Title: Protective Measurement and the Interpretation of the Wave Function

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Abstract: Shan Gao

We investigate the validity of the field explanation of the wave function by analyzing the mass and charge density distributions of a quantum system. According to protective measurement, a charged quantum system has effective mass and charge density distributed in space, proportional to the square of the absolute value of its wave function. If the wave function is a description of a physical field, then the mass and charge density will be distributed in space simultaneously for a charged quantum system, and thus there will exist a remarkable electrostatic self-interaction of its wave function, though the gravitational self-interaction is too weak to be detected presently. This not only violates the superposition principle of quantum mechanics but also contradicts experimental observations.

Protective Measurement and the Interpretation of the Wave Function

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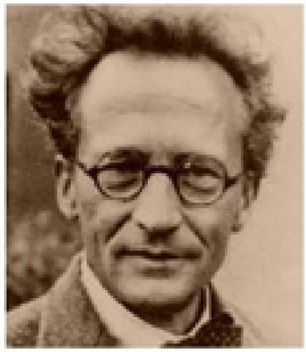
PM & the Interpretation of the Wave Function

Schrödinger asked at the fifth Solvay Conference (1927):



What does the Ψ-function mean now, that is, how does the system described by it really look like in three dimensions?

PM & the Interpretation of the Wave Function

- Two views
- PM idea
- My analysis

Two views

Two realistic views:

1. The wave function is a physical field.

   dBB theory, MWI, dynamical collapse theories etc.

2. The wave function is a description of some sort of ergodic motion of particles.

   It is assumed by stochastic interpretation etc.

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Two views

de Broglie-Bohm theory:

- The wave function is generally considered as an objective physical field, called Ψ-field.
- Various views on the nature of the field
  - a field similar to electromagnetic field (Bohm 1952)
  - active information field (Bohm and Hiley 1993)
  - a field carrying energy and momentum (Holland 1993)
  - causal agent more abstract than ordinary fields (Valentini 1997)

* nomological view (Dürr, Goldstein and Zanghì 1997)

Two views

One essential difference between them:

- A field exists throughout space at each instant.
- A particle is in one position at each instant, and only during a time interval the ergodic motion of the particle spreads throughout space.

Which view is right?

Two views

Outline of my argument

The above two views of the wave function can be tested by analyzing the **mass and charge density** of a quantum system.

- The field interpretation leads to self-interactions that contradict experimental observations.
- A further analysis may also determine which sort of ergodic motion of particles the wave function describes.

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PM idea

How do mass and charge distribute for a single quantum system?

The mass and charge of a classical system always localize in a definite position in space.

According to PM, a quantum system has effective mass and charge density distributing in space, proportional to the modulus square of its wave function.

(Aharonov, Anandan and Vaidman 1993)

PM idea

Standard von Neumann procedure

$$H_I = g(t)PA$$

1. Conventional impulse measurements

   Coupling interaction: short duration and strong.
   Measurement result: eigenvalues of A.
   Expectation value of A is obtained from the ensemble average.

2. Weak measurements

   Coupling interaction: short duration but **weak**.
   Measurement result: **expectation value** of A.
   Individual measurement is imprecise. A normal ensemble is needed.

3. **Protective measurements**

   Coupling interaction: **long duration** and **weak**.
   Measurement result: **expectation value** of A.
   Individual measurement is **precise**. Only a small ensemble is needed.

PM idea

The mass and charge density can be measured by PM as expectation values of certain variables for a single quantum system.

- An appropriate adiabatic measurement of the *Gauss* flux out of a certain region will yield the value of the total charge inside this region, namely the integral of the effective charge density $Q|\psi(x,t)|^2$ over this region.

- Similarly, we can measure the effective mass density of the system in principle by an appropriate adiabatic measurement of the flux of its gravitational field.

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PM idea

A quantum system has effective mass and charge density distributing in space, proportional to the modulus square of its wave function.

- PM strongly suggests a realistic view of QM because the wave function can be measured by it even for a single quantum system, though there were some controversies about this conclusion. (see, e.g. Rovelli 1994; Uffink 1999; Dass and Qureshi 1999)
- Anyway if one insists on a realistic interpretation, then PM will have strict restrictions on the realistic views.

Which view is consistent with this result?

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My analysis

- If the mass and charge density **simultaneously** distributes in space (i.e. taking the wave function as a physical field),
- Then the densities in different regions will have gravitational and electrostatic interactions.
- This not only violates the superposition principle of QM but also contradicts experimental observations.

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My analysis

- The free Schrödinger equation with electrostatic self-interaction for an electron is

$$i\hbar\frac{\partial\psi(x,t)}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi(x,t) + ke^2\int\frac{|\psi(x',t)|^2}{|x-x'|}d^3x'\,\psi(x,t)$$

- The measure of the strength of the electrostatic self-interaction (Salzman 2005) is

$$\varepsilon^2 = \left(\frac{4ke^2}{\hbar c}\right)^2 \approx 1\times10^{-3}$$

- The evolution of the wave function of an electron will be observably different from that predicted by QM and confirmed by experiments.

