Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others
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For a bipartite system, the preferred decomposition is the Schmidt decomposition

\[ |\psi(t)\rangle^{AB} = \sum_i c_i |u_i(t)\rangle^A |v_i(t)\rangle^B \]

where \[ \langle u_i(t)|u_j(t)\rangle = \delta_{ij} \]
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\[ \sum_{i,j} A_{i,j} \Delta \phi_{i} v_{j} \]
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Recall the Stern-Gerlach experiment

$$(a| \uparrow\rangle + b| \downarrow\rangle) \otimes |\text{"ready"}\rangle$$

$$\rightarrow a| \uparrow\rangle \otimes |\text{"up"}\rangle + b| \downarrow\rangle \otimes |\text{"down"}\rangle$$
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\[
\rho^A = \frac{1}{2} \left( \frac{1}{\sqrt{2}} |1 + n_A^B \rangle \langle 1 - n_A^B| + \frac{1}{\sqrt{2}} |1 - n_A^B \rangle \langle 1 + n_A^B| \right)
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How to generalize to n-partite systems?
How to generalize to $n$-partite systems?
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Perspectival approach - Systems only possess properties in relation to something else (not clear that this is genuinely realist)
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**Outstanding problems:**
instability of preferred decomposition
infinite-dimensional systems
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**Outstanding problems:**
instability of preferred decomposition
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**Criticisms:**
Underdetermination of dynamics
Failure of Lorentz invariance
Collapse theories
<table>
<thead>
<tr>
<th>Inconsistencies of the orthodox interpretation</th>
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<tr>
<td><strong>By the collapse postulate</strong></td>
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<td>(applied to the system)</td>
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The quantum measurement problem

\[(a\ket{\uparrow} + b\ket{\downarrow})\ket{\text{"ready"}} \rightarrow a\ket{\uparrow}\ket{\text{"up"}} + b\ket{\downarrow}\ket{\text{"down"}}\]
Responses to the measurement problem
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2. Deny representational completeness of $\psi$
   - $\psi$-ontic hidden variable models (e.g. deBroglie-Bohm)
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5. Deny some other feature of the realist framework?
Collapse theories

Posit a new dynamical evolution law: either nonlinear or indeterministic or both.

Recover unitary evolution and the collapse postulate as special cases.
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Microscopic systems obey unitary dynamics to good approximation
Macroscopic systems obey collapse dynamics to good approximation
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Motivations:
• Achieves realism
• Maintains $\psi$-completeness
• No “cut”, i.e. one universal dynamics (unlike a hybrid model)
Nonlinear deterministic models

\[ | \uparrow \rangle | \text{"ready"} \rangle \rightarrow | \uparrow \rangle | \text{"up"} \rangle \]
\[ | \downarrow \rangle | \text{"ready"} \rangle \rightarrow | \downarrow \rangle | \text{"down"} \rangle \]

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Final state depends on details of the initial state

Ignorance of those details implies subjective indeterminism
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Final state depends on details of the initial state

Ignorance of those details implies subjective indeterminism

Many problems with nonlinearities
Linear indeterministic models

The goal:

\[(a|\uparrow \rangle + b|\downarrow \rangle)|\text{“ready”}\rangle \rightarrow |\uparrow \rangle|\text{“up”}\rangle \text{ with probability } |a|^2\]
\[\rightarrow |\downarrow \rangle|\text{“down”}\rangle \text{ with probability } |b|^2\]
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The preferred decomposition issue

Into what states do collapses occur?
Linear indeterministic models

The goal:

\[(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}\rangle \quad \text{with probability} \quad |a|^2\]

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The preferred decomposition issue

Into what states do collapses occur?

The trigger issue

When and how do collapses occur?
The Ghirardi-Rimini-Weber model
The Ghirardi-Rimini-Weber model

At most times:

\[ i\hbar \frac{\partial}{\partial t} \psi(r_1, ..., r_N, t) = H \psi(r_1, ..., r_N, t) \]

Schrödinger's equation
The Ghirardi-Rimini-Weber model

At most times:

\[ i\hbar \frac{\partial}{\partial t} \psi(r_1, \ldots, r_N, t) = H \psi(r_1, \ldots, r_N, t) \]  \quad \text{Schrödinger's equation}

