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Title: Wavefunction Collapse via a Nonlocal Relativistic Variational Principle

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Wavefunction Collapse via a Nonlocal Relativistic Variational Principle: A New Theory of Quantum Mechanics

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XCP-1

T-2 Seminar
and
Quantum Lunch

June 19, 2012

LA-UR 12-20374

Abstract

Since the origin of quantum theory in the 1920's, some of its practitioners (and founders!) have been troubled by some of its features, including indeterminacy, nonlocality and entanglement. The "collapse" process described in the Copenhagen Interpretation is suspect for several reasons, and the act of "measurement," which is supposed to delimit its regime of validity, has never been unambiguously defined. In recent decades, nonlocality and entanglement have been studied energetically, both theoretically and experimentally, and the theory has been reinterpreted in imaginative ways, but many mysteries remain.

We propose that it is necessary to *replace the theory* by one that is explicitly nonlinear and nonlocal, and does not distinguish between measurement and non-measurement regimes. We have constructed such a theory, for which the phase of the wavefunction plays the role of a hidden variable via the process of zitterbewegung. To capture this effect, the theory must be relativistic, even when describing nonrelativistic phenomena. It is formulated as a variational principle, in which Nature attempts to minimize the sum of two spacetime integrals. The first integral tends to drive the solution toward a solution of the standard quantum mechanical wave equation, and also enforces the Born rule of outcome probabilities. The second integral drives the collapse process.

We demonstrate that the new theory correctly predicts the possible outcomes of the electron two-slit experiment, including the infamous "delayed-choice" variant. We observe that it appears to resolve some long-standing mysteries, but introduces new ones, including possible retrocausality (a cause later than its effect). It is not clear whether the new theory is deterministic.

Outline

- Defining the task (view from 20,000 feet)
  - What's wrong with standard quantum mechanics?
  - Characteristics of a new theory
  - But are hidden-variable theories allowed?
- The proposed variational principle
  - Nature minimizes a sum of integrals over all (or regions of) spacetime
  - A_1 term drives toward wave equation solution
  - A_2 term drives collapse
  - A_1 limits collapse rate
  - A_1 enforces Born rule
- Example calculation—the electron two-slit experiment
  - Original and "delay-choice" variants
  - Calculation of the original form of the experiment
  - Prediction for the delayed-choice form
- Quantum mysteries old and new
- Where do we go from here?

What’s wrong with standard quantum mechanics: Wave function versus “collapse”

Wave equation is linear, deterministic, and time-symmetric

Collapse process is nonlinear, intrinsically random, and asymmetric in time; its workings are unknown and *unknowable*

Regimes of validity depend on the answer to the question, “Is a measurement being made?”—but “measurement” is not well-defined

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—E. Schrödinger, quoted by John Bell.

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> [S]o long as the wave packet reduction is an essential component, and so long as we do not know exactly when and how it takes over from the Schrödinger equation, we do not have an exact and unambiguous formulation of our most fundamental physical theory.
>
> —John Bell, "On wave packet reduction in the Coleman-Hepp model," in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, 2nd ed. (Cambridge, 2004).

What’s wrong with standard quantum mechanics: Dependence on the observer

Who qualifies as an observer?

So what do you do for the wavefunction of the universe?

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Was the world wavefunction waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it it have to wait a little longer for some more highly qualified measurer—with a Ph.D.?

—John Bell, "Quantum mechanics for cosmologists," in J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics*, 2nd ed. (Cambridge, 2004).

What’s wrong with standard quantum mechanics: More complaints

I am suspicious of the following:

Intrinsic randomness of nature

Time asymmetry of the collapse process

Re-interpretation of QM as a theory of the observer’s knowledge

We were all taught to accept these features,
but is there an alternative?

Many other "fixes" have been proposed

Here are a few (far from a complete list!):

Pilot-wave theory
L. de Broglie (1927), D. Bohm (1952)

Relative state ("many worlds") interpretation
H. Everett (1957)

Nonlinear Schrödinger equations
P. Pearle (1976)

Stochastic wave equations, collapse theories
P. Pearle (1979), N. Gisin (1984), G. Ghirardi, A. Rimini, T. Weber (1986), L. Diosi (1990)

Transactional interpretation
J. Cramer (1980)

Decoherence
H. D. Zeh (1980), W. Zurek (1981 etc.)