[The energy levels of hydrogen atoms will be observably changed]

My analysis

- Therefore, the mass and charge density cannot exist throughout space simultaneously.
- This means that at each instant there is only a localized particle with mass and charge, and only during a time interval, the time average of the ergodic motion of the particle forms the effective mass and charge density.
- The wave function is a description of some sort of **ergodic motion of particles**.

My analysis

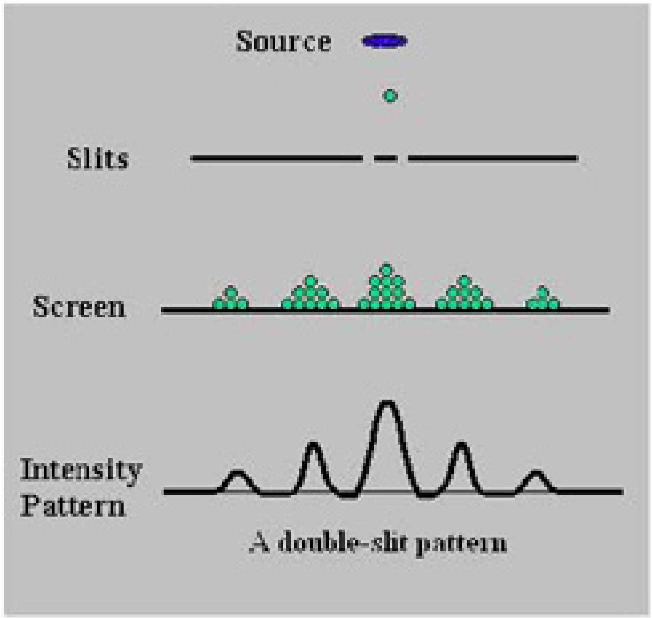
Which sort of ergodic motion?

- The classical ergodic models that assume continuous motion of particles are not consistent with QM.
  - problems of stochastic interpretation (Nelson 2005)
  - infinite velocity at the nodes of a stationary state
  - sudden acceleration and large radiation near these nodes
  - finite ergodic time

- The ergodic motion must be discontinuous.

My analysis

Double-slit experiment



A double-slit pattern

A single particle passes through both slits in a discontinuous way.

> A phenomenon which is impossible, absolutely impossible, to explain in any classical way.
>
> —R. Feynman

My analysis

By assuming the wave function is a (complete) description for the motion of particles, we can reach this conclusion in a more direct way, independent of the above analysis.

- The modulus square of the wave function not only gives the probability density of **finding** a particle in certain locations, but also gives the objective probability density of the particle **being** there.

  (they should be the same when assuming M reflects R)

- Obviously, this kind of motion is essentially random and discontinuous.

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My analysis

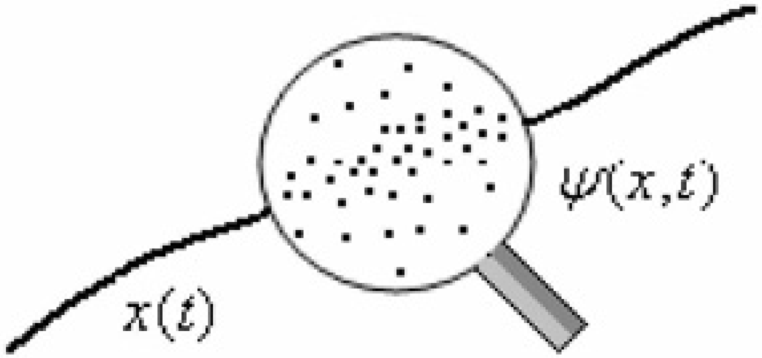
> The wavefunction gives not the density of stuff, but gives rather (on squaring its modulus) the density of probability. Probability of what exactly? Not of **the electron being there**, but of **the electron being found there**, if its position is 'measured'. Why this aversion to 'being' and insistence on 'finding'? The founding fathers were unable to form a clear picture of things on the remote atomic scale.
>
> — J. S. Bell, Against "measurement" (1990)

Bell's Everett (?) theory (1986)

My analysis

PM suggests:

The wave function is a description of quantum motion of particles, which is essentially discontinuous and random.



Motion Is Discontinuous and Random

My analysis

- **Some results and left problems:**
  - de Broglie-Bohm theory is problematic.
  - QM is a one-world theory.
  - Dynamical collapse theories are in the right direction.

But existing theories require major revision

- Ontology-revised from field to particle
- Reformulated in the framework of RDM (e.g. the random source to collapse the wave function is not a classical field but the inherent random motion of particles)

There are still some hard problems, e.g. energy conservation, Lorentz invariance, physical origin of collapse…

PM & the Interpretation of the Wave Function

Summary

PM implies WF has mass and charge density.

- The field view leads to self-interactions.
- Classical ergodic models of particles also fail.

What the wave function describes is random discontinuous motion of particles.

Shan Gao (2010), *Meaning of the wave function.* (http://philsci-archive.pitt.edu/8342/)

Selected Publications

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