XXXth International Workshop on High Energy Physics

How far can a pragmatist go into quantum theory?

History and philosophy of quantum theory

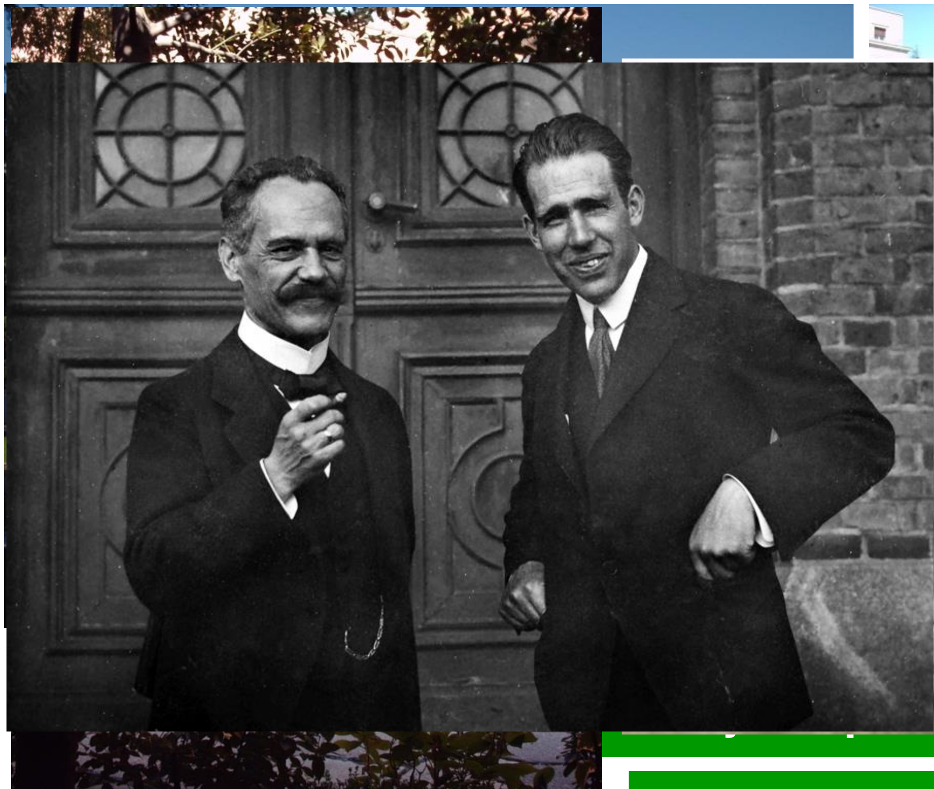
A critical view on current understanding of quantum phenomena

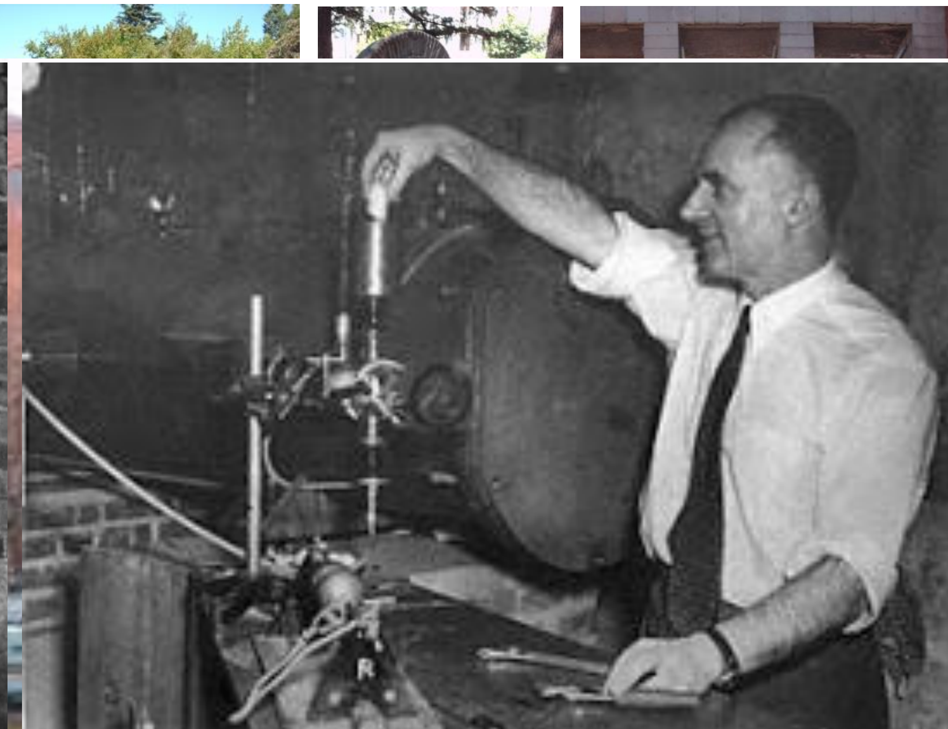
Ángel S. Sanz

Instituto de Física Fundamental (CSIC), Madrid, Spain

Protvino, June 25, 2014

The CSIC Institute of Fundamental Physics





Centro de Física "Miguel Antonio Catalán" (CFMAC)

Eckert, Arnold Sommerfeld – Science, Life and Turbulent Times (1868-1951) (Springer, New York, 2013)

Instituto de Estructura de la Materia (IEM)

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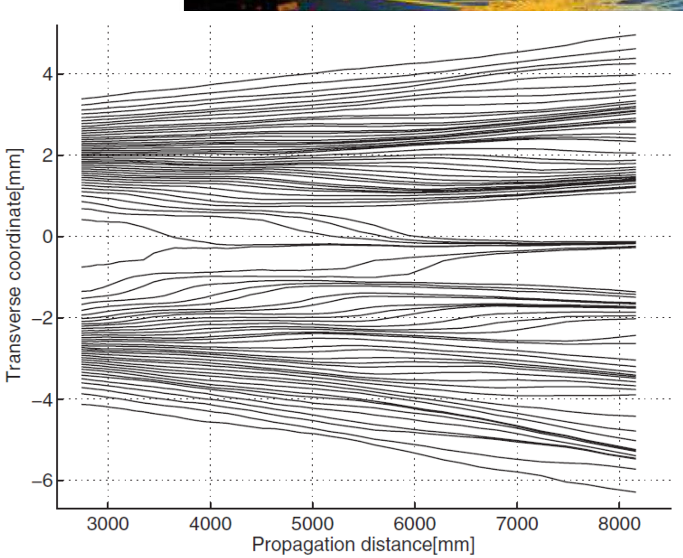
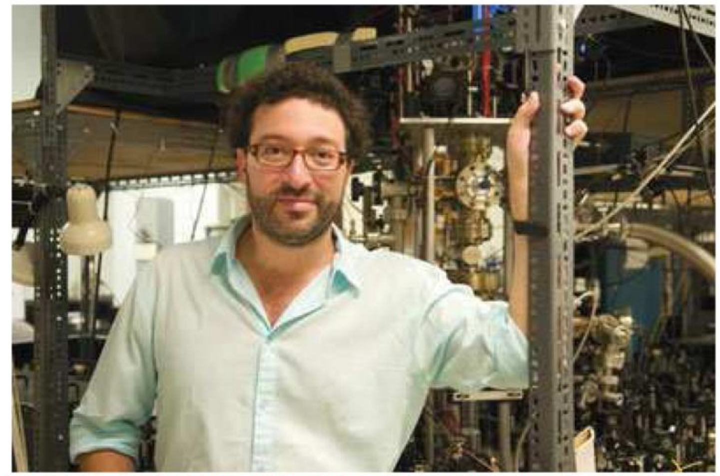
Physics World breakthroughs