Consistent histories
R. Griffiths (1984)

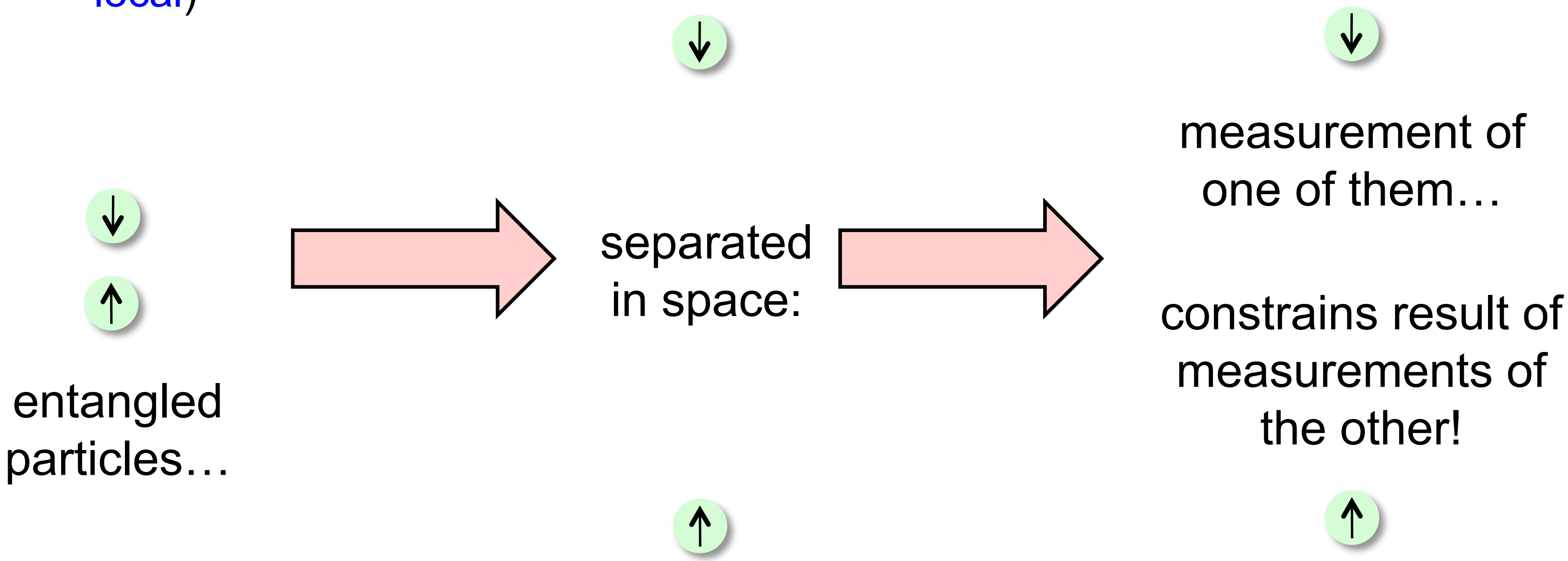
Characteristics desired for the new theory

- Unified formulation for measurement, non-measurement regimes
- Phase of the wavefunction as a hidden variable
  - Manifested in zitterbewegung (beats between positive- and negative-energy modes)
  - Zitterbewegung frequency ~ 10^{20} Hz, so "hidden" from experimenters
  - Relativistic formulation required (even for non-relativistic systems)
- Nonlinear, nonlocal form
  - Nonlocality ⇨ integral form ⇨ variational principle
  - Relativistic requirement ⇨ integrals over 4-D spacetime
- Consistent with the experimental record; e.g., satisfies the Born rule (the rule that outcome probabilities = square of initial amplitudes in original superposition)

But aren’t hidden-variable theories impossible?

Einstein, Podolsky and Rosen (1935) thought experiment

They described a thought experiment with nonlocal effects that seem wrong—unless one adds hidden variables to the theory (and thus keeps the effects local)



But EPR's disagreement with the orthodox (Copenhagen) interpretation appeared to be merely philosophical (that is, not experimentally testable)

John Bell (1964) discovered a way to resolve the dispute experimentally

One makes a large number of EPR-type measurements, collecting statistics

If nature is described by a local hidden-variable theory, statistics will satisfy the "Bell inequality."

On the other hand, standard quantum mechanics (SQM) will violate the Bell inequality.

Many such experiments have been conducted (Clauser et al., Aspect et al., …) and always found to agree with SQM.

This rules out local hidden-variable theories.

Bell-type measurements still admit the possibility of *nonlocal* hidden-variable theories

To those for whom nonlocality is anathema, Bell's Theorem finally spells the death of the hidden-variables program. But not for Bell. None of the no-hidden-variables theorems persuaded him that hidden variables were impossible. What Bell's Theorem did suggest to Bell was the need to reexamine our understanding of Lorentz invariance…. "What is proved by impossibility proofs," Bell declared, "is lack of imagination."

—N. D. Mermin, "Hidden variables and the two theorems of John Bell," Rev. Mod. Phys. 65(3), 803-815 (1993).

But didn't von Neumann prove that hidden-variable theories are untenable?

(1932) John von Neumann publishes "proof" that hidden-variable theories are not possible

(1935) Grete Hermann points out fatal flaw in von Neumann's argument—unnoticed

(1952) David Bohm publishes hidden-variables theory (based on work by de Broglie, 1927) that predicts same results as SQM (and thus cannot be disproved!)—gains little attention

(published 1966) John Bell realizes that Bohm's theory is an existence proof, and rediscovers von Neumann's error

No, he didn't.

The proposed variational principle (VP)

- Nature minimizes a sum of integrals over all (or regions of) spacetime

$$\delta(A_1 + \epsilon A_2) = 0$$

- A_1 term drives solution toward solution of standard QM wave equation
- A_2 term drives wavefunction collapse
- A_1 limits collapse rate
- A_1 enforces Born rule
- ϵ is constant and dimensionless (and presently unknown)

A_1 term drives solution toward solution of standard QM wave equation

For the Dirac equation

$$(\not{\pi} - m)\,\psi = 0$$

we take

$$A_1 = \left\langle (\not{\pi}^{\dagger} - m)\,(\not{\pi} - m) \right\rangle$$

$$= \frac{\int_{\mathcal{R}} d^4x\ \psi^{\dagger}\,(\not{\pi}^{\dagger} - m)\,(\not{\pi} - m)\,\psi}{m^2 \int_{\mathcal{R}} d^4x\ \psi^{\dagger}\,\psi}$$

(integration over one spacetime position)

A_2 term drives wavefunction collapse

We minimize the position-momentum (and time-energy) uncertainty by defining

$$A_2 = \left\langle \left\{ \left(x_1^\mu - x_2^\mu \right) \left[p_{3\mu}(x_3) - p_{4\mu}(x_4) \right] \right\}^2 \right\rangle$$

$$= \left\langle \left(\delta t \, \delta E - \overrightarrow{\delta x} \cdot \overrightarrow{\delta p} \right)^2 \right\rangle$$

(four-point integration).

A superposition of states has greater uncertainty A_2 than a pure state, so A_2 drives the wavefunction toward collapse.

Nonlocality of A_2 term: Integration variables must be spacelike separated

Two-point integral:
$$\int d^4x\, d^4y\, \psi^\dagger(x)\, \psi^\dagger(y)\, \mathcal{O}(x,y)\, \psi(x)\, \psi(y)\, f(x-y)$$

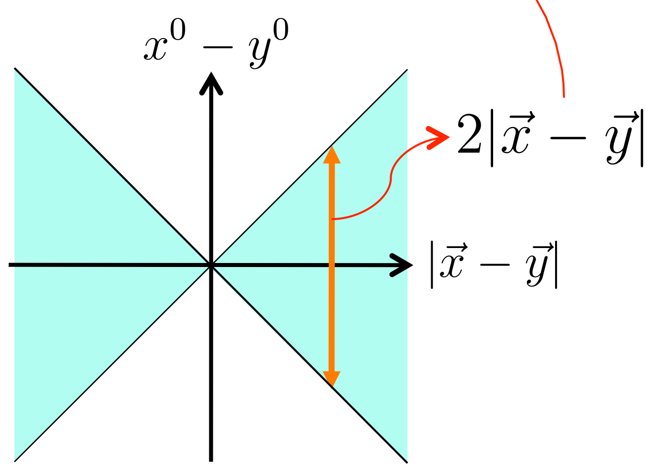
unit step function

spacelike separated
$$f(z) = u(-z^\mu z_\mu) = u\left[|\vec{z}|^2 - (z^0)^2\right]$$

spacelike separated, weighted
$$f(z) = \frac{u(-z^\mu z_\mu)}{2|\vec{z}|} \quad ☆$$

spacelike separated, weighted, relativistically covariant
$$f(z) = \frac{u(-z^\mu z_\mu)}{\pi\sqrt{-z^\mu z_\mu}} \quad ☆$$

☆ has property $\int dy^0\, f(x-y) = 1$



We extend this idea to four points for the A_2 term

The f factor allows spacetime integrals to factor

If $\mathcal{O}(x,y) = R(x)\,S(y)$ and $\psi^\dagger(x)\,\psi(x)$ vary slowly in time,

we can use the property $\int dy^0\, f(x-y) = 1$

to write

$$\int d^4x\, d^4y\;\psi^\dagger(x)\,\psi^\dagger(y)\,\mathcal{O}(x,y)\,\psi(x)\,\psi(y)\,f(x-y)$$

$$\cong \int dx^0 \int d^3x\, d^3y\;\psi^\dagger(x^0,\vec{x})\,\psi^\dagger(x^0,\vec{y})\,R(x^0,\vec{x})\,S(x^0,\vec{y})\,\psi(x^0,\vec{x})\,\psi(x^0,\vec{y}) \int dy^0\, f(x-y)$$

$$= \int dt \left[\int d^3x\;\psi^\dagger(t,\vec{x})\,R(t,\vec{x})\,\psi(t,\vec{x})\right]\left[\int d^3y\;\psi^\dagger(t,\vec{y})\,S(t,\vec{y})\,\psi(t,\vec{y})\right]$$

and then use ordinary 3-space orthonormality relations to evaluate integrals!

We extend this idea to four points for the A_2 term

A_1 term limits collapse rate

If we expand

$$\psi(t,\vec{x}) = \sum_j C_j(t)\,\psi_j(t,\vec{x})$$

then it turns out that

$$A_1 \propto \int dt\,\sum_j |C_j'(t)|^2$$

which penalizes rapid changes in the wavefunction.

This prevents collapse from being instantaneous.

The experimental record (interpreted according to standard QM) cannot resolve below $\Delta t \lesssim \hbar/\Delta E$, so there is no contradiction.

A_1 term enforces Born rule

Let $C_j(t;t_i) = C_j$ at time t, if measurement began at time t_i

$A_1 = 0 \Rightarrow |C_j(t;t_i)|^2 \simeq |C_j(t_i;t_i)|^2 + \text{zitterbewegung}$

so (1) outcome depends on start time t_i ,

~10^{20} Hz function of t_i

(2) zitterbewegung is the mechanism, and

(3) Born rule is satisfied; averaging over t_i,

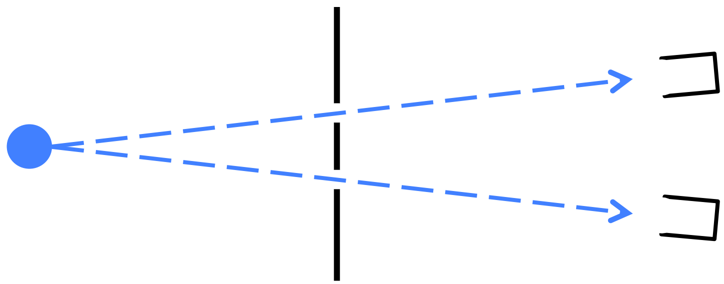
$$\Rightarrow \overline{|C_j(t)|^2} \simeq \text{constant}$$

But at initial time, $\overline{|C_j(t)|^2}$ is initial weight of mode *j*

At final time, $\overline{|C_j(t)|^2}$ is probability that system ended up in mode *j*

Equality of these quantities is the Born rule!

The two-slit interference experiment is a classic demonstration of wave-particle duality



particle detectors ⇨ position measurement

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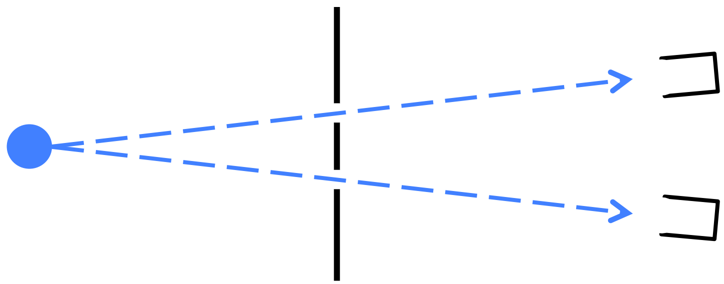
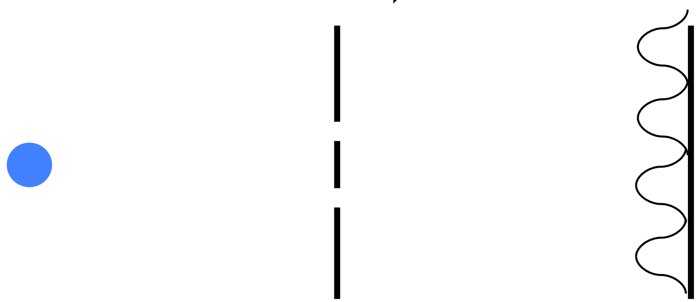


particle detectors → position measurement



extended detector → wavelength measurement

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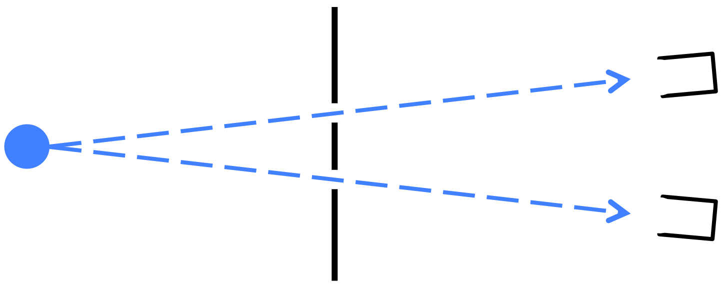
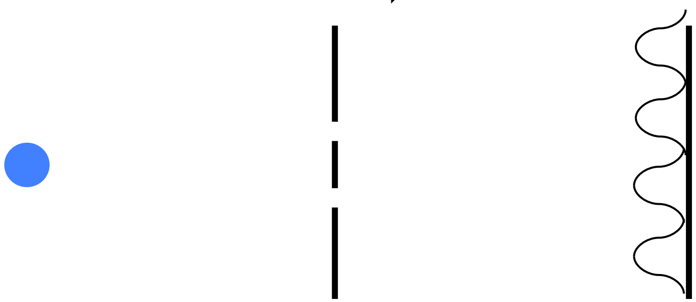


particle detectors ⇨ position measurement



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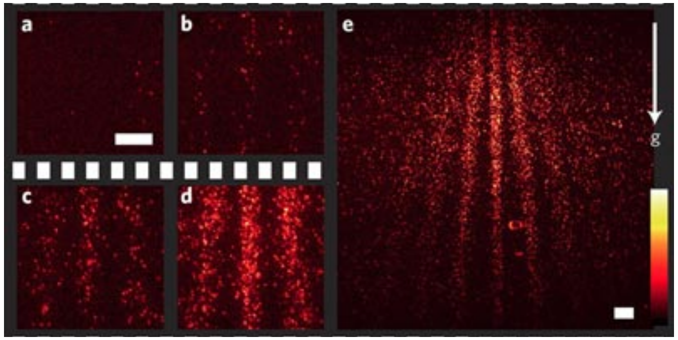

one particle at a time ⇨
build up wavelength measurement

IMAGE: Thomas Juffmann, Adriana Milic, Michael Müllneritsch, Peter Asenbaum, Alexander Tsukernik, Jens Tüxen, Marcel Mayor, Ori Cheshnovsky & Markus Arndt, “Real-time single-molecule imaging of quantum interference,” Nature Nanotechnology (2012) doi:10.1038/nnano.2012.34, published online 25 March 2012. Image posted March 29, 2012 at http://physicsworld.com/cws/article/news/2012/mar/29/quantum-interference-the-movie.

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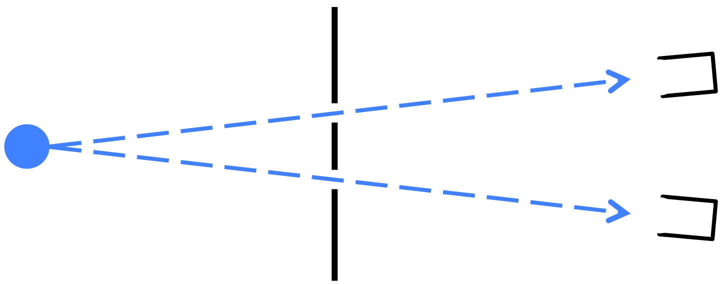

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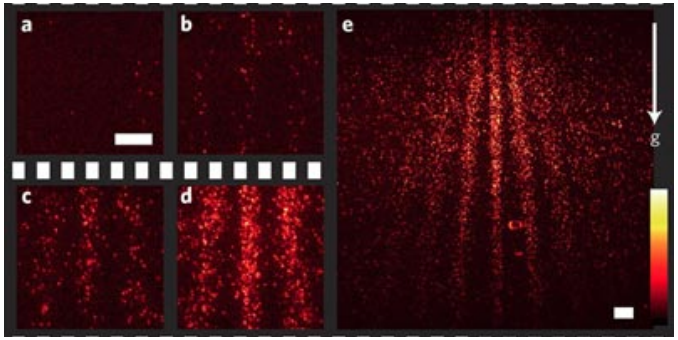
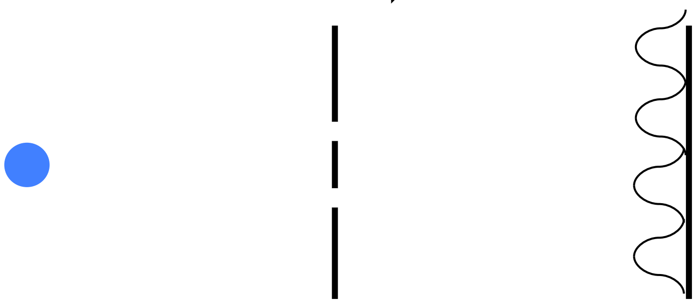
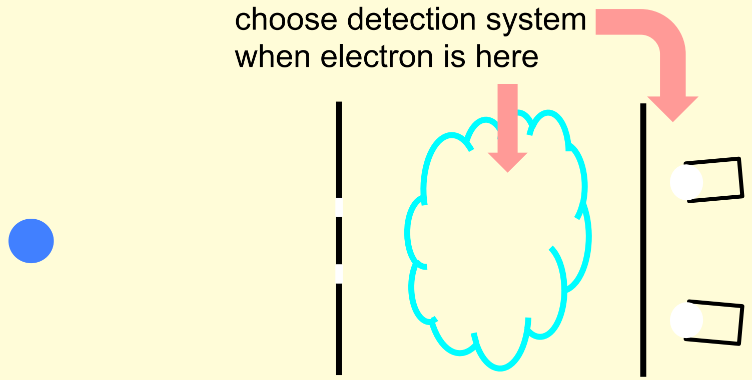


one particle at a time ⇨
build up wavelength measurement

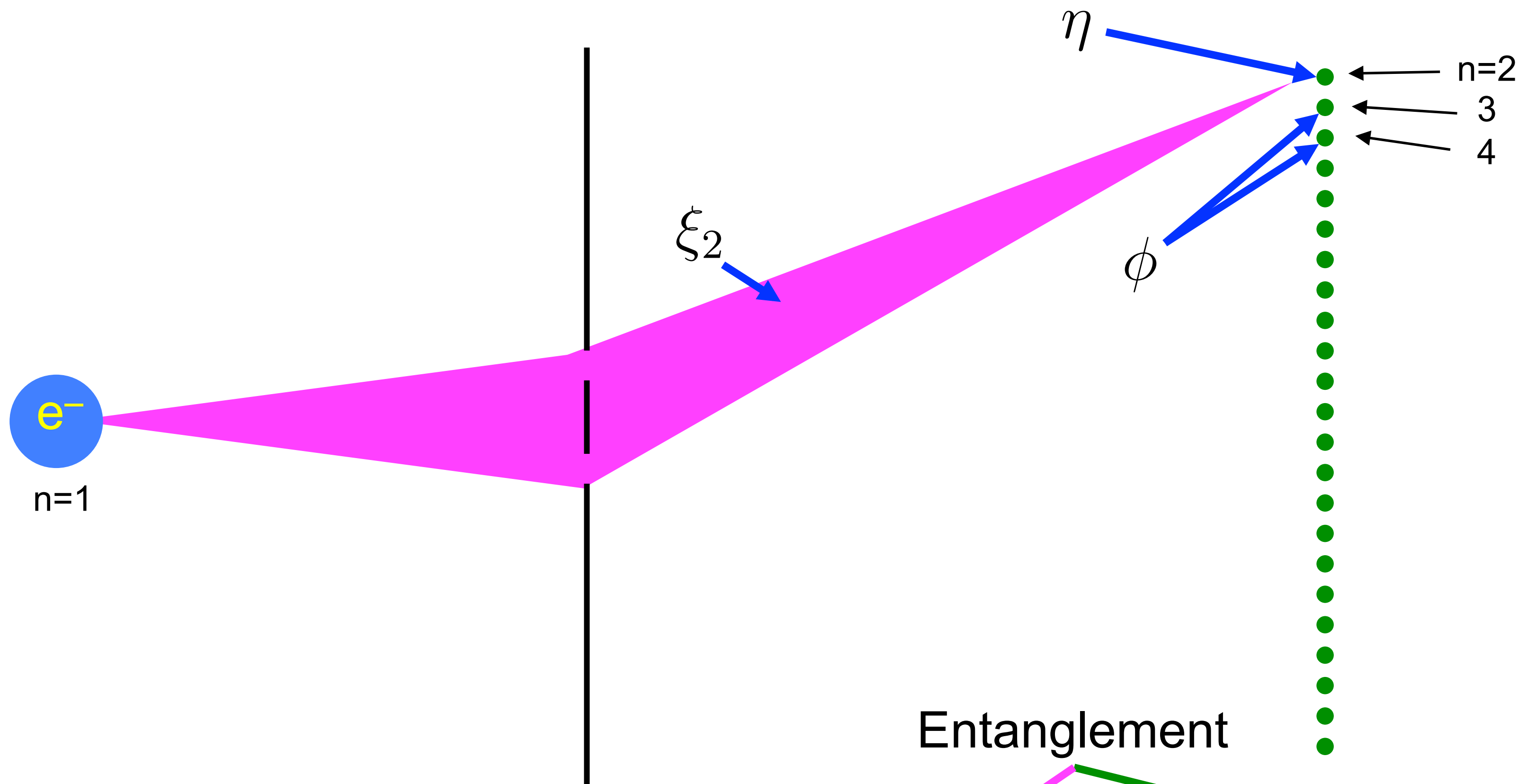


extended detector ⇨ wavelength measurement



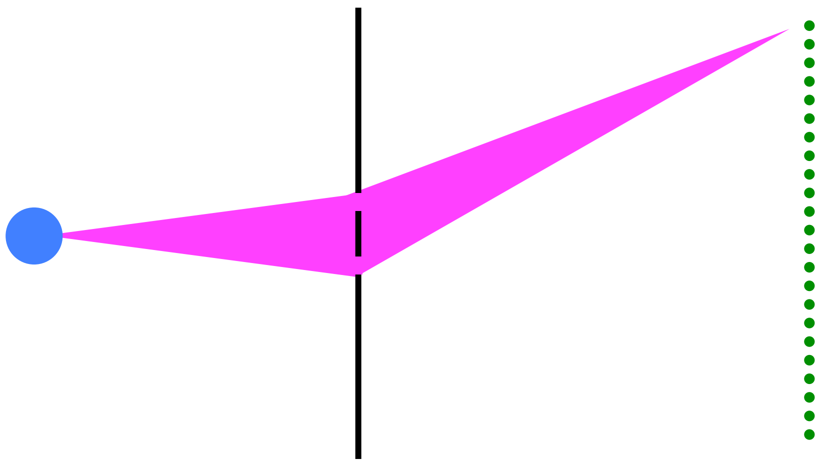
“delayed choice” ⇨
same as original experiment!

We apply the VP to the electron two-slit experiment



$$\psi(x_1, x_2, x_3, \ldots, x_N) = \sum_{n=2}^{N} C_n(x_1^0)\,\xi_n(x_1)\,\eta(x_n - b_n) \prod_{\substack{m=2 \\ m \neq n}}^{N} \phi(x_m - b_m)$$

The VP predicts the results of the electron two-slit experiment



A_2 = *x-p* uncertainty (e[-])
+ zero-point uncertainty (e[-])
+ *t-E* uncertainty (atoms)
+ zero-point uncertainty (atoms)

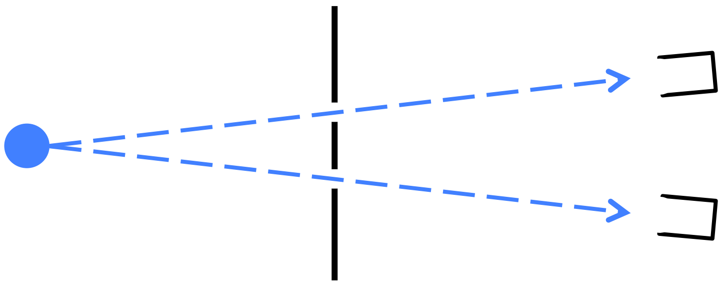
minimized if superposition contains only one term

constant

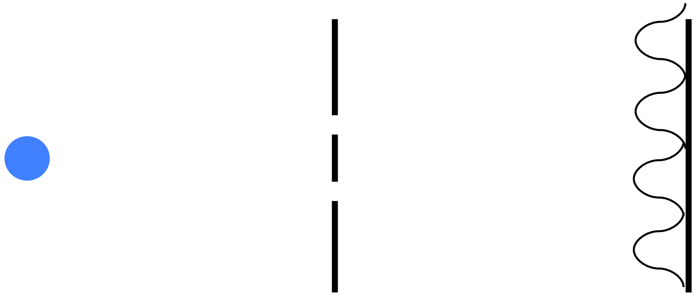
A_2 forces collapse ⇨ localized measurement gives position
A_1 forces collapse to be smooth
A_1 enforces Born rule ⇨ detected positions sum to interference pattern

so we predict position measurements, wavelength measurements, and the transition from one to the other!

How do we understand this solution intuitively?



It's not ballistic motion



nor a solution to the conventional wave equation

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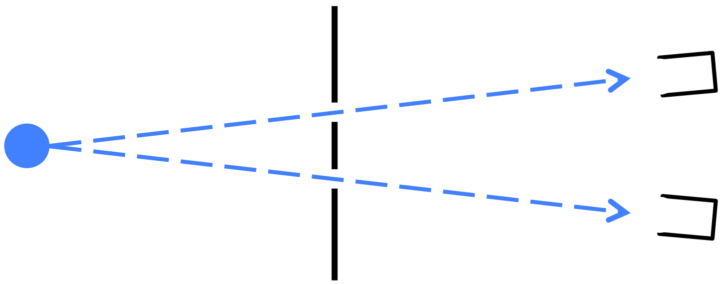

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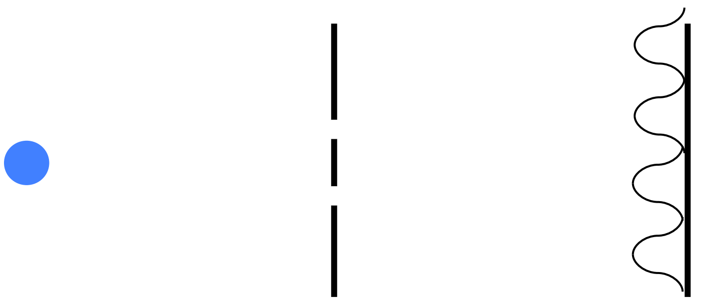

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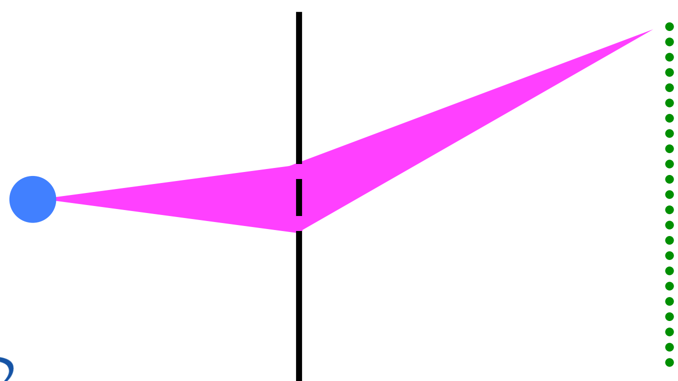
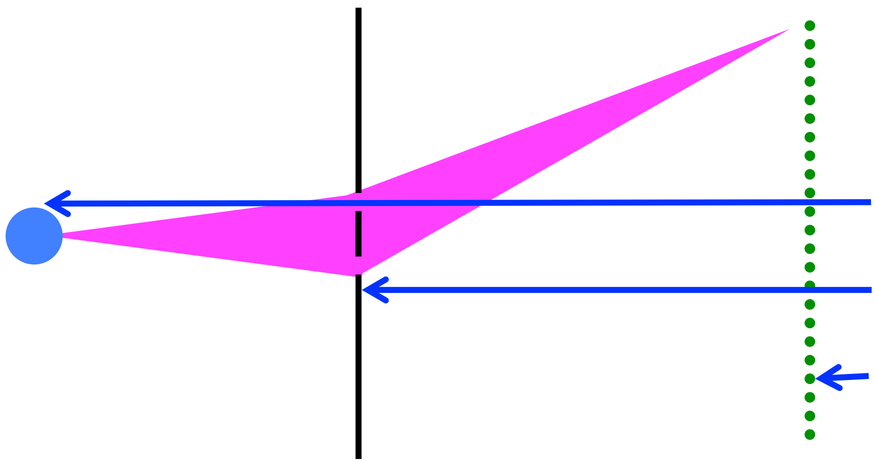


but a wave that satisfies the VP, and ends up at a well-defined location

What about the delayed-choice variant?



