Title: Foundations of Quantum Mech. (PHYS 639) - Lecture 14

Date: Dec 17, 2009 11:00 AM

URL: http://pirsa.org/09120091

Abstract:

perimeter scholars
international

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Ontic state: $\{|\psi(t)\rangle, |\Phi(t)\rangle\}$

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Ontic state: $\{|\psi(t)\rangle, |\Phi(t)\rangle\}$

Standard distribution: $Pr(|\Phi(t)\rangle = |\chi_i(t)\rangle) = |c_i|^2$

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Ontic state: $\{|\psi(t)\rangle, |\Phi(t)\rangle\}$

Standard distribution: $Pr(|\Phi(t)\rangle = |\chi_i(t)\rangle) = |c_i|^2$

Evolution: Schrodinger eq'n for $|\psi(t)\rangle$
Stochastic Markovian master eq'n for $|\Phi(t)\rangle$
that preserves the standard distribution

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Ontic state: $\{|\psi(t)\rangle, |\Phi(t)\rangle\}$

Standard distribution: $Pr(|\Phi(t)\rangle = |\chi_i(t)\rangle) = |c_i|^2$

Evolution: Schrodinger eq'n for $|\psi(t)\rangle$
Stochastic Markovian master eq'n for $|\Phi(t)\rangle$ that preserves the standard distribution

In modal interpretations, the preferred decomposition is

Modal interpretations

Introduced by van Frassen, Kochen, Healey, and Dieks
Developed by Vermaas, Clifton, Bacciagaluppi, Dickson and others

Apply orthodox rule for property-ascription not to Ψ, but to an element in a preferred decomposition of Ψ

$$|\psi(t)\rangle = \sum_i c_i |\chi_i(t)\rangle$$

Supplementary variable: $|\Phi(t)\rangle \in \{|\chi_i(t)\rangle\}$

Ontic state: $\{|\psi(t)\rangle, |\Phi(t)\rangle\}$

Standard distribution: $Pr(|\Phi(t)\rangle = |\chi_i(t)\rangle) = |c_i|^2$

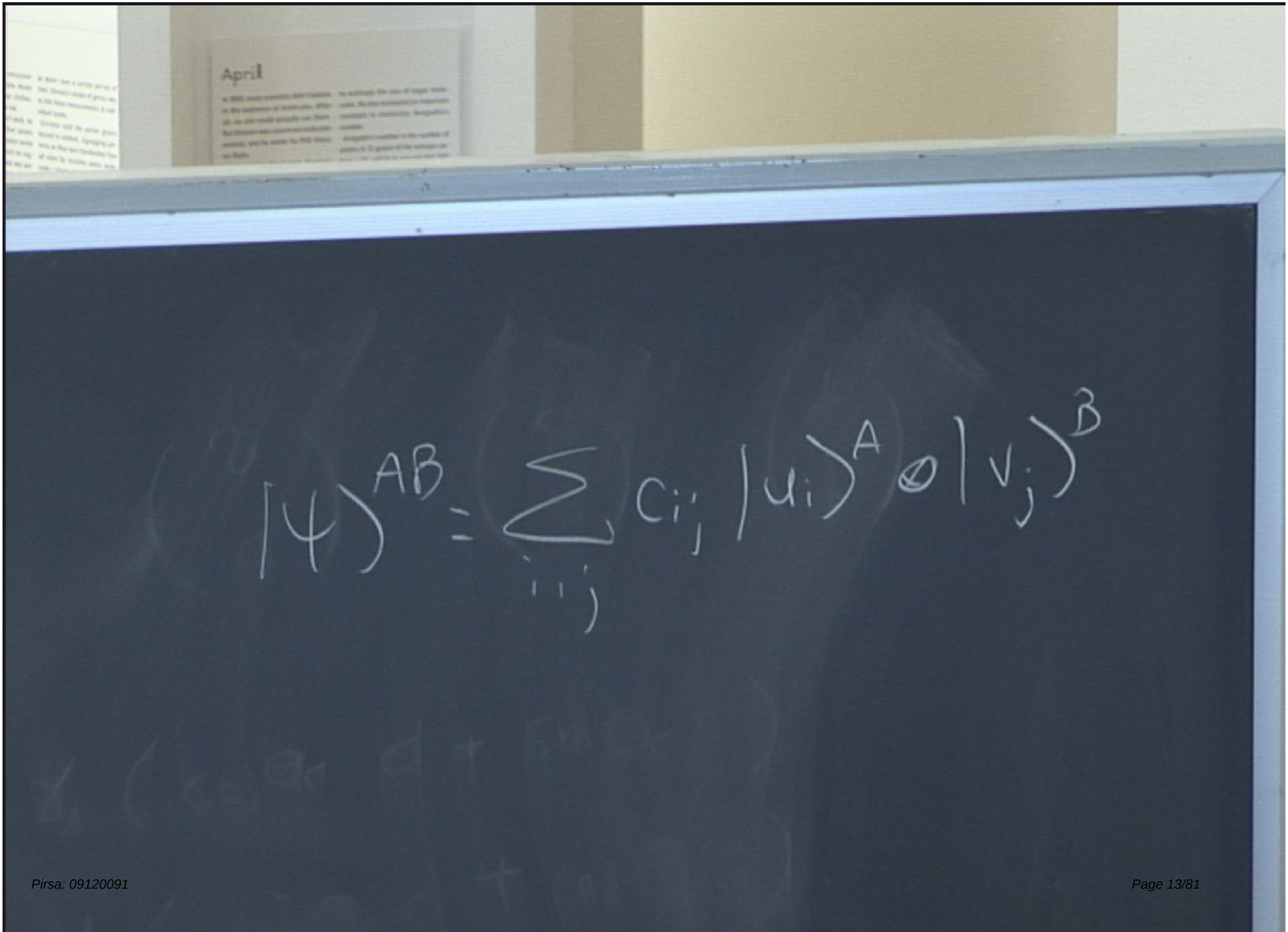
Evolution: Schrodinger eq'n for $|\psi(t)\rangle$
Stochastic Markovian master eq'n for $|\Phi(t)\rangle$ that preserves the standard distribution

In modal interpretations, the preferred decomposition is

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 $$\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$$
$$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$$


April
$|\psi\rangle^{AB} = \sum_{i,j} c_{ij} |u_i\rangle^A \otimes |v_j\rangle^B$

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 $$\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$$

$$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$$

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 $\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$

$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$

Recall the Stern-Gerlach experiment

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

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{“up”}\rangle \quad + \quad b|\downarrow\rangle \otimes |\text{“down”}\rangle$$

$$|\psi\rangle^{AB} = \sum_{i,j} c_{ij} \, |u_i\rangle^{A} \otimes |v_j\rangle^{B}$$

$$\frac{1}{\sqrt{2}} |+n\rangle^{A} |-n\rangle^{B} + \frac{1}{\sqrt{2}} |-n\rangle^{A} |+n\rangle^{B}$$

$$\rho^{A} = \frac{\mathbb{1}}{2}$$

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
$$\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$$
$$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$$

Recall the Stern-Gerlach experiment

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

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{“up”}\rangle \quad + \quad b|\downarrow\rangle \otimes |\text{“down”}\rangle$$

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 $$\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$$
$$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$$

Recall the Stern-Gerlach experiment

$$(a|\uparrow\rangle + b|\downarrow\rangle) \otimes |\text{“ready”}\rangle \otimes |E_0\rangle$$

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{“up”}\rangle \otimes |E_1\rangle \; + \; b|\downarrow\rangle \otimes |\text{“down”}\rangle \otimes |E_2\rangle$$

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 $\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$

$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$

Recall the Stern-Gerlach experiment

$$(a|\uparrow\rangle + b|\downarrow\rangle) \otimes |\text{``ready''}\rangle \otimes |E_0\rangle$$

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{``up''}\rangle \otimes |E_1\rangle \; + \; b|\downarrow\rangle \otimes |\text{``down''}\rangle \otimes |E_2\rangle$$

How to generalize to n-partite systems?

