[\, |\Psi_t\rangle\langle\Psi_t| \,\right]$$

   with $\rho_t^f = \Phi_t \cdot \rho_0^f$ where for standard QFT Φ_t is given by a quadratic Feynman-Vernon influence functional.

3. **Unravel** it, i.e. find random $|\psi_t^f\rangle$ such that:

$$\mathbb{E}\left[\, |\psi_t^f\rangle\langle\psi_t^f| \,\right] = \rho_t^f$$

   (non unique but always doable)

Summary of the idea

Tracing out

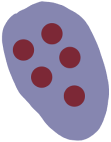
$\rho_f = \mathrm{tr}_b[|\Psi\rangle\langle\Psi|]$

Unraveling

$|\psi_f\rangle$ such that:
$\rho_f = \mathbb{E}[|\psi_f\rangle\langle\psi_f|]$

Interacting QFT → **"Open" QFT of fermions** → **Collapse model for fermions**

$\partial_t|\Psi\rangle = -iH_{\mathrm{tot}}|\Psi\rangle$



$\rho_f(t) = \Phi_t \cdot \rho_f(0)$

$\partial_t|\psi_f\rangle = -iH_f|\psi_f\rangle + f_\xi(|\psi_f\rangle)$

Empirically equivalent

Unraveling

Computations done in `arXiv:1702.06325` for Yukawa

The crucial point lies in the ability to "unravel":

$$\rho_t = \Phi_t \cdot \rho_0 \xrightarrow[\text{unraveling}]{} \partial_t |\psi_t\rangle = f(|\psi\rangle, \eta) \text{ with } \mathbb{E}\left[\, |\psi_t\rangle\langle\psi_t| \,\right] = \rho_t$$

doable (Diósi - Ferialdi) for Φ_t coming from:

- bosonic bath
- linearly coupled in bosonic $a^\dagger$ and a
- in a Gaussian state, e.g. $|0\rangle_b$, at the beginning of time

Important: does not provide a numerically efficient technique to solve QFT.

Which QFT to start from

Provided we have a sufficiently nice interacting theory fermions and bosons, we can construct a collapse model for the fermions. This brings the question:

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$\Longrightarrow$ **No need to add anything!**
Just take a bosonic sector of the standard model, like QED or Higgs.

V – Discussion

What is the impact of the previous discussion on QFT and on the collapse program?

Some consequences

- Such an approach solves the measurement problem (maybe with the help of some primitive ontology) $\implies$ realistic QFT
- The empirical content is left unchanged
- When there is experimentally some decoherence of bosonic origin, there is actually a corresponding objective collapse going on.
- Collapse can be shielded from, but all warm macroscopic bodies are collapsed
- In practice, one would still use the old formalism and introduce bosons as tools to make perturbative QFT computations.
- No miracle: the technical problems of QFT are still there
- If collapse models can be so easily hidden, does it make sense to test some that predict modifications?

Summary

Standard collapse models:

- are constructed starting from a stochastic Schrödinger equation (SSE)
- are empirically indistinguishable from unitary dynamics with **peculiar** hidden degrees of freedom
- give predictions different from SM and are hard to generalize

What we are testing experimentally are signatures of this peculiarity.

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Take home message

Objective collapse mechanisms can be carved into existing decoherence sources with no impact on the empirical content. They can thus be seen as foundations rather than modifications of quantum theory.