The integrals in the VP have significant contributions from electron wavefunction

here, only at early times

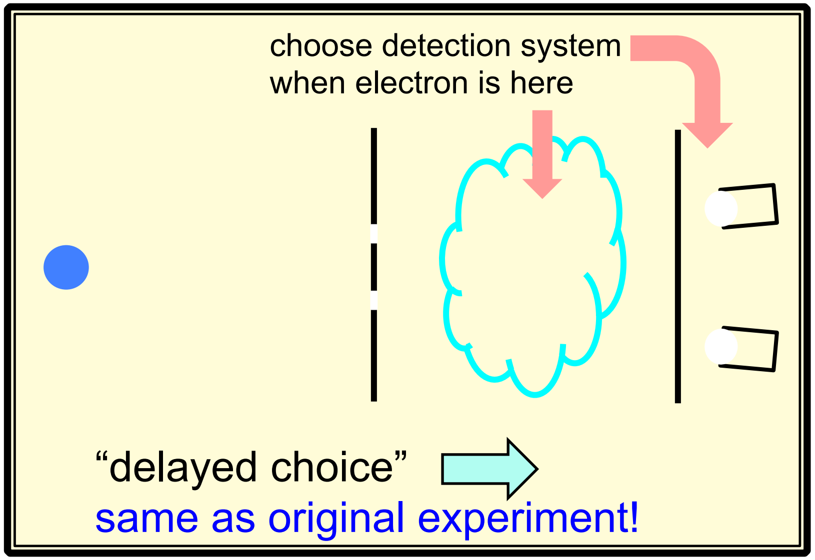
here, only at intermediate times

here, only at late times

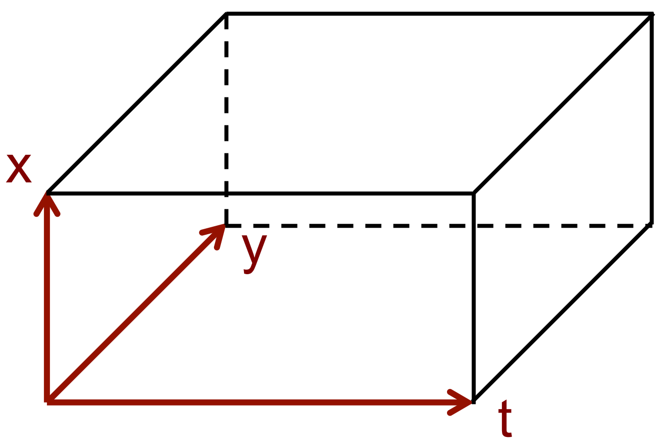
…so the solution doesn't care when the detection system was set up, as long as it is there when the electron arrives!

Therefore the VP correctly predicts that the "delayed-choice" variant has the same outcome as the original experiment.

What happened to the paradox?



The "paradox" is the question "*When* did the electron decide whether to go through one slit or both?"



But we assert that Nature chooses solutions based on considering a block of spacetime (not just space)

So the decision was not made at a moment in time, but *outside of time!*

Old mysteries addressed by this theory

- Unified theory for linear (unitary) and nonlinear (collapse) behavior
- No need for “observer” or special definition of “measurement”
- Not a theory about someone’s knowledge
- Time-symmetric

New mysteries to ponder

- Possible retrocausation (causes after effects)
  - How does Nature avoid paradoxes?
- How does Nature solve the optimization problem?
  - Local or global solution?
- Is the theory deterministic?
- How can *we* solve the optimization problem?

Where do we go from here?

- Apply theory to various *gedanken* and real experiments
- Experimental tests of the theory
  - Can the (nonzero) duration of the "collapse" process be measured?
  - Since competition with A_2 prevents A_1 from always being precisely zero, Born rule isn't exact; can we predict and measure deviations from it?
  - Is it possible to make repeated measurements quickly enough to detect temporal correlations arising from the phase of the wavefunction?
- Extend to quantum field theory
  - Apply to photon experiments, e.g., "quantum eraser" variant of two-slit experiment
  - Apply at higher energies
- etc.

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He is, however, solely responsible for all errors and deficiencies in the work.

References to this work

A. K. Harrison, “Wavefunction Collapse via a Nonlocal Relativistic Variational Principle,” LA-UR-12-20152, submitted to Foundations of Physics; arXiv: 1204.3969v1 [quant-ph].

A. K. Harrison, “Calculation of the electron two slit experiment using a quantum mechanical variational principle,” LA-UR-12-20455, submitted to Physica Scripta; proceedings of the conference “Frontiers of Quantum and Mesoscopic Thermodynamics,” Jul. 25-30, 2011, Prague, Czech Republic.