***Physics World* reveals its top 10 breakthroughs for 2012**



***Physics World* reveals its top 10 breakthroughs for 2011**

c 16, 2011 13 comments



Aephraim Steinberg wants you to throw off your quantum biases

The two physics stories that dominated the news in 2011 were questions rather than solid scientific results, namely "Do neutrinos travel faster than light?" and "Has the Higgs boson been found?". However, there have also been some fantastic bona fide research discoveries over the last 12 months, which made it difficult to decide on the *Physics World* 2011 Breakthrough of the Year.

But after much debate among the *Physics World* editorial team, this year's honour goes to Aephraim Steinberg and colleagues from the University of Toronto in Canada for their experimental work on the fundamentals of quantum mechanics. Using an emerging technique called "weak measurement", the team is the first to track the average paths of single photons passing through a Young's double-slit experiment – something that Steinberg says physicists had been "brainwashed" into thinking is impossible.

How to interpret the quantum world?

von Neumann (1930's)

Collapse of the wave function

Quantum mechanics is complete

No hidden variables

How to interpret the quantum world?

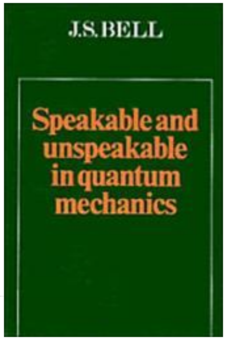
von Neumann (1930's)

Col e wave function

Qua hanics is complete

hidden variables

Bohm (1952)

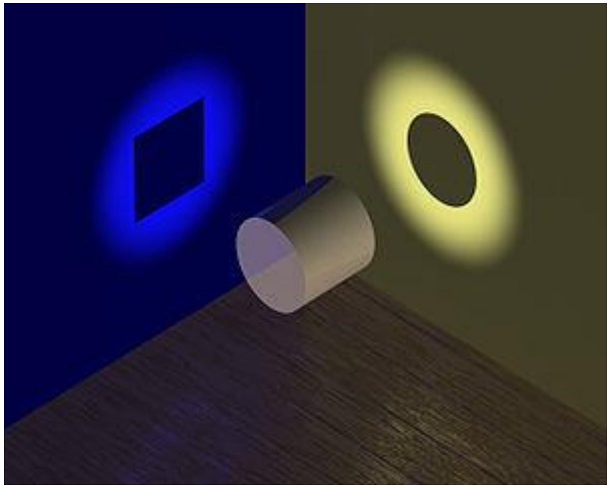


Bell (1960's)

local realism ⟶ ~~local hidden variable models/theories~~

nonlocal realism ⟶ nonlocal hidden variable "theories"

How to interpret the quantum world?



Copenhagen

No solution until observation

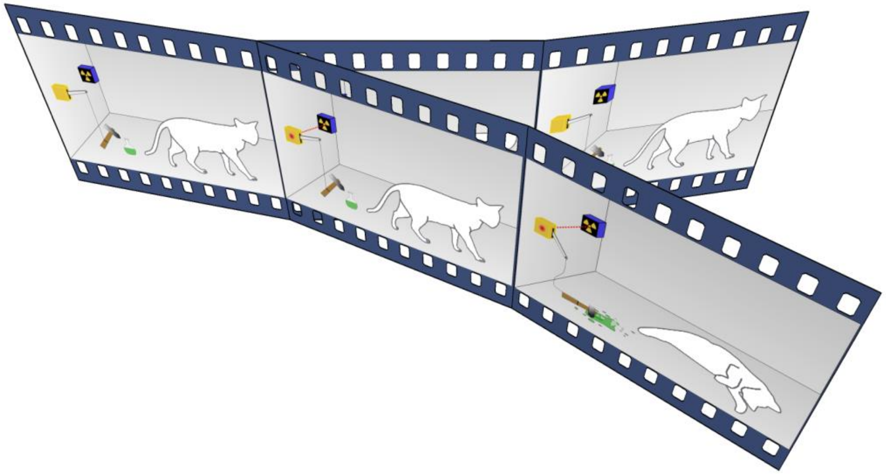
System collapse

Subjective (external observer)

Objective (e.g., gravity)

Quantum Information

No description of the physical world, but of the knowledge about it



Many worlds (multiverses)

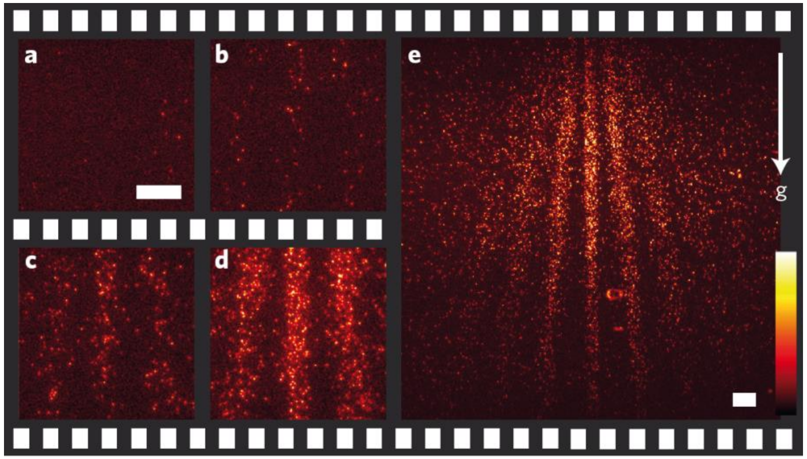
One solution for each universe

Consistent Histories

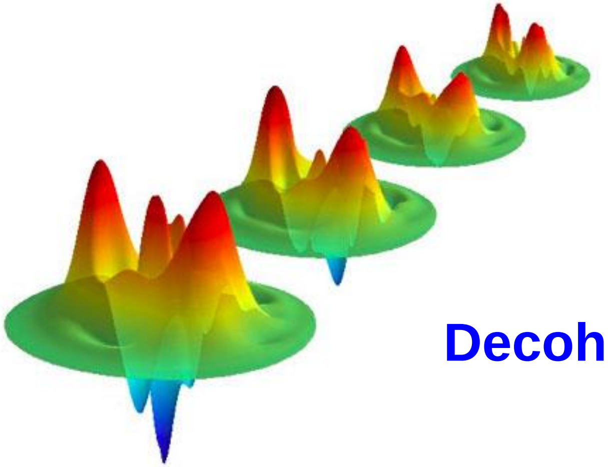
A probability is assigned to the history of a system

How to interpret the quantum world?