How to generalize to n-partite systems?

How to generalize to n-partite systems?

Perspectival approach - Systems only possess properties in relation to something else
(not clear that this is genuinely realist)

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 $\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$

$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$

Recall the Stern-Gerlach experiment

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

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{“up”}\rangle \quad + \quad b|\downarrow\rangle \otimes |\text{“down”}\rangle$$

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 $\langle u_i(t)|u_j(t)\rangle = \delta_{ij}$

$\langle v_i(t)|v_j(t)\rangle = \delta_{ij}$

Recall the Stern-Gerlach experiment

$$(a|\uparrow\rangle + b|\downarrow\rangle) \otimes |\text{``ready''}\rangle \otimes |E_0\rangle$$

$$\rightarrow \quad a|\uparrow\rangle \otimes |\text{``up''}\rangle \otimes |E_1\rangle \; + \; b|\downarrow\rangle \otimes |\text{``down''}\rangle \otimes |E_2\rangle$$

How to generalize to n-partite systems?

How to generalize to n-partite systems?

Perspectival approach - Systems only possess properties in relation to something else
(not clear that this is genuinely realist)

How to generalize to n-partite systems?

Perspectival approach - Systems only possess properties in relation to something else
(not clear that this is genuinely realist)

Atomic approach - use spectral resolutions of reduced density operators for a preferred factorization of Hilbert space
(not clear that it is empirically adequate)

How to generalize to n-partite systems?

Perspectival approach - Systems only possess properties in relation to something else
(not clear that this is genuinely realist)

Atomic approach - use spectral resolutions of reduced density operators for a preferred factorization of Hilbert space
(not clear that it is empirically adequate)

Outstanding problems:
instability of preferred decomposition
infinite-dimensional systems

How to generalize to n-partite systems?

Perspectival approach - Systems only possess properties in relation to something else
(not clear that this is genuinely realist)

Atomic approach - use spectral resolutions of reduced density operators for a preferred factorization of Hilbert space
(not clear that it is empirically adequate)

Outstanding problems:
instability of preferred decomposition
infinite-dimensional systems

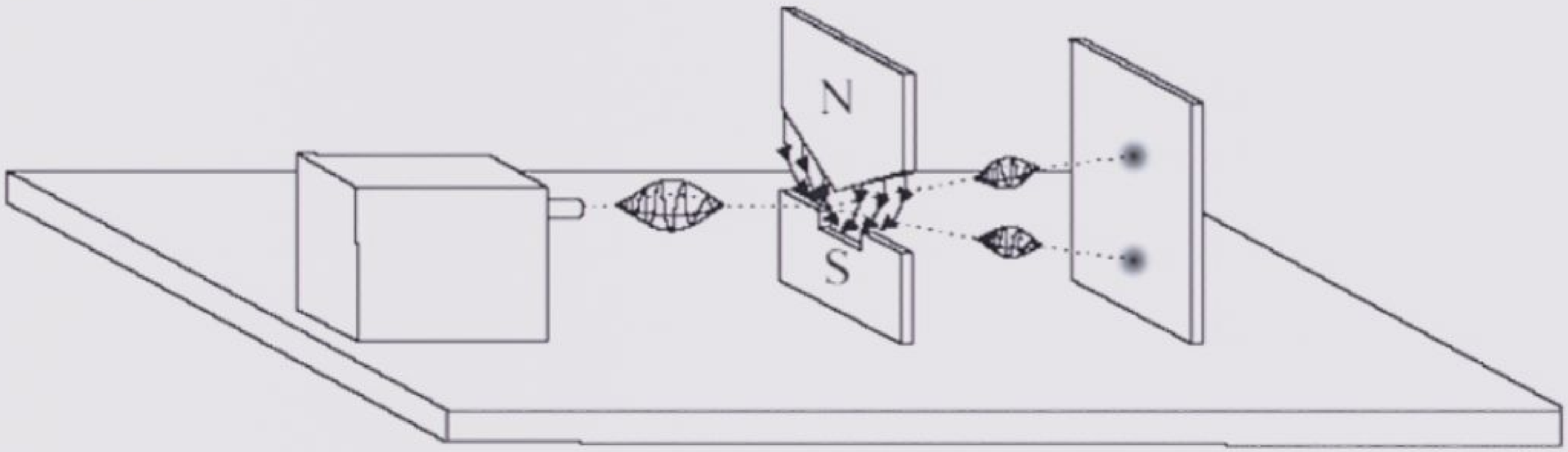
Criticisms:
Underdetermination of dynamics
Failure of Lorentz invariance

Collapse theories

Inconsistencies of the orthodox interpretation

By the collapse postulate (applied to the system)	By unitary evolution postulate (applied to isolated system that includes the apparatus)
Indeterministic and discontinuous evolution	Deterministic and continuous evolution
Determinate properties	Indeterminate properties

The quantum measurement problem



$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle$$

$$\rightarrow a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle$$

Responses to the measurement problem

Responses to the measurement problem

2. Deny representational completeness of ψ

- ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
- ψ-epistemic hidden variable models

Responses to the measurement problem

2. Deny representational completeness of ψ

- ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
- ψ-epistemic hidden variable models

4. Deny some aspect of classical logic or classical probability theory

- Quantum logic and quantum Bayesianism

Responses to the measurement problem

1. Deny universality of quantum dynamics

   - Quantum-classical hybrid models
   - Collapse models

2. Deny representational completeness of ψ

   - ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
   - ψ-epistemic hidden variable models

4. Deny some aspect of classical logic or classical probability theory

   - Quantum logic and quantum Bayesianism

Responses to the measurement problem

1. Deny universality of quantum dynamics
   - Quantum-classical hybrid models
   - Collapse models

2. Deny representational completeness of ψ
   - ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
   - ψ-epistemic hidden variable models

3. Deny that there is a unique outcome
   - Everett's relative state interpretation (many worlds)

4. Deny some aspect of classical logic or classical probability theory
   - Quantum logic and quantum Bayesianism

Responses to the measurement problem

1. Deny universality of quantum dynamics

    - Quantum-classical hybrid models
    - Collapse models

2. Deny representational completeness of ψ

    - ψ-ontic hidden variable models (e.g. deBroglie-Bohm)
    - ψ-epistemic hidden variable models

3. Deny that there is a unique outcome

    - Everett's relative state interpretation (many worlds)

4. Deny some aspect of classical logic or classical probability theory

    - Quantum logic and quantum Bayesianism

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

Collapse theories

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

Recover unitary evolution and the collapse postulate as special cases

Microscopic systems obey unitary dynamics to good approximation
Macroscopic systems obey collapse dynamics to good approximation

Collapse theories

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

Recover unitary evolution and the collapse postulate as special cases

Microscopic systems obey unitary dynamics to good approximation
Macroscopic systems obey collapse dynamics to good approximation

Motivations:
- Achieves realism

Collapse theories

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

Recover unitary evolution and the collapse postulate as special cases

Microscopic systems obey unitary dynamics to good approximation
Macroscopic systems obey collapse dynamics to good approximation

