Classical-Quantum Coexistence: 'Free Will' Test

Lajos Diósi

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The physics issue *Cambridge, 1999*

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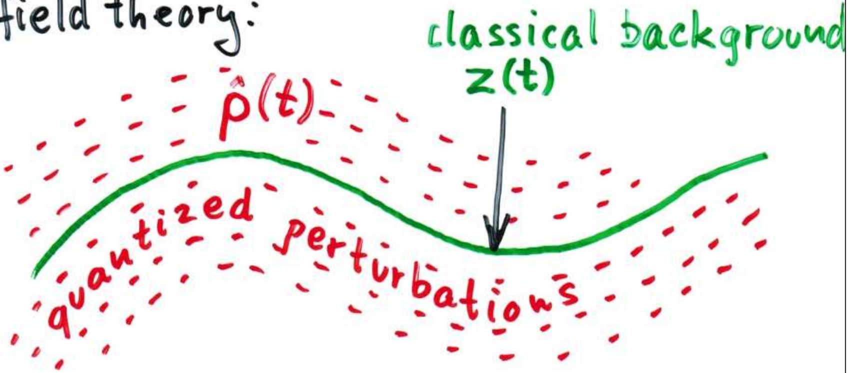
Q-field theory:



no backreaction $\hat{\rho}(t) \to z(t)$

Study the coexistence of $\hat{\rho}(t)$ & $z(t)$!

Vocabulary

- **Classical continuum:** a smooth real function $z(t)$ of time
- **Quantum theory:** dynamics of the density matrix $\rho(t)$ plus its statistical interpretation
- **Coexistence:** $\rho(t)$ and $z(t)$ coexist and depend on each other
- **'Free Will':** my freedom to, conditioned on z, perturbe the dynamics of ρ. I call z **tangible** then.
- **Causality:** perturbation at t has no effect at times $< t$ prior to t
- **Measurement:** math procedure (selective stochastic map) on ρ

Sensitively interrelated: 'Free Will" perturbation vs statistical interpretation, smoothness vs causality.

The quantum-classical coexistence issue

There must be mutual classical⇔quantum influences.

Classical on quantum is trivial:

$$\frac{d\rho}{dt} = \frac{-\mathrm{i}}{\hbar}[H(z), \rho]$$

Quantum on classical (back-reaction) is problematic:

- Mean-Field
  *Moller*1962,*Rosenfeld*1963
- de Broglie-Bohm$^{1927-1952}$
- Decoherence
  *Zeh*1970,*Zurek*1982
- Decoherent Histories
  *Griffith*1984,*Gell−MannHartle*1993
- Measurement
  *vonNeumann*1932
- Continuous Measurement
  *Belavkin*1988,*Diosi*1988
- Hybrid Dynamics
  *SherrySudarshan*1979,...,*Elze*2011

Influence of quantum on classical: Mean-Field?

Classical continuum variable = quantum expectation value:

$$z = \mathrm{tr}[q\rho]$$

Most succesful approximation in optics, cosmology, e.t.c.
Mean-Field z(t) is smooth and causal.

Free Will test: make $H(t)$ depend on $z(t)$.
Recall influence of classical on quantum:

$$\frac{d\rho}{dt} = \frac{-\mathrm{i}}{\hbar}[H(z), \rho]$$

Nonlinear evolution for ρ denies statistical interpretation. **Free Will doesn't work, Mean-Field z is not tangible.**

Influence of quantum on classical: Bohm theory?

Restricted for pure states $\rho = \rho^2$ and for coordinate $q \Rightarrow z$.
Amazing: Born probability density is preserved for $z(t)$.

Classical continuum variable senses the quantum potential $V_\rho(z)$:

$$m\frac{d^2 z}{dt^2} = -V'(z) - V'_\rho(z)$$

Oldest non-standard theory to generate classical from quantum.
Bohm's z(t) is smooth and causal.

Time-local Free Will test passes, $H(t)$ depends on $z(t)$:

$$\frac{d\rho}{dt} = \frac{-\mathrm{i}}{\hbar}[H(z), \rho]$$

Does Bohm remain consistent when $H(t)$ depends on $z(t' < t)$?
If causal Free Will fails: Bohm's z is not tangible.

Influence of quantum on classical: Measurement?

Classical variable = outcome of quantum measurement:

$$\rho \longrightarrow \frac{P(z)\rho P(z)}{p(z)} \equiv \rho_z \text{ with prob. } p(z)$$

Standard theory to generate classical from quantum.
Measurement $\mathbf{z}(\mathbf{t})$ is not continuous (though causal).

Free Will test, make H depend on z and average the dynamics over z:

$$\rho(t) = \sum_z p(z) e^{-(i/\hbar)H(z)t} \rho_z e^{(i/\hbar)H(z)t} = \sum_z U(z,t)P(z)\rho_z P(z)U^\dagger(z,t)$$

This is linear for ρ. **Free Will works, Measurement $\mathbf{z}$ is tangible.**

Influence of quantum on classical: Continuous Measurement?

Classical variable = outcome of time-continuous quantum measurement:

$$z = \mathrm{tr}[q\rho] + \text{white-noise}$$

Now standard theory to generate classical from quantum in Markovian approximation. **Continuous Measurement $\mathbf{z}(\mathbf{t})$ is not smooth (though continuous and causal).**

Free Will test: make $H(t)$ depend on $z(<t)$ and average over z. We get linear equation for ρ at the end. **Free Will works, the Continuous Measurement $\mathbf{z}(\mathbf{t})$ is tangible.**

The quantum-classical coexistence issue (re-shown)

There must be mutual classical⇔quantum influences.

Classical on quantum is trivial:

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Quantum on classical (back-reaction) is problematic:

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Summary: Coexistence (co-influence) of quantum and classical

Classical on quantum is trivial:

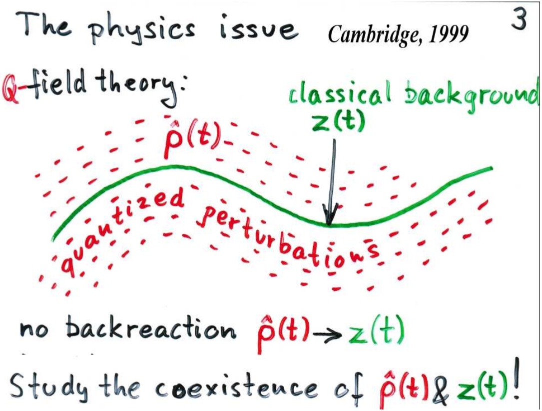
$$\frac{d\rho}{dt} = \frac{-\mathrm{i}}{\hbar}[H(z), \rho]$$

Quantum on classical (back reaction): The only **tangible (cf. Free Will)** and **smooth** classical 'field' $\mathbf{z}(\mathbf{t})$:

Classical variable = outcome of time-continuous non-Markovian quantum measurement:

$$z = \mathrm{tr}[q\rho] + \text{colored-noise}$$

Causality structure of Non-Markovian Continuous Measurement is tricky. Progress after Cambridge 1999, with recent debates[*JackColletWalls*, *WisemanGambetta*, *Diosi* (1999−2011)].



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