Every \( \tau/N \) time interval on average

\[ \psi(r_1, \ldots, r_N, t + dt) = \frac{1}{\sqrt{p(q_k)}} j_{q_k}(r_k) \psi(r_1, \ldots, r_N, t) \]  \quad \text{“Collapse”}

where \[ j_{q_k}(r) = K \exp\left(-\frac{(r-q_k)^2}{2\sigma^2}\right) \]
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where

\[ j_{q_k}(\mathbf{r}) = K \exp\left(-\frac{(\mathbf{r}-\mathbf{q}_k)^2}{2\sigma^2}\right) \]

\[ p(q_k) = \int d\mathbf{r}_1 \ldots d\mathbf{r}_N \ |j_{q_k}(q_k)\psi(\mathbf{r}_1, \ldots, \mathbf{r}_N, t)|^2 \]
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\[ j_{q_k}(r) = K \exp(-\frac{(r-q_k)^2}{2\sigma^2}) \]
\[ p(q_k) = \int dr_1...dr_N |j_{q_k}(r_k)\psi(r_1, ..., r_N, t)|^2 \]

\( k \) is chosen uniformly at random

\( q_k \) is chosen by sampling from \( p(q_k) \)
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Two new fundamental constants:

\[ \tau \approx 10^{15} \text{s} \approx 100 \text{ million years} \quad \text{mean time between collapses for one particle} \]
The Ghirardi-Rimini-Weber model

At most times:

\[ i\hbar \frac{\partial}{\partial t} |\psi(t)\rangle = H |\psi(t)\rangle \]

Schrödinger's equation

Every \( \frac{\tau}{N} \) time interval on average

\[ |\psi(t + dt)\rangle = \frac{1}{\sqrt{p(q_k)}} Q^{(k)}(q_k) |\psi(t)\rangle \]

"Collapse"

where

\[ Q^{(k)}(q_k) = \int dr_k \ j(q_k) \left| r_k \right\rangle \left\langle r_k \right| \]

\[ p(q_k) = \langle \psi(t) | Q^{(k)^\dagger}(q_k) Q^{(k)}(q_k) |\psi(t)\rangle \]

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Two new fundamental constants:

\[ \tau \approx 10^{15} s \approx 100 \text{ million years} \]

mean time between collapses for one particle
Single particle in 1D
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\[ \psi(x) = K \left( \frac{\sqrt{3}}{2} \phi_a(x) + \frac{1}{2} \phi_b(x) \right) \]
Single particle in 1D

\[ r(x) = K \left( \frac{\sqrt{3}}{2} \phi_a(x) + \frac{1}{2} \phi_b(x) \right) \]

\[ j_q(x) = K \exp\left( -\frac{(x-q)^2}{2\sigma^2} \right) \]
Single particle in 1D

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Single particle in 1D

\[ v(x) = K \left( \frac{\sqrt{3}}{2} \phi_a(x) + \frac{1}{2} \phi_b(x) \right) \]

\[ j_q(x) = K \exp\left(-\frac{(x-q)^2}{2\sigma^2}\right) \]

Two particles in 1D

\[ \psi(x_1, x_2) = K \left( \frac{\sqrt{3}}{2} \phi_a(x_1) \chi_a(x_2) + \frac{1}{2} \phi_b(x_1) \chi_b(x_2) \right) \]
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Two particles in 1D

\[ \psi(x_1, x_2) = K \left( \frac{\sqrt{3}}{2} \phi_a(x_1) \chi_a(x_2) + \frac{1}{2} \phi_b(x_1) \chi_b(x_2) \right) \]

\[ \psi'(x_1, x_2) \approx \phi_a(x_1) \chi'_a(x_2) \]
Single particle in 1D

\[ v(x) = K \left( \frac{\sqrt{3}}{2} \phi_a(x) + \frac{1}{2} \phi_b(x) \right) \]

\[ j_q(x) = K \exp\left( -\frac{(x-q)^2}{2\sigma^2} \right) \]

Two particles in 1D

\[ \psi(x_1, x_2) = K \left( \frac{\sqrt{3}}{2} \phi_a(x_1) \chi_a(x_2) + \frac{1}{2} \phi_b(x_1) \chi_b(x_2) \right) \]

\[ \psi'(x_1, x_2) \approx \phi_a(x_1) \chi_a'(x_2) \]
\[ \psi = a \, \phi_a(\mathbf{r}_1) \chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b \, \phi_b(\mathbf{r}_1) \chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \]
\[ \psi = a \, \phi_a(\mathbf{r}_1) \chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b \, \phi_b(\mathbf{r}_1) \chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \]
\[ \psi = a \phi_a(r_1) \chi_a(r_2, ..., r_M) + b \phi_b(r_1) \chi_b(r_2, ..., r_M) \]

Suppose \( \chi_a(...r_k...) \chi_b(...r_k...) \approx 0 \) for macroscopic \# of components
\[ \psi = a \, \phi_a(\mathbf{r}_1) \chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b \, \phi_b(\mathbf{r}_1) \chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \]

Suppose \( \chi_a(\ldots\mathbf{r}_k\ldots) \chi_b(\ldots\mathbf{r}_k\ldots) \approx 0 \) for macroscopic \# of components.

**One particle is hit \( \rightarrow \) all are localized**
\( \psi = a \phi_a(\mathbf{r}_1) \chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b \phi_b(\mathbf{r}_1) \chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \)

Suppose \( \chi_a(...\mathbf{r}_k...) \chi_b(...\mathbf{r}_k...) \approx 0 \) for macroscopic \# of components

One particle is hit \( \rightarrow \) all are localized

\( \psi' = \phi_a(\mathbf{r}_1) \chi'_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) \) with probability \( |a|^2 \)

\( \psi' = \phi_b(\mathbf{r}_1) \chi'_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \) with probability \( |b|^2 \)
\[ \psi = a \phi_a(r_1)x_a(r_2, \ldots, r_M) + b \phi_b(r_1)x_b(r_2, \ldots, r_M) \]

Suppose \( x_a(\ldots r_k \ldots)x_b(\ldots r_k \ldots) \approx 0 \) for macroscopic \# of components

One particle is hit \( \rightarrow \) all are localized

\[ \psi' = \phi_a(r_1)x'_a(r_2, \ldots, r_M) \text{ with probability } |a|^2 \]

\[ \psi' = \phi_b(r_1)x'_b(r_2, \ldots, r_M) \text{ with probability } |b|^2 \]

For \( M \approx 10^{20} \) particles

This happens every \( \frac{10^{15}}{10^{20}} \text{s} \approx 10^{-5} \text{s} \)
\[
\psi = a \phi_a(\mathbf{r}_1) \chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b \phi_b(\mathbf{r}_1) \chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M)
\]

Suppose \( \chi_a(\mathbf{r}_k) \chi_b(\mathbf{r}_k) \approx 0 \) for macroscopic \# of components

One particle is hit \( \Rightarrow \) all are localized

\[
\psi' = \phi_a(\mathbf{r}_1) \chi'_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) \quad \text{with probability } |a|^2
\]

\[
\psi' = \phi_b(\mathbf{r}_1) \chi'_b(\mathbf{r}_2, \ldots, \mathbf{r}_M) \quad \text{with probability } |b|^2
\]

For \( M \approx 10^{20} \) particles

This happens every \( \frac{10^{15}}{10^{20}} \approx 10^{-5} \) seconds

The apparatus gets determinate properties.
Constraints on parameters

\( \tau \) too big \( \rightarrow \) persistence of coherence of macro objects

\( \tau \) too small \( \rightarrow \) loss of coherence of micro objects
Constraints on parameters

\( \tau \) too big \( \rightarrow \) persistence of coherence of macro objects
\( \tau \) too small \( \rightarrow \) loss of coherence of micro objects

\( \sigma \) too big \( \rightarrow \) delocalized macro objects
\( \sigma \) too small \( \rightarrow \) excitation and heating
Constraints on parameters

\( \tau \) too big \( \rightarrow \) persistence of coherence of macro objects
\( \tau \) too small \( \rightarrow \) loss of coherence of micro objects

\( \sigma \) too big \( \rightarrow \) delocalized macro objects
\( \sigma \) too small \( \rightarrow \) excitation and heating

Experimental status

Difficult to distinguish fundamental collapse from decoherence
Difficult to detect anomalous heating
Continuous Spontaneous localization

Philip Pearle

Collapse is a continuous process governed by a randomly fluctuating field “gambler’s ruin”
What causes dynamical collapse?
What causes dynamical collapse?

gravity?

complexity?

new fields?
What causes dynamical collapse?

gravity?

complexity?

new fields?

Criticisms

The "tails" problem
What causes dynamical collapse?

gravity?

complexity?

new fields?

Criticisms

The “tails” problem

Failure of energy conservation

Failure of Lorentz invariance for current models