Statistics



Juffmann *et al.*, Nature Nanotech. **7**, 297 (2012)



Decoherence

Bohmian mechanics

Towards a single-event description

Quantum phenomena occur in real time

Molecular configuration

Entanglement dynamics

Electron ionization

Quantum observables ⇒ statistical outcomes

Pozzi et al., *Am. J. Phys.* **57**, 117 (1989); Matteucci et al., Eur. J. Phys. **34**, 511 (2013)

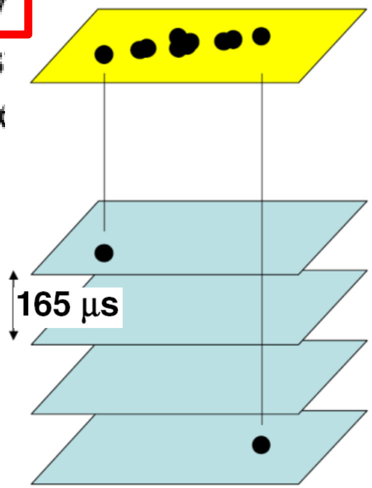
Jönsson, *Am. J. Phys.* **57**, 117 (1989)

Shimizu et al., *Phys. Rev. A* **46**, R17 (1992)

In this chapter we shall tackle immediately the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality, it contains the *only* mystery. We cannot make the mystery go away by "explaining" how it works. We will jus *tell* you how it works. In telling you how it works we will have told you about th basic peculiarities of all quantum mechanics.

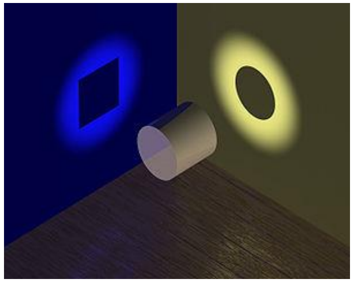
Tonomura *et al*., *Am. J. Phys.* **57**, 117 (1989)

Juffmann *et al*., Nat. Nano. **7**, 297 (2012)



No time coherence ⇒ one particle is unaware of what others do!

Towards a single-event description



$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + V \right] \Psi$$

Bohmian mechanics …

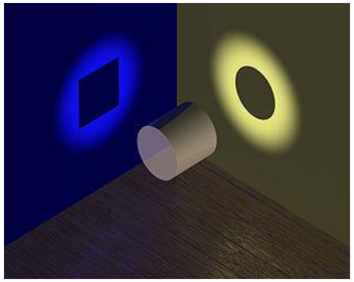
PHYSICAL REVIEW VOLUME 85, NUMBER 2 JANUARY 15, 1952

A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. I

DAVID BOHM*
Palmer Physical Laboratory, Princeton University, Princeton, New Jersey
(Received July 5, 1951)

The usual interpretation of the quantum theory is self-consistent, but it involves an assumption that cannot be tested experimentally, *viz.*, that the most complete possible specification of an individual system is in terms of a wave function that determines only probable results of actual measurement processes. The only way of investigating the truth of this assumption is by trying to find some other interpretation of the quantum theory in terms of at present "hidden" variables, which in principle determine the precise behavior of an individual system, but which are in practice averaged over in measurements of the types that can now be carried out. In this paper and in a subsequent paper, an interpretation of the quantum theory in terms of just such "hidden" variables is suggested. It is shown that as long as the mathematical theory retains its present general form, this suggested interpretation leads to precisely the same results for all physical processes as does the usual interpretation. Nevertheless, the suggested interpretation provides a broader conceptual framework than the usual interpretation, because it makes possible a precise and continuous description of all processes, even at the quantum level. This broader conceptual framework allows more general mathematical formulations of the theory than those allowed by the usual interpretation. Now, the usual mathematical formulation seems to lead to insoluble difficulties when it is extrapolated into the domain of distances of the order of 10^{-13} cm or less. It is therefore entirely possible that the interpretation suggested here may be needed for the resolution of these difficulties. In any case, the mere possibility of such an interpretation proves that it is not necessary for us to give up a precise, rational, and objective description of individual systems at a quantum level of accuracy.

Towards a single-event description



$$i\hbar\frac{\partial\Psi}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 + V\right]\Psi$$

Physical system

$$\begin{cases} i\hbar\dfrac{\partial\Psi}{\partial t} = \left[-\dfrac{\hbar^2}{2m}\nabla^2 + V\right]\Psi \\ \boldsymbol{v} = \dot{\boldsymbol{r}} = \dfrac{\boldsymbol{\nabla} S}{m} \end{cases}$$

… the pilot wave …

PHYSIQUE MATHÉMATIQUE. — *Sur la possibilité de relier les phénomènes d'interférence et de diffraction à la théorie des quanta de lumière.* Note de M. **Louis de Broglie**, transmise par M. M. de Broglie.

La propagation des ondes lumineuses est régie par l'équation

$$\Delta u = \frac{1}{c^2} \cdot \frac{\partial^2 u}{\partial t^2}. \tag{1}$$

Pour chaque problème d'interférence ou de diffraction, l'optique classique cherche une solution de la forme

$$u = a(x, y, z)\, e^{i\omega[t - \varphi(x,y,z)]} \tag{2}$$

satisfaisant aux conditions aux limites imposées par la présence des écrans ou autres obstacles rencontrés par l'onde. La nouvelle optique des quanta de lumière envisage une solution à amplitude variable de la forme

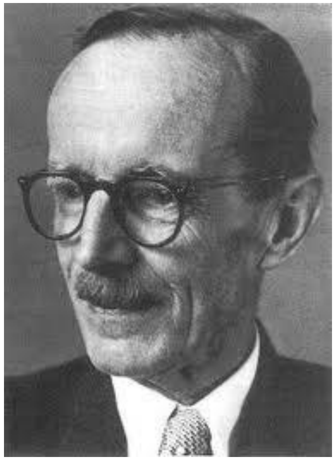
$$u = f(x, y, z, t)\, e^{i\omega[t - \varphi(x,y,z)]}, \tag{3}$$

où φ est la même fonction que dans (2). La fonction f comporte des singularités mobiles le long des courbes normales aux surfaces $\varphi = \text{const.}$; ces singularités constituent les quanta d'énergie radiante. La vitesse du quantum passant au point M à l'instant t est nécessairement

$$U = \left(- \frac{\frac{\partial f}{\partial t}}{\frac{\partial f}{\partial n}} \right)_{M,t}, \tag{4}$$

la variable n étant comptée le long de la trajectoire et les dérivées étant prises en M à l'instant t.

… and quantum hydrodynamics



Quantentheorie in hydrodynamischer Form.

Von **E. Madelung** in Frankfurt a. M.

(Eingegangen am 25. Oktober 1926.)

Es wird gezeigt, daß man die Schrödingersche Gleichung des Einelektronenproblems in die Form der hydrodynamischen Gleichungen transformieren kann.