Motivations:
- Achieves realism
- Maintains ψ-completeness

Collapse theories

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

Recover unitary evolution and the collapse postulate as special cases

Microscopic systems obey unitary dynamics to good approximation
Macroscopic systems obey collapse dynamics to good approximation

Motivations:
- Achieves realism
- Maintains ψ-completeness
- No "cut", i.e. one universal dynamics (unlike a hybrid model)

Nonlinear deterministic models

$$|\uparrow\rangle|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}\rangle$$

$$|\downarrow\rangle|\text{“ready”}\rangle \rightarrow |\downarrow\rangle|\text{“down”}\rangle$$

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow \quad a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle$$

Nonlinear deterministic models

$$|\uparrow\rangle|\text{"ready"}\rangle \rightarrow |\uparrow\rangle|\text{"up"}\rangle$$

$$|\downarrow\rangle|\text{"ready"}\rangle \rightarrow |\downarrow\rangle|\text{"down"}\rangle$$

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

rather $(a|\uparrow\rangle + b|\downarrow\rangle)|\text{"ready"}\rangle \rightarrow |\uparrow\rangle|\text{"up"}_{a,b}\rangle$

or

$$|\downarrow\rangle|\text{"down"}_{a,b}\rangle$$

Nonlinear deterministic models

$$|\uparrow\rangle|\text{"ready"}\rangle \rightarrow |\uparrow\rangle|\text{"up"}\rangle$$

$$|\downarrow\rangle|\text{"ready"}\rangle \rightarrow |\downarrow\rangle|\text{"down"}\rangle$$

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

rather $(a|\uparrow\rangle + b|\downarrow\rangle)|\text{"ready"}\rangle \rightarrow |\uparrow\rangle|\text{"up"}_{a,b}\rangle$

or

$|\downarrow\rangle|\text{"down"}_{a,b}\rangle$

Final state depends on details of the initial state

Ignorance of those details implies subjective indeterminism

Nonlinear deterministic models

$$|\uparrow\rangle|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}\rangle$$

$$|\downarrow\rangle|\text{“ready”}\rangle \rightarrow |\downarrow\rangle|\text{“down”}\rangle$$

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle$$

rather $(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}_{a,b}\rangle$

or

$|\downarrow\rangle|\text{“down”}_{a,b}\rangle$

Final state depends on details of the initial state

Ignorance of those details implies subjective indeterminism

Nonlinear deterministic models

$$|\uparrow\rangle|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}\rangle$$

$$|\downarrow\rangle|\text{“ready”}\rangle \rightarrow |\downarrow\rangle|\text{“down”}\rangle$$

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow \cancel{a|\uparrow\rangle|\text{“up”}\rangle + b|\downarrow\rangle|\text{“down”}\rangle}$$

rather $(a|\uparrow\rangle + b|\downarrow\rangle)|\text{“ready”}\rangle \rightarrow |\uparrow\rangle|\text{“up”}_{a,b}\rangle$

or

$|\downarrow\rangle|\text{“down”}_{a,b}\rangle$

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:

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

$$\rightarrow \quad |\downarrow\rangle|\text{“down”}\rangle \quad \text{with probability } |b|^2$$

Linear indeterministic models

The goal:

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

$$\rightarrow\; |\downarrow\rangle|\text{“down”}\rangle \quad \text{with probability } |b|^2$$

The preferred decomposition issue

Into what states do collapses occur?

Linear indeterministic models

The goal:

$$(a|\uparrow\rangle + b|\downarrow\rangle)|\text{"ready"}\rangle \;\rightarrow\; |\uparrow\rangle|\text{"up"}\rangle \quad \text{with probability } |a|^2$$

$$\rightarrow\; |\downarrow\rangle|\text{"down"}\rangle \quad \text{with probability } |b|^2$$

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:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r}_1,\ldots,\mathbf{r}_N,t) = H\psi(\mathbf{r}_1,\ldots,\mathbf{r}_N,t)$$ Schrödinger's equation

The Ghirardi-Rimini-Weber model

At most times:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r}_1,...,\mathbf{r}_N,t) = H\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ Schrödinger's equation

Every τ/N time interval on average

$$\psi(\mathbf{r}_1,...,\mathbf{r}_N,t+dt) = \frac{1}{\sqrt{p(\mathbf{q}_k)}}\, j_{\mathbf{q}_k}(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ "Collapse"

where $j_{\mathbf{q}_k}(\mathbf{r}) = K\exp(-\frac{(\mathbf{r}-\mathbf{q}_k)^2}{2\sigma^2})$

The Ghirardi-Rimini-Weber model

At most times:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r}_1,...,\mathbf{r}_N,t) = H\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ Schrödinger's equation

Every τ/N time interval on average

$$\psi(\mathbf{r}_1,...,\mathbf{r}_N,t+dt) = \frac{1}{\sqrt{p(\mathbf{q}_k)}}\, j\mathbf{q}_k(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ "Collapse"

where $$j\mathbf{q}_k(\mathbf{r}) = K\exp(-\frac{(\mathbf{r}-\mathbf{q}_k)^2}{2\sigma^2})$$

$$p(\mathbf{q}_k) = \int d\mathbf{r}_1...d\mathbf{r}_N\, \left|j\mathbf{q}_k(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)\right|^2$$

The Ghirardi-Rimini-Weber model

At most times:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r}_1,...,\mathbf{r}_N,t) = H\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ Schrödinger's equation

Every τ/N time interval on average

$$\psi(\mathbf{r}_1,...,\mathbf{r}_N,t+dt) = \frac{1}{\sqrt{p(\mathbf{q}_k)}}\, j_{\mathbf{q}_k}(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ "Collapse"

where $$j_{\mathbf{q}_k}(\mathbf{r}) = K\exp(-\frac{(\mathbf{r}-\mathbf{q}_k)^2}{2\sigma^2})$$

$$p(\mathbf{q}_k) = \int d\mathbf{r}_1...d\mathbf{r}_N\, \left|j_{\mathbf{q}_k}(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)\right|^2$$

k is chosen uniformly at random

$\mathbf{q}_k$ is chosen by sampling from $p(\mathbf{q}_k)$

The Ghirardi-Rimini-Weber model

At most times:

$$i\hbar\frac{\partial}{\partial t}\psi(\mathbf{r}_1,...,\mathbf{r}_N,t) = H\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ Schrödinger's equation

Every τ/N time interval on average

$$\psi(\mathbf{r}_1,...,\mathbf{r}_N,t+dt) = \frac{1}{\sqrt{p(\mathbf{q}_k)}}\,j_{\mathbf{q}_k}(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)$$ "Collapse"

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

$$p(\mathbf{q}_k) = \int d\mathbf{r}_1...d\mathbf{r}_N\,\left|j_{\mathbf{q}_k}(\mathbf{r}_k)\psi(\mathbf{r}_1,...,\mathbf{r}_N,t)\right|^2$$

k is chosen uniformly at random

$\mathbf{q}_k$ is chosen by sampling from $p(\mathbf{q}_k)$

Two new fundamental constants:

$\tau \approx 10^{15}\mathrm{s} \approx 100$ million years 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 τ/N time interval on average

$$|\psi(t+dt)\rangle = \frac{1}{\sqrt{p(\mathbf{q}_k)}} Q^{(k)}(\mathbf{q}_k)|\psi(t)\rangle$$ "Collapse"

where $Q^{(k)}(\mathbf{q}_k) = \int d\mathbf{r}_k \; j_{\mathbf{q}_k}(\mathbf{r}_k)|\mathbf{r}_k\rangle\langle\mathbf{r}_k|$

$$p(\mathbf{q}_k) = \langle\psi(t)|Q^{(k)\dagger}(\mathbf{q}_k)Q^{(k)}(\mathbf{q}_k)|\psi(t)\rangle$$

k is chosen uniformly at random

$\mathbf{q}_k$ is chosen by sampling from $p(\mathbf{q}_k)$

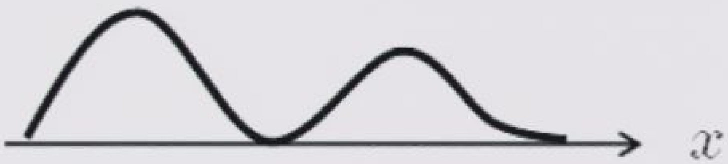
Two new fundamental constants:

$\tau \approx 10^{15}\text{s} \approx 100$ million years mean time between collapses for one particle

Single particle in 1D

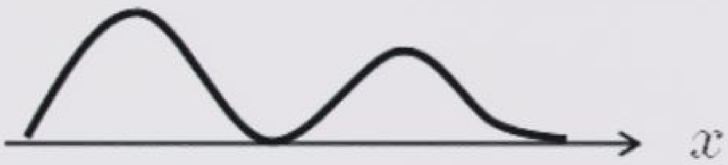
Single particle in 1D

$$\psi(x) = K(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x))$$

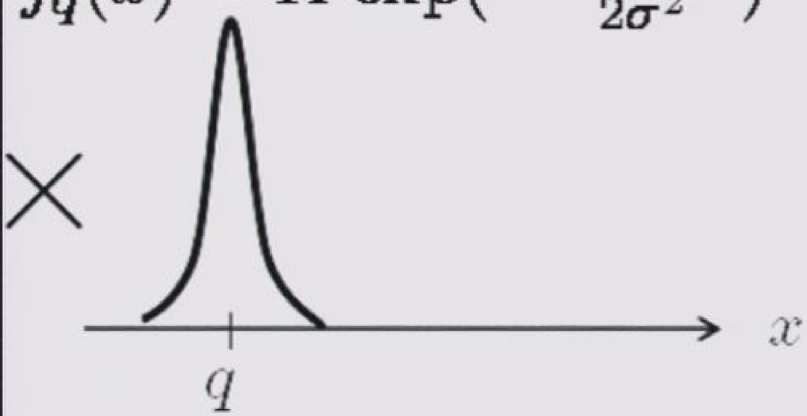


Single particle in 1D

$$\psi(x) = K\left(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x)\right)$$

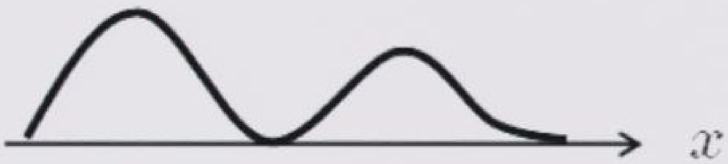


$$j_q(x) = K\exp\left(-\frac{(x-q)^2}{2\sigma^2}\right)$$



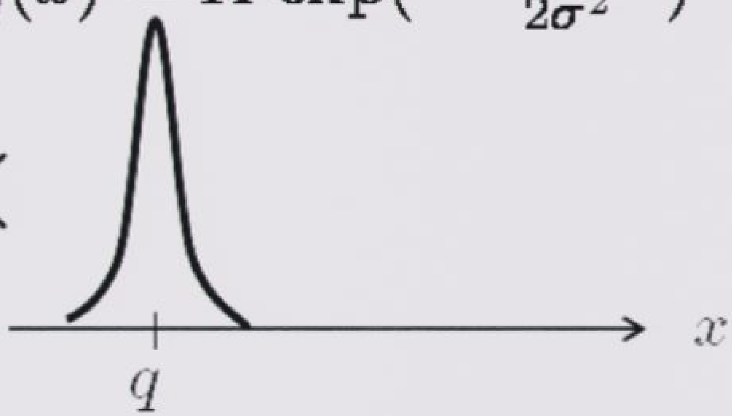
Single particle in 1D

$$\psi(x) = K(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x))$$

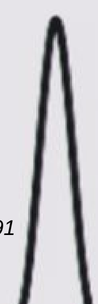


$$\psi_q(x) = K\exp(-\frac{(x-q)^2}{2\sigma^2})$$

$\times$

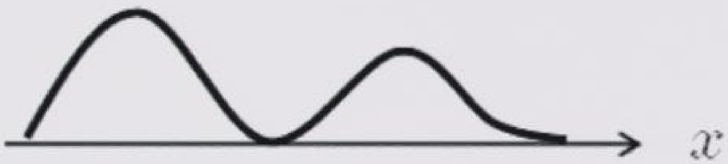


$=$



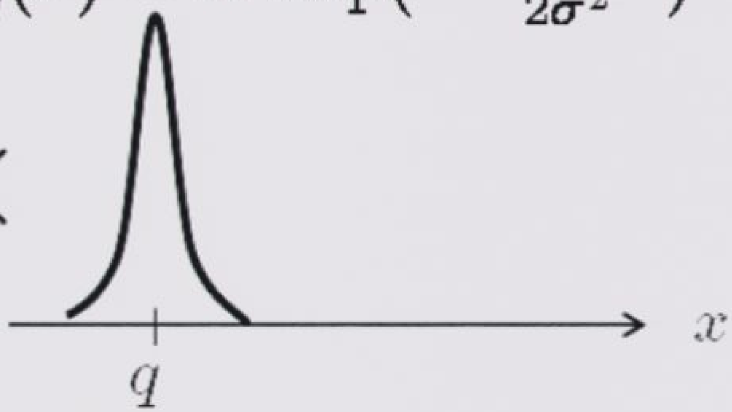
Single particle in 1D

$$\psi(x) = K(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x))$$

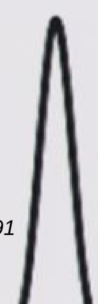


$$j_q(x) = K\exp(-\frac{(x-q)^2}{2\sigma^2})$$

$\times$

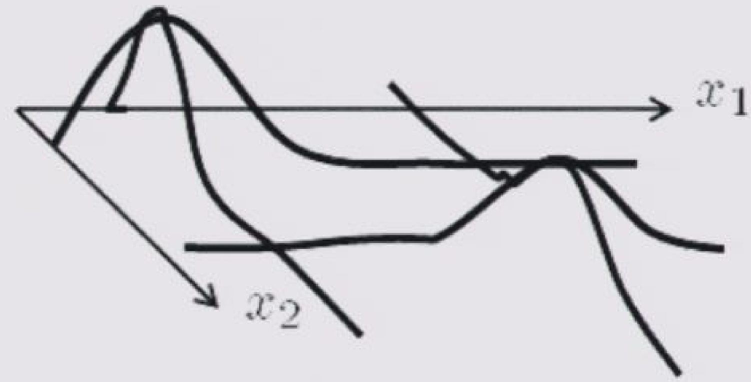


$=$



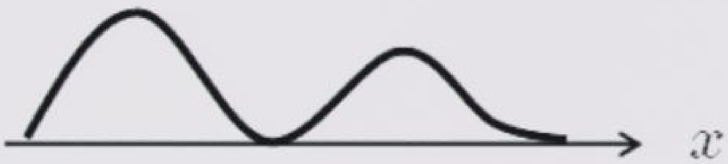
Two particles in 1D

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

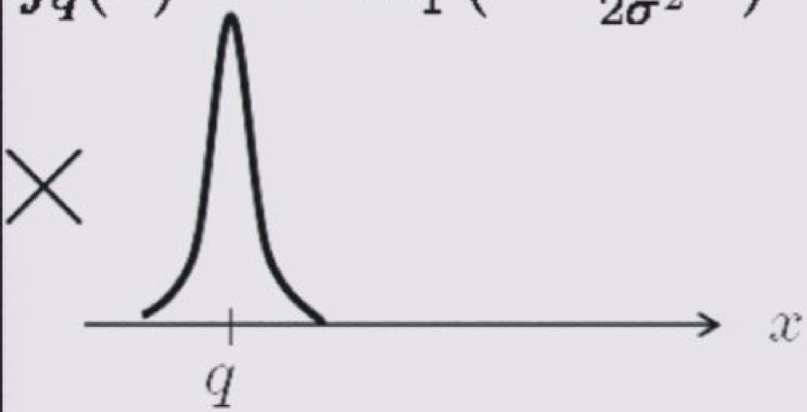


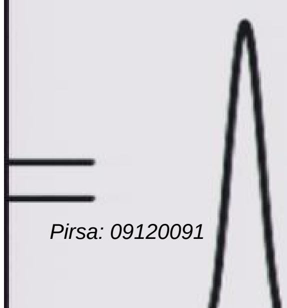
Single particle in 1D

$$\psi(x) = K(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x))$$



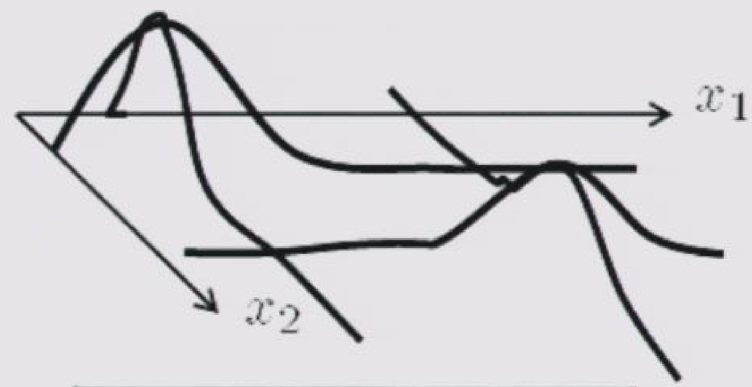
$$j_q(x) = K\exp(-\frac{(x-q)^2}{2\sigma^2})$$

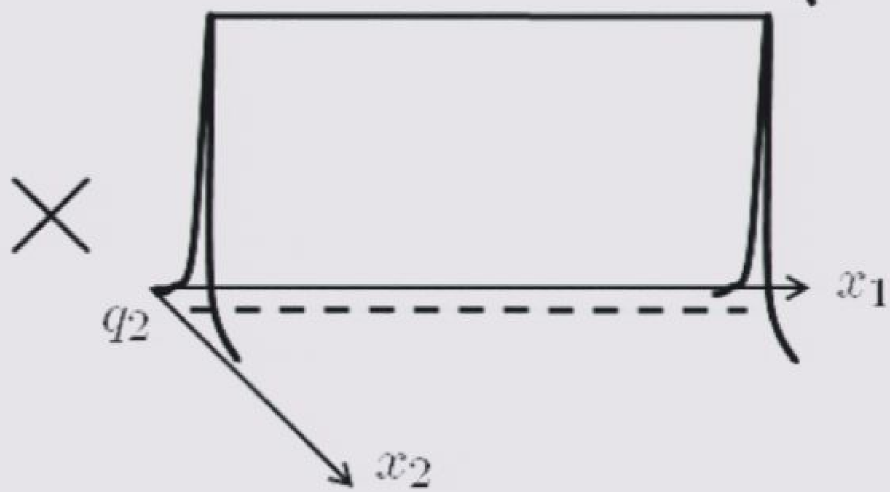




Two particles in 1D

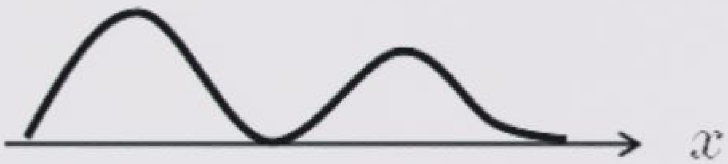
$$\psi(x_1, x_2) = K(\frac{\sqrt{3}}{2}\phi_a(x_1)\chi_a(x_2) + \frac{1}{2}\phi_b(x_1)\chi_b(x_2))$$



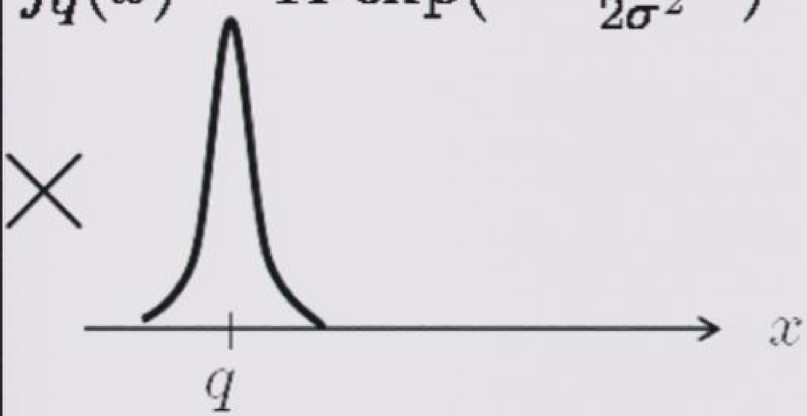


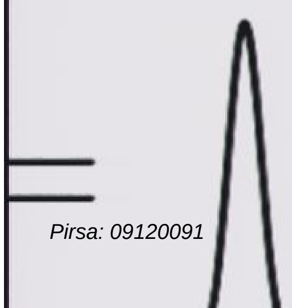
Single particle in 1D

$$\psi(x) = K\left(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x)\right)$$



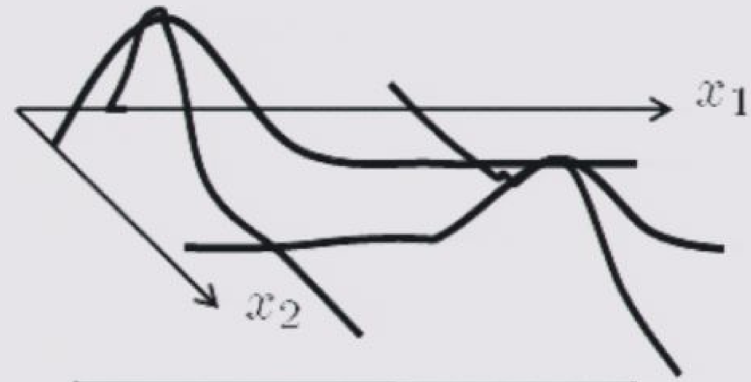
$$j_q(x) = K\exp\left(-\frac{(x-q)^2}{2\sigma^2}\right)$$

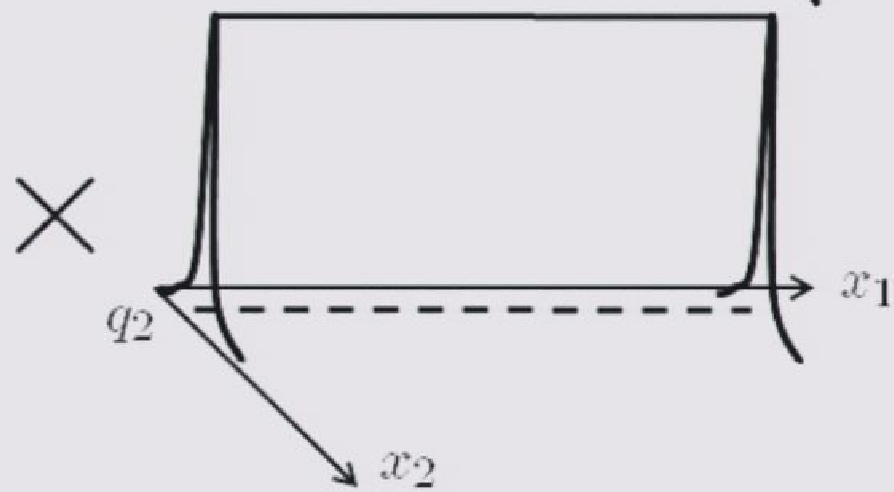




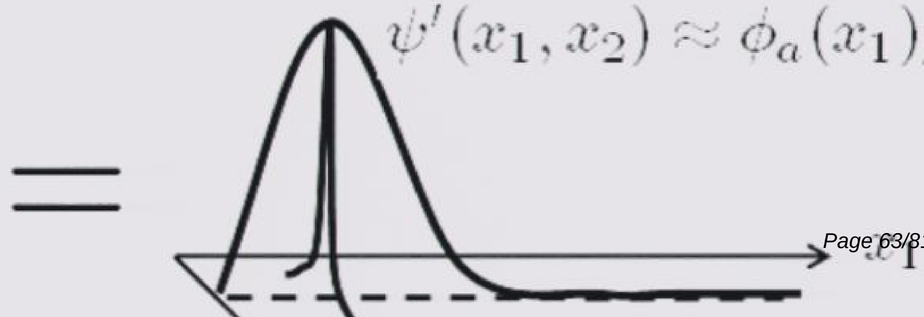
Two particles in 1D

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



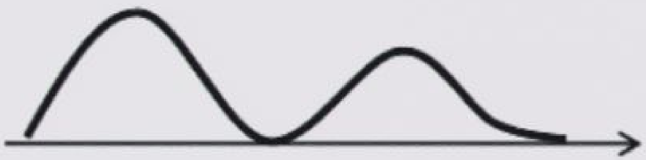


$$\psi'(x_1, x_2) \approx \phi_a(x_1)\chi'_a(x_2)$$



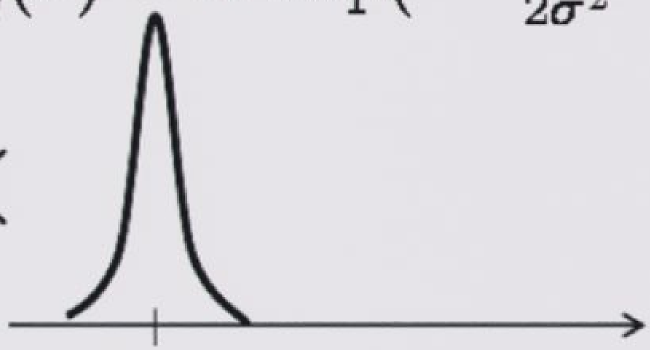
Single particle in 1D

$$\psi(x) = K(\frac{\sqrt{3}}{2}\phi_a(x) + \frac{1}{2}\phi_b(x))$$

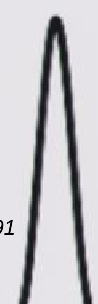


$$j_q(x) = K\exp(-\frac{(x-q)^2}{2\sigma^2})$$

$\times$

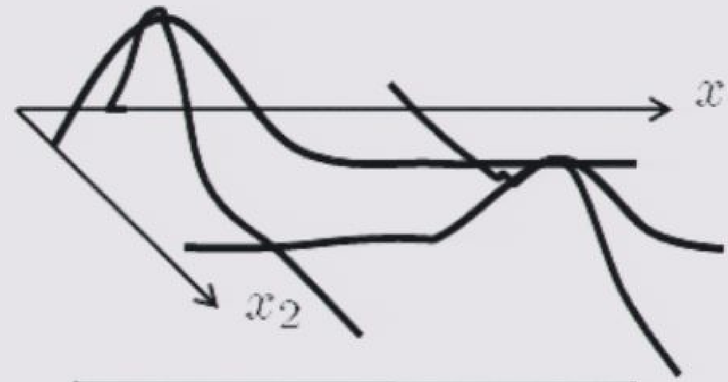


$=$

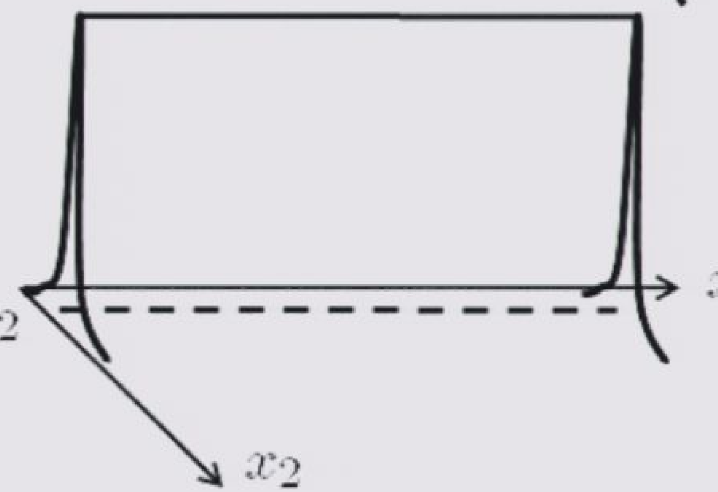


Two particles in 1D

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

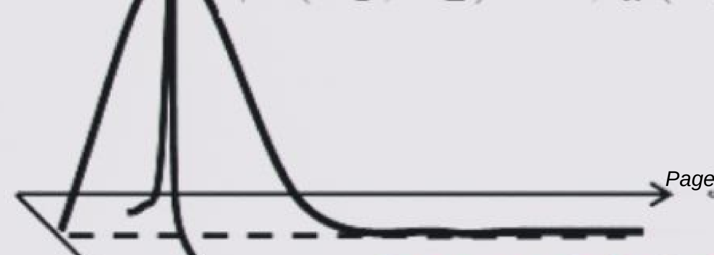


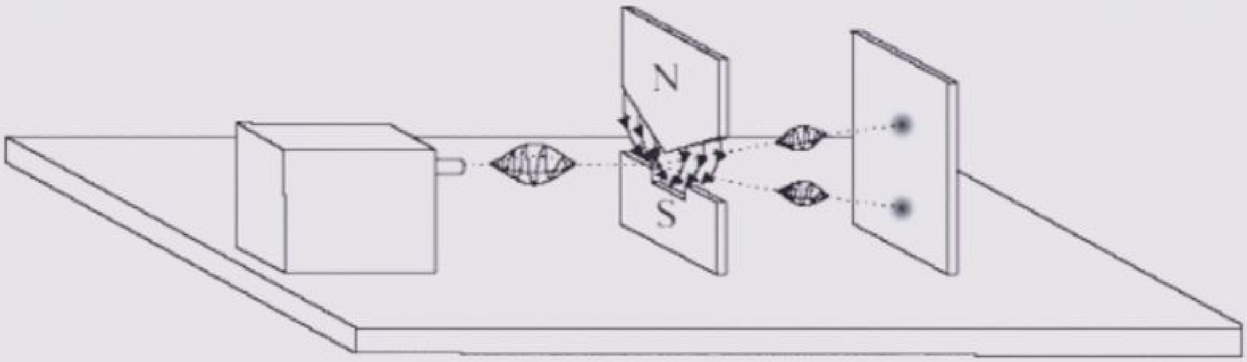
$\times$

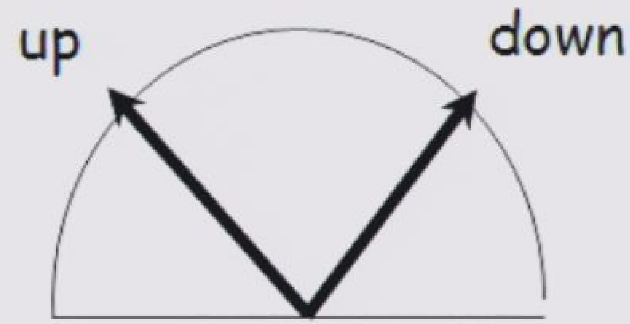


$=$

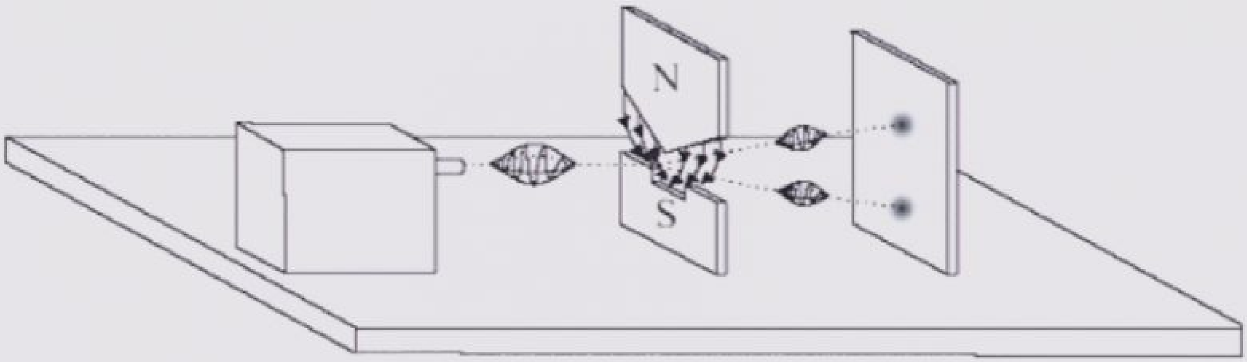
$$\psi'(x_1, x_2) \approx \phi_a(x_1)\chi'_a(x_2$$

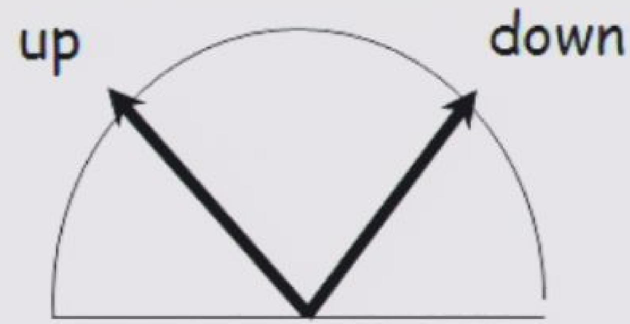




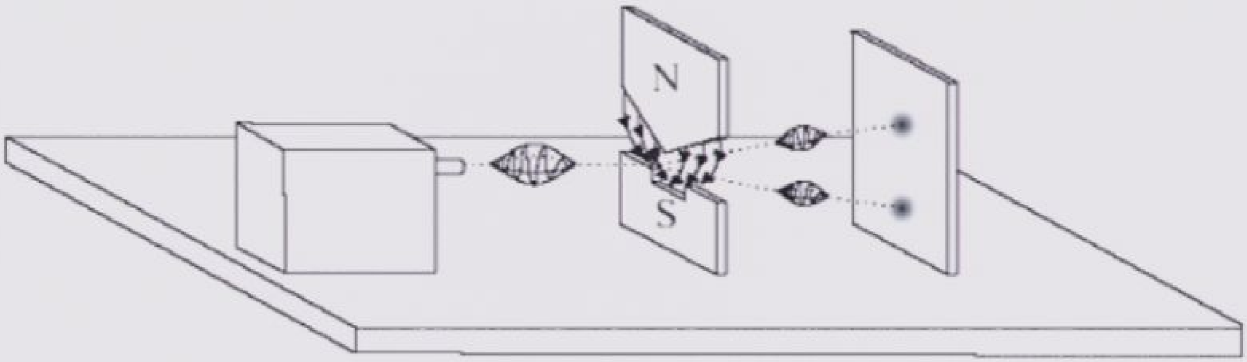


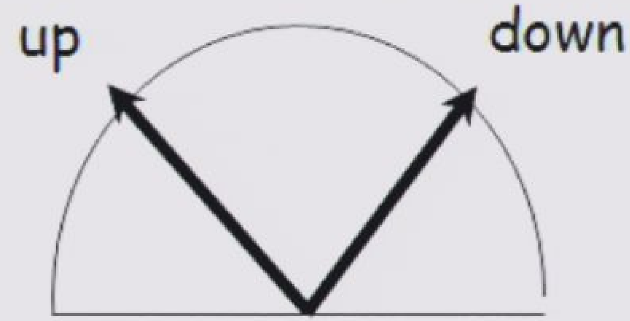
$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M)$$





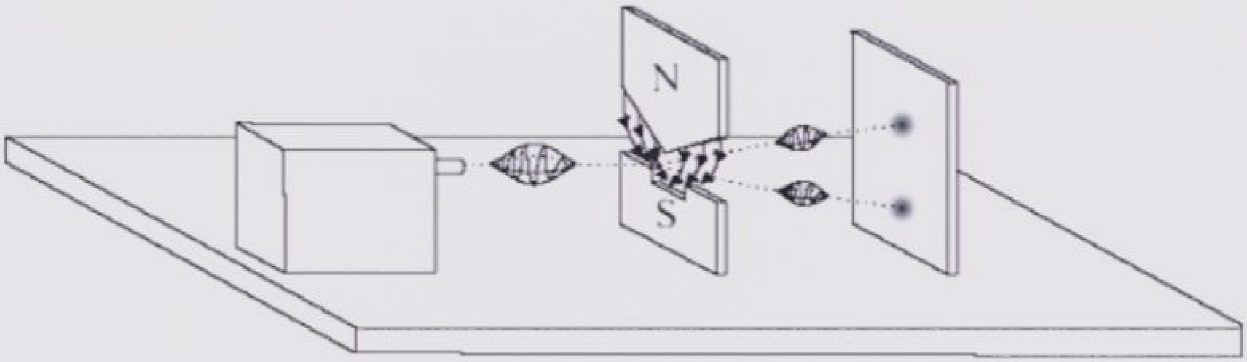
$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, ..., \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, ..., \mathbf{r}_M)$$

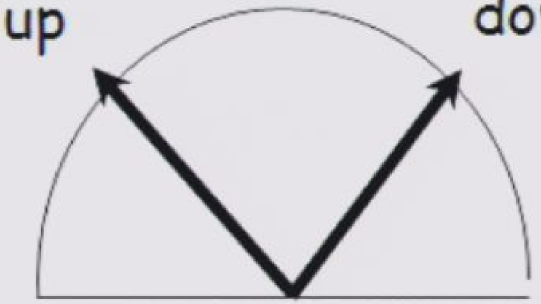




$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M)$$

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

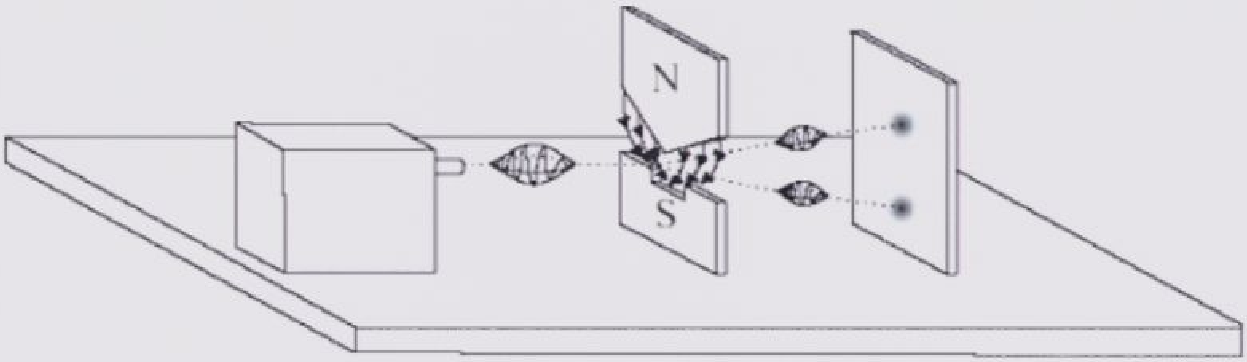


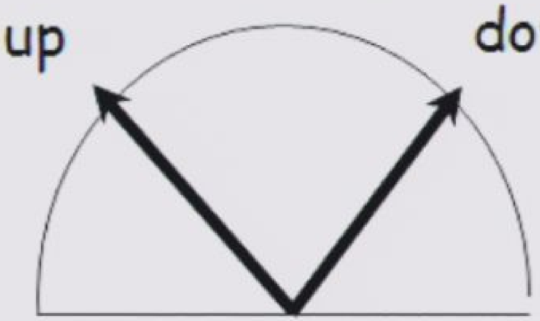


$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M)$$

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 → all are localized





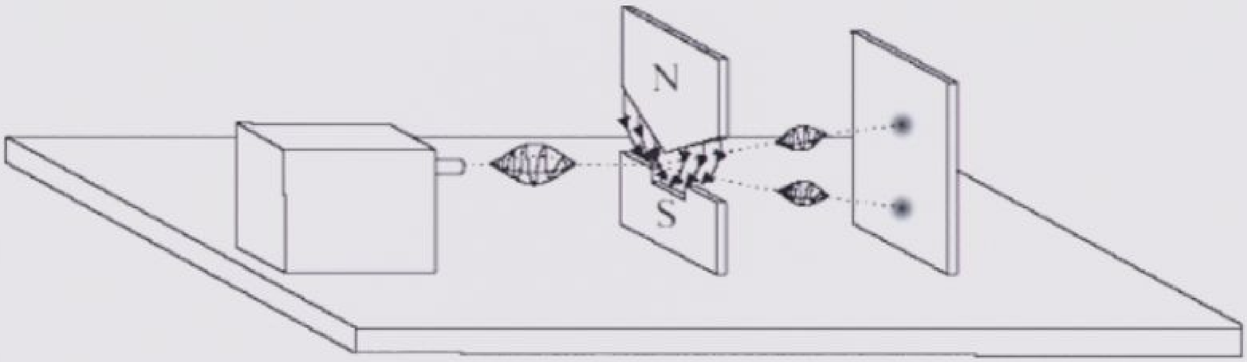
$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, ..., \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, ..., \mathbf{r}_M)$$

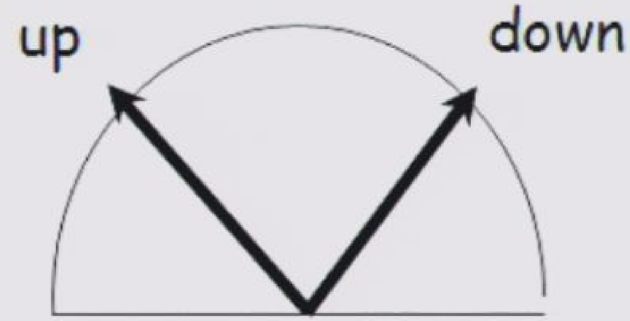
Suppose $\chi_a(\ldots\mathbf{r}_k\ldots)\chi_b(\ldots\mathbf{r}_k\ldots) \approx 0$ for macroscopic # of components

One particle is hit → all are localized

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

$$\psi' = \phi_b(\mathbf{r}_1)\chi'_b(\mathbf{r}_2, ..., \mathbf{r}_M)$$ with probability $|b|^2$





$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, \ldots, \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, \ldots, \mathbf{r}_M)$$

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

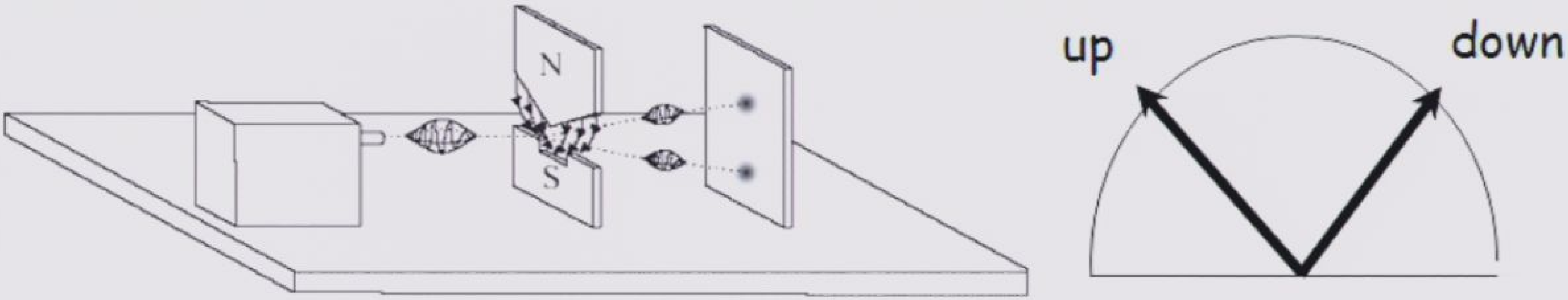
One particle is hit → all are localized

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

$$\psi' = \phi_b(\mathbf{r}_1)\chi_b'(\mathbf{r}_2, \ldots, \mathbf{r}_M)$$ with probability $|b|^2$

For $M \approx 10^{20}$ particles

This happens every $\frac{10^{15}\mathrm{s}}{10^{20}} \approx 10^{-5}\mathrm{s}$



$$\psi = a\ \phi_a(\mathbf{r}_1)\chi_a(\mathbf{r}_2, ..., \mathbf{r}_M) + b\ \phi_b(\mathbf{r}_1)\chi_b(\mathbf{r}_2, ..., \mathbf{r}_M)$$

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

One particle is hit → all are localized

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

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

For $M \approx 10^{20}$ particles

This happens every $\frac{10^{15}\mathrm{s}}{10^{20}} \approx 10^{-5}\mathrm{s}$

The apparatus gets determinate properties

Constraints on parameters

τ too big → persistence of coherence of macro objects

τ too small → loss of coherence of micro objects

Constraints on parameters

τ too big → persistence of coherence of macro objects

τ too small → loss of coherence of micro objects

σ too big → delocalized macro objects

σ too small → excitation and heating

Constraints on parameters

τ too big → persistence of coherence of macro objects
τ too small → loss of coherence of micro objects

σ too big → delocalized macro objects
σ too small → excitation and heating

Experimental status

Difficult to distinguish fundamental collapse from decoherence
Difficult to detect anamolous 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

PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

perimeter scholars
international