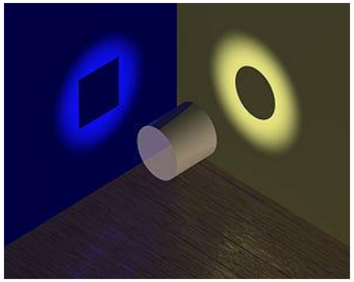
Quantum hydrodynamics

$$\rho = R^2 = \Psi^* \Psi$$

$$\boldsymbol{J} = \rho \boldsymbol{v} = R^2 \frac{\boldsymbol{\nabla} S}{m}$$

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{J} = 0$$

Towards a single-event description



$$i\hbar \frac{\partial \Psi}{\partial t} = \left[-\frac{\hbar^2}{2m} \nabla^2 + V \right] \Psi$$

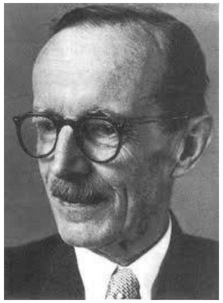
$$\Psi(\boldsymbol{r}, t) = R(\boldsymbol{r}, t) e^{iS(\boldsymbol{r},t)/\hbar}$$

$$\longrightarrow \begin{cases} \dfrac{\partial R^2}{\partial t} + \boldsymbol{\nabla} \cdot \left(R^2 \dfrac{\boldsymbol{\nabla} S}{m} \right) = 0 \\ \dfrac{\partial S}{\partial t} + \dfrac{(\boldsymbol{\nabla} S)^2}{2m} + V - \dfrac{\hbar^2}{2m} \dfrac{\nabla^2 R}{R} = 0 \end{cases}$$

Physical system

$$\begin{cases} i\hbar \dfrac{\partial \Psi}{\partial t} = \left[-\dfrac{\hbar^2}{2m} \nabla^2 + V \right] \Psi \\ \boldsymbol{v} = \dot{\boldsymbol{r}} = \dfrac{\boldsymbol{\nabla} S}{m} \end{cases}$$

Quantum hydrodynamics



$$\rho = R^2 = \Psi^* \Psi$$

$$\boldsymbol{J} = \rho \boldsymbol{v} = R^2 \frac{\boldsymbol{\nabla} S}{m}$$

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot \boldsymbol{J} = 0$$

Alternative pictures of quantum mechanics

Heisenberg's matrix formulation

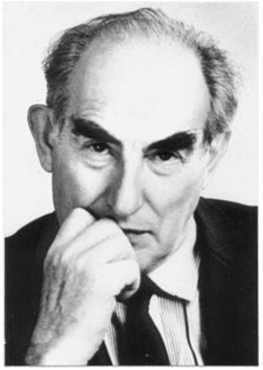
Schrödinger's wave mechanics

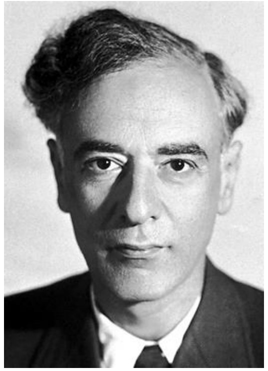
} **Dirac's (interaction) representation**

Feynman's path integrals

Phase-space representations

- **Wigner–Moyal–Hiley**
- **Husimi**





$$\Psi(\boldsymbol{r}, t) = R(\boldsymbol{r}, t)\mathrm{e}^{\mathrm{i}S(\boldsymbol{r},t)/\hbar}$$

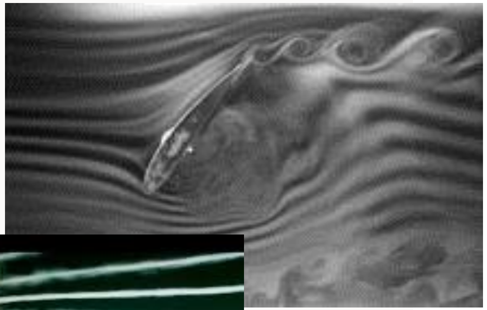
Quantum hydrodynamics (fluid dynamics) approach, aka Bohmian mechanics

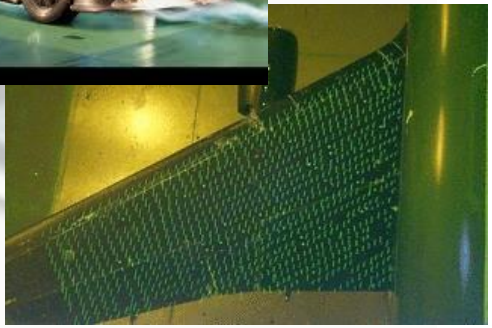
Madelung–de Broglie–Bohm–Takabayasi–Landau–Bialynicki-Birula

"Hidden" quantum properties ≠ hidden variables!

Quantum tracer particles

Bohmian particles are the quantum equivalent of classical tracer particles



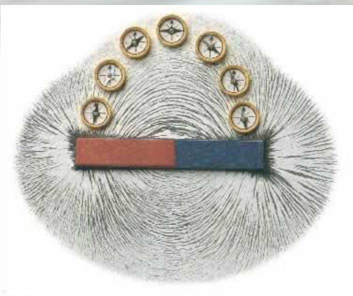


Continuum media: hydrodynamics

gas - smoke

liquid
- tinny floating particles (e.g., pollen, charcoal)
- other liquids (e.g., ink)

Universe as a fluid – galaxies, stars, etc.



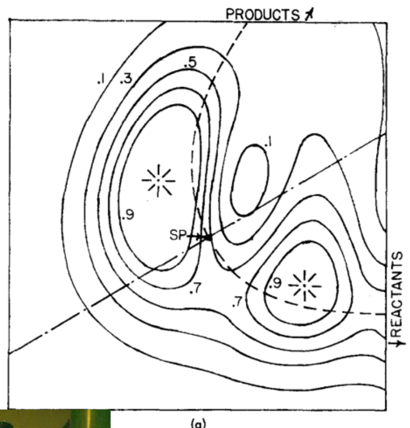
Do *real* quantum particles move along Bohmian trajectories?

Hydrodynamic approaches in the literature

Quantum Dynamics of the Collinear (H, H_2) Reaction*

EDWARD A. MCCULLOUGH, JR.,† AND ROBERT E. WYATT
Department of Chemistry, The University of Texas at Austin, Austin, Texas 78712
(Received 21 March 1969)

J. Chem. Phys. **51**, 1253 (1969)



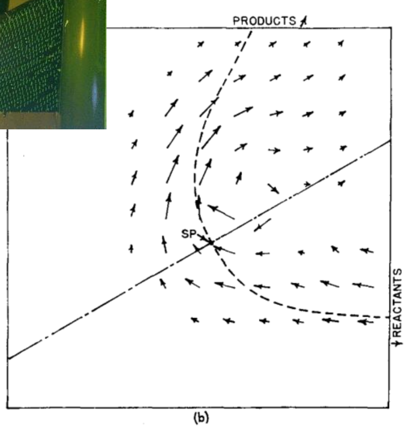
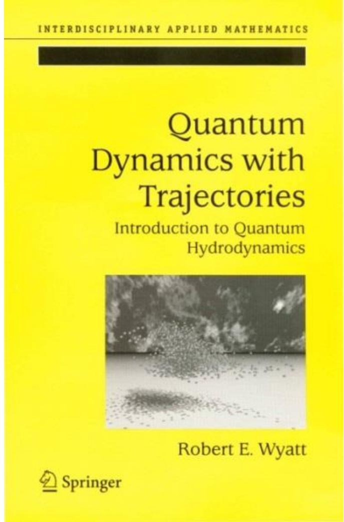


FIG. 1. Saddle point region, time step 85, showing the saddle point (SP), reaction path (- - -), and symmetric stretch line (-•-). Region is 1.28 a.u. square. (a) Probably density. (b) Flux. Length of largest vector is 1.70×10^{14} a.u.$^{-1}\cdot$sec^{-1}. The four vectors closest to the "sink" are magnified by 2.5.



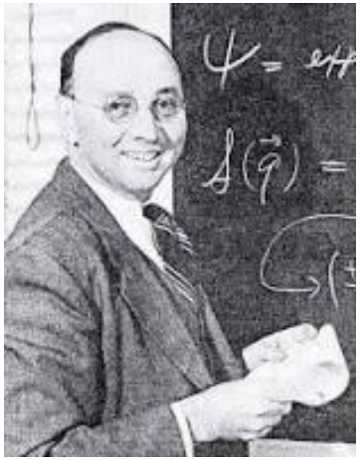
THE JOURNAL OF CHEMICAL PHYSICS VOLUME 54, NUMBER 8 15 APRIL 1971

Dynamics of the Collinear $H+H_2$ Reaction. I. Probability Density and Flux*

EDWARD A. MCCULLOUGH, JR.† AND ROBERT E. WYATT
Department of Chemistry, The University of Texas at Austin, Austin, Texas 78712
(Received 13 November 1970)

The time evolution of the collinear $H+H_2$ reaction as given by classical mechanics and by time-dependent quantum mechanics has been studied. The calculations employed the Porter–Karplus potential surface. The relevant equations of motion were solved to high accuracy by direct numerical integration. The evolution of the quantal probability density in the interaction region of the potential surface is shown in a series of perspective plots. Classical mechanics gives an amazingly good description of the probability density and flux patterns during most of the reaction; however, the classical and quantal descriptions begin to diverge near the end of the reaction. Essentially, the classical reaction terminates before the quantal reaction. The dynamic behavior of the reaction is hydrodynamically turbulent, as shown by transient whirlpool formation on the inside of the reaction path. All results reported in this paper are for one average system energy, namely, 0.65 eV (initial average translational energy = 0.38 eV).

Hydrodynamic approaches in the literature



Quantum mechanical streamlines. I. Square potential barrier*

Joseph O. Hirschfelder and Albert C. Christoph

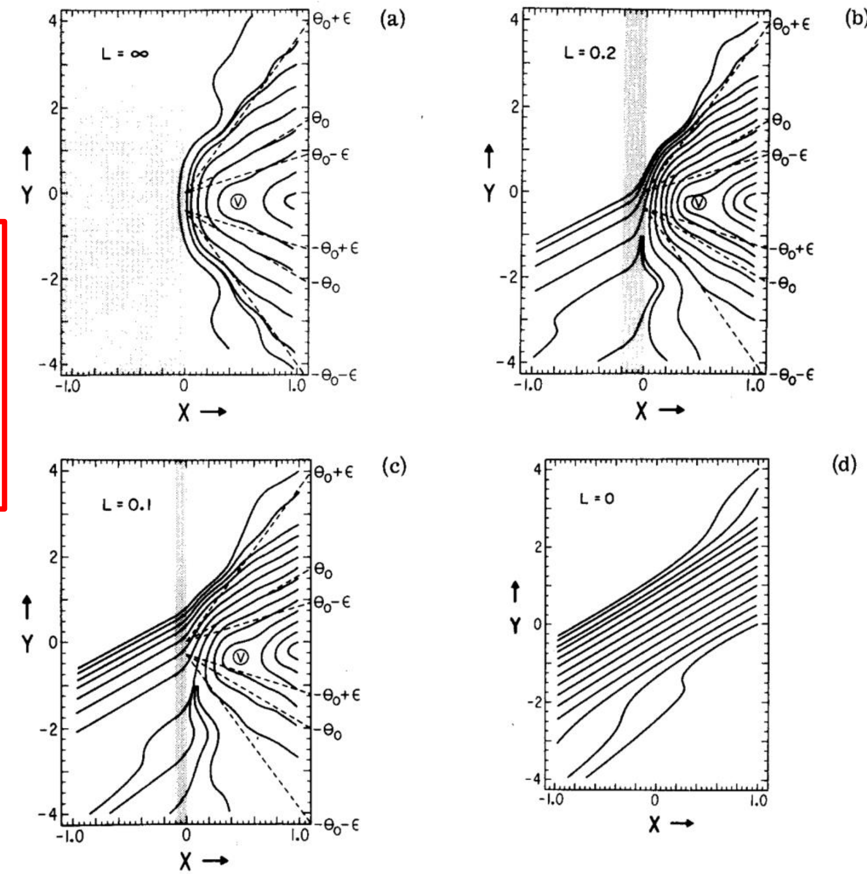
Theoretical Chemistry Institute, University of Wiconsin-Madison, Madison, Wisconsin 53706

William E. Palke

Department of Chemistry, University of California-Santa Barbara, Santa Barbara, California 93106
(Received 24 July 1974)

J. Chem. Phys. **61**, 5435 (1974)

This paper has resulted from an effort to get a better understanding of quantum mechanics by making a thorough study of a very simple problem, the reflection and transmission of a beam of particles hitting a two-dimensional square potential barrier. The mathematics is simple, but the analysis is far-reaching.



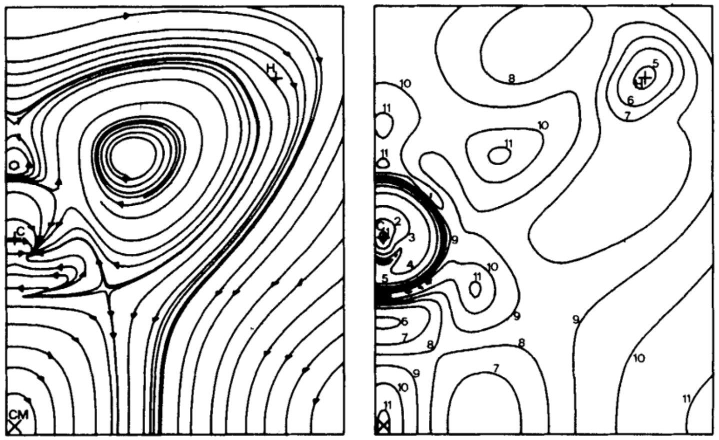
Hydrodynamic approaches in the literature

INTERNATIONAL JOURNAL OF QUANTUM CHEMISTRY, Vol. XXV, 929–940 (1984)

Singularities of Magnetic-Field Induced Electron Current Density: A Study of the Ethylene Molecule

P. LAZZERETTI, E. ROSSI, AND R. ZANASI
Istituto di Chimica Organica e Centro di Calcolo Elettronico dell'Universitá, via Campi 183, I-41100 Modena, Italy

A representation of the electron flow induced by the external field can be extremely useful to understand molecular magnetism. To this end, maps reporting modulus and trajectory of quantum-mechanical current density revealed a fundamental tool [1–3], whose importance could be hardly overestimated.



(a) (b)

Figure 1. (a) Trajectory of the current density in the σ_h plane perpendicular to the magnetic field. Diamagnetic circulations are clockwise. (b) Modulus of the current density in the same plane as (a). Curves are marked according to the correspondence: 1 = 0.1, 2 = 0.03, 3 = 0.01, 4 = 0.003, 5 = 0.0015, 6 = 0.001, 7 = 0.0008, 8 = 0.00065, 9 = 0.0005, 10 = 0.0003, 11 = 0.0001 (in a.u.).

Hydrodynamic approaches in the literature

Stagnation Graphs and Topological Models of Magnetic-Field Induced Electron Current Density for Some Small Molecules in Connection With Their Magnetic Symmetry

STEFANO PELLONI, PAOLO LAZZERETTI

Dipartimento di Chimica, Università degli Studi di Modena e Reggio Emilia, Via Campi 183, 41100 Modena, Italy

Received 14 December 2009; accepted 9 February 2010
Published online 2 June 2010 in Wiley Online Library (wileyonlinelibrary.com).
DOI 10.1002/qua.22658

ABSTRACT: Spatial models of magnetic-field induced electronic currents have been constructed for a series of small molecules of different point group symmetry via stagnation graphs and current density maps. These tools provide fundamental help for rationalization of magnetic response properties, such as magnetizability and nuclear magnetic shielding. Int J Quantum Chem 111: 356–367, 2011

Int. J. Quantum Chem. **111**, 356 (2011)

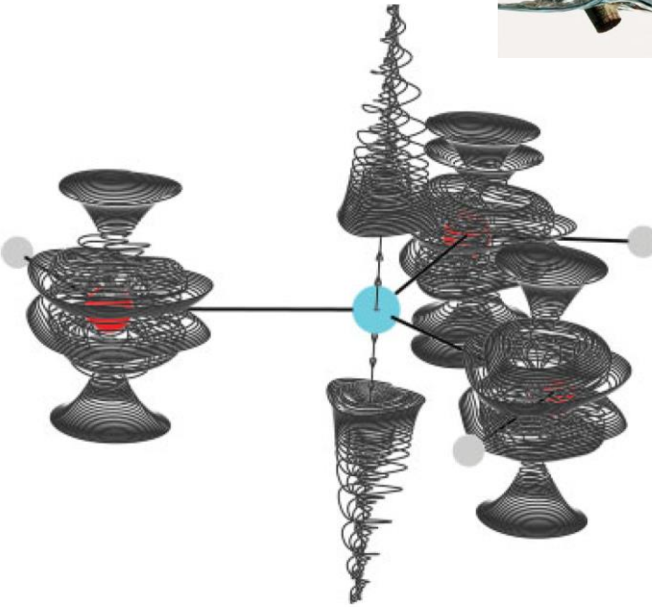


FIGURE 4. Perspective view of the current density vector field in H_3BO_3, with magnetic symmetry C_{3h}. The uniform external magnetic field **B** is perpendicular to the plane of the atoms. The figure shows diatropic streamlines spiralling about $(3, \pm 1)$ foci at the boron and oxygen nuclei, above and below the σ_h symmetry plane, which cannot crossed by the flow. Diatropic limit cycles, separating upper and lower spirals, lie on σ_h. Two pairs of arrows indicate the direction of the local eigenvectors corresponding to the real eigenvalue of the Jacobian matrix at the boron nucleus. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Hydrodynamic approaches in the literature

Math. Ann. **47**, 317 (1896)

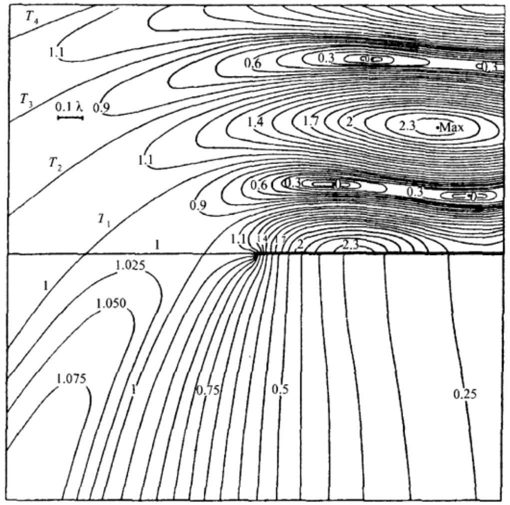


Fig. 11.12 Amplitude contours of H_z (amplitude of incident wave is taken as unity) for diffraction of a normally incident *H*-polarized plane wave by a perfectly conducting half-plane. (After W. Braunbek and G. Laukien, *Optik*, **9** (1952), 174.)

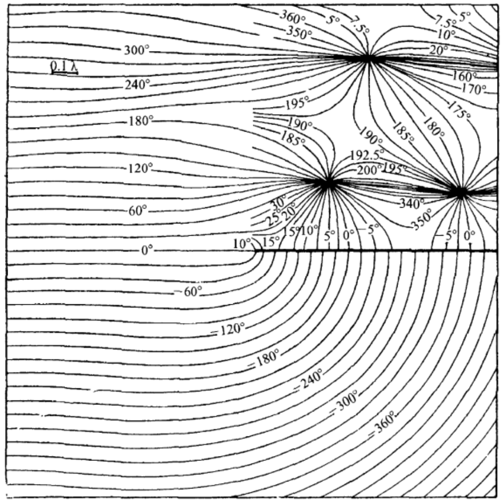


Fig. 11.13 Phase contours of H_z for diffraction of a normally incident *H*-polarized plane wave by a perfectly conducting half-plane. (After W. Braunbek and G. Laukien, *Optik*, **9** (1952), 174.)

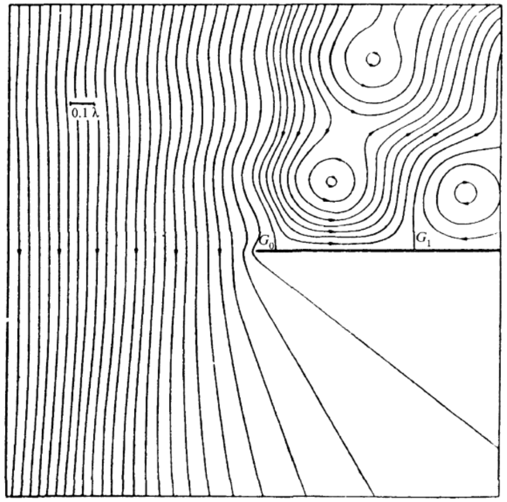


Fig. 11.14 Lines of average energy flow for diffraction of a normally incident *H*-polarized plane wave by a perfectly conducting half-plane. (After W. Braunbek and G. Laukien, *Optik*, **9** (1952), 174.)

Optik **9**, 174 (1952)

Hydrodynamic approaches in the literature

International Journal of Theoretical Physics, Vol. 15, No. 3 (1976), pp. 169–180

The Interpretation of Diffraction and Interference in Terms of Energy Flow

R. D. PROSSER

Physics Department, University of Stirling, Stirling, Scotland

Received: 20 *December* 1974

Abstract

Solutions to Maxwell's equations at a semi-infinite plane and a double slit are used to construct lines of constant amplitude, constant phase and energy flow. The lines of energy flow show how the electromagnetic boundary conditions necessitate a particular undulation in the path of the light energy and that the consequent redistribution of energy corresponds with a diffraction or interference pattern. This interpretation complements the interpretation in terms of the interaction of secondary wavelets due to Huygens.

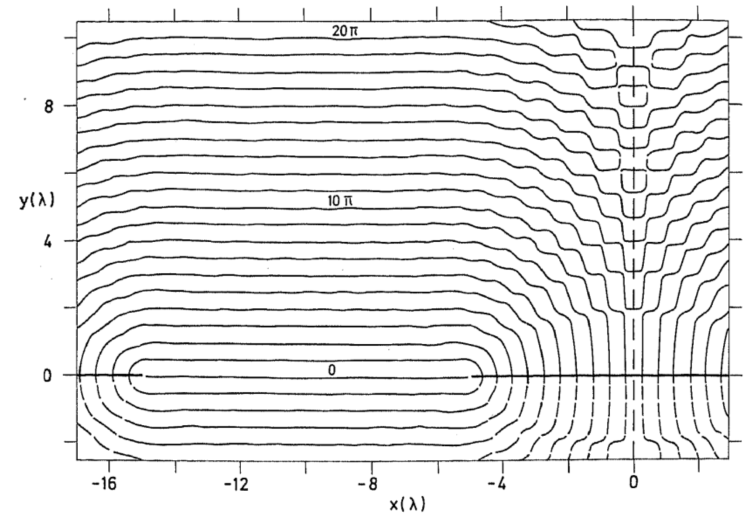


Figure 3b.

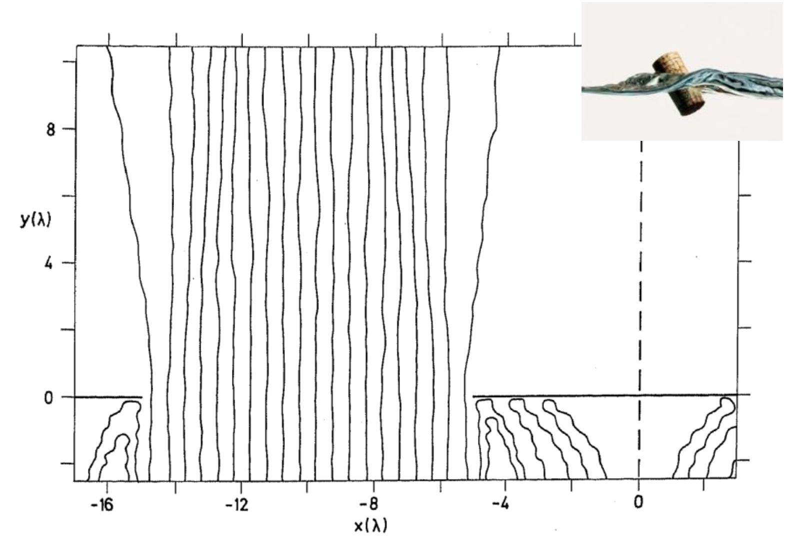
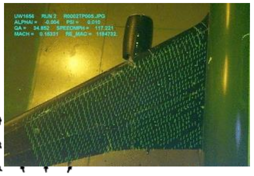


Figure 3c.

Hydrodynamic approaches in the literature



Energy streamlines of a sound source

R. V. Waterhouse,[a)] T. W. Yates,[b)] D. Feit, and Y. N. Liu
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(Received 17 February 1985; accepted for publication 8 April 1985)

A method is presented for computing the energy streamlines of a sound source. This enables charts to be plotted showing, as continuous lines, the flow paths of the sound energy from the vibrating surface to the nearfield and beyond. Energy streamlines appear to be a new construct; they have some similarities to the velocity streamlines used in fluid dynamics. Examples of the energy streamlines are given for the point-driven plate in water.

J. Acoust. Soc. Am. **78**, 758 (1985)

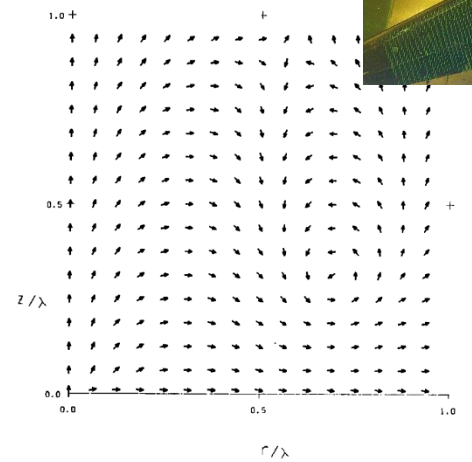

FIG. 1. Intensity vectors in the *rz* plane for a point-driven plate in water. The axis *z* is normal to the plate. The lengths of the vectors are not to scale, but have been made all the same. The point drive is at 0 and *λ* is the wavelength of bending waves on the plate *in vacuo*.

Intensity meters have been commercially available for the last year or two, and several papers[1,2] have appeared giving measured intensity data for various sound sources. Generally, the data have been presented in a plot similar to those shown in Figs. 1 and 2, where the arrows show the directions of the intensity vectors at a number of points uniformly spaced on a rectangular grid. The vectors may be adjusted to have the same length, to focus attention on the directions of the energy flow, or they may have lengths proportional to the magnitudes of the intensities at the various points. Similar plots have been used to present the theoretical results of intensity calculations.[3,4]

The purpose of this paper is to present a development of the above scheme, which enables continuous streamlines of intensity (i.e., energy flow) to be calculated and plotted. These streamlines make it easier for the eye to follow the energy flow from the source into the nearfield and beyond. These paths are complicated, in some cases, but are of considerable interest from several points of view.

To demonstrate the method, examples are given of the energy streamlines for a point-driven plate in water.

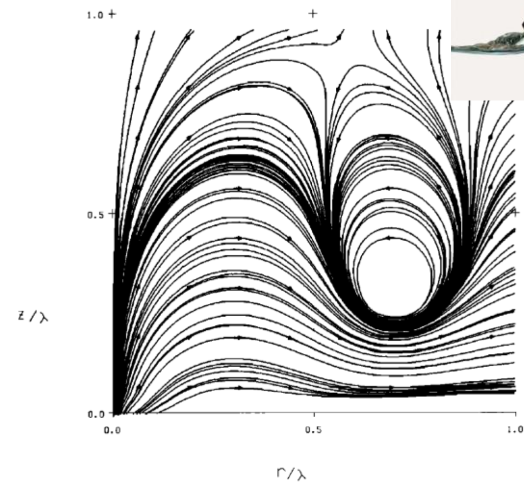

FIG. 3. Energy streamlines in the nearfield of a point-driven plate in water, derived from the data shown in Figs. 1 and 2. Here, 32 grid points per *λ* were used.

What about classical waves?

PRL **97,** 154101 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

Single-Particle Diffraction and Interference at a Macroscopic Scale

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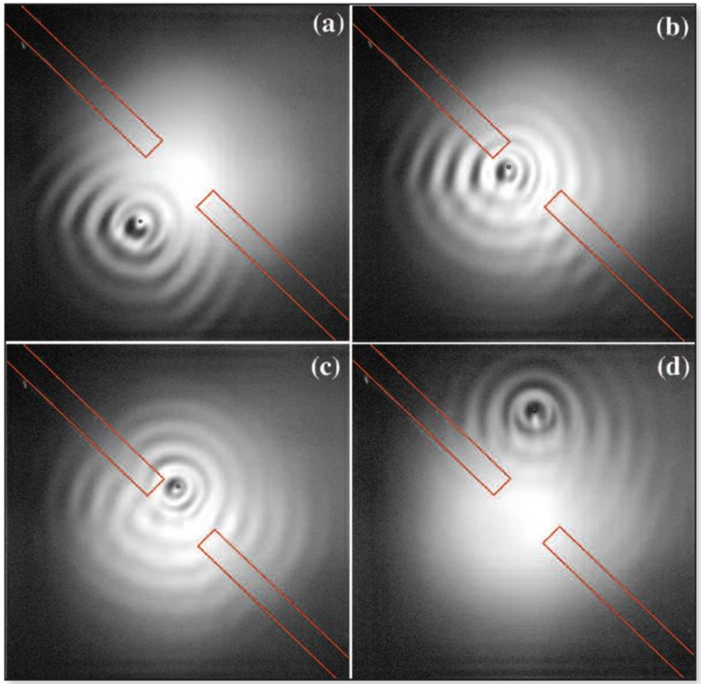
(Received 13 July 2006; published 13 October 2006)

A droplet bouncing on a vertically vibrated bath can become coupled to the surface wave it generates. It thus becomes a "walker" moving at constant velocity on the interface. Here the motion of these walkers is investigated when they pass through one or two slits limiting the transverse extent of their wave. In both cases a given single walker seems randomly scattered. However, diffraction or interference patterns are recovered in the histogram of the deviations of many successive walkers. The similarities and differences of these results with those obtained with single particles at the quantum scale are discussed.



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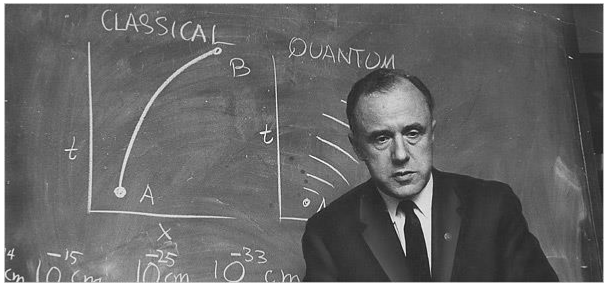
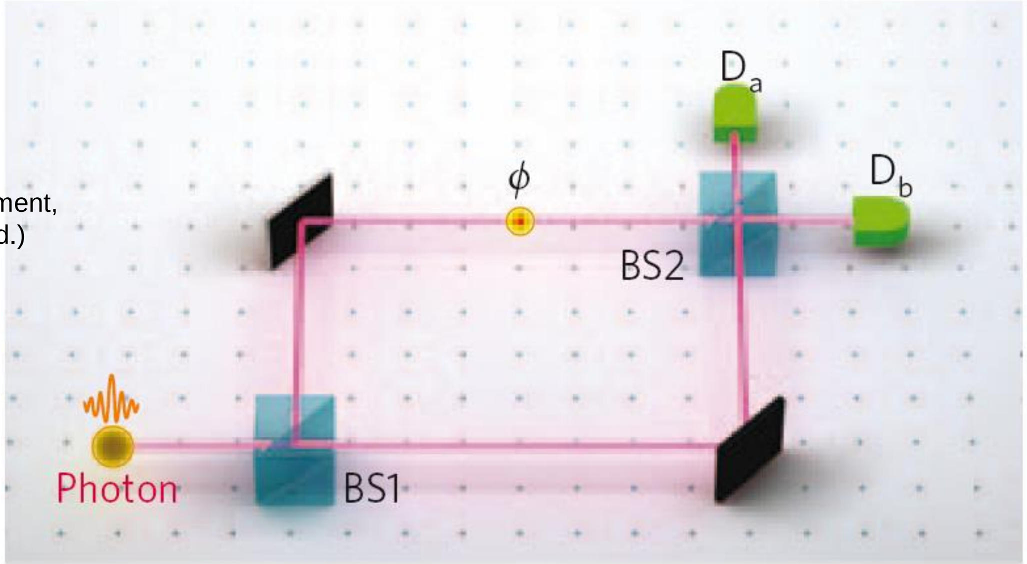
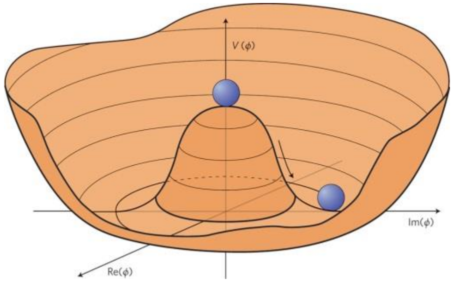
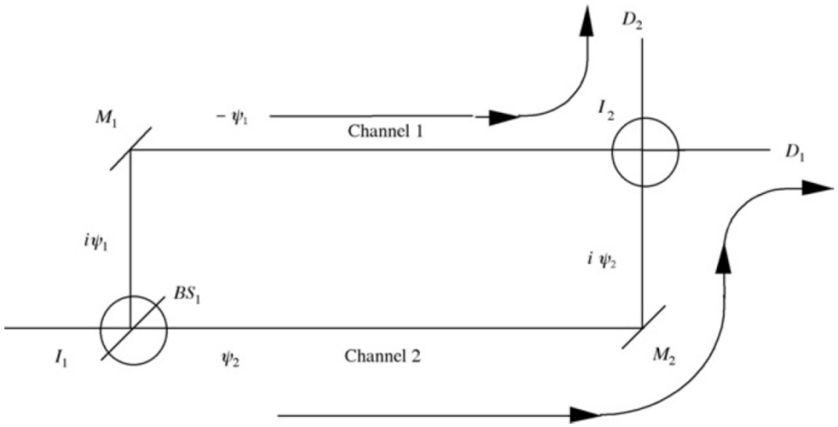
Wheeler's delayed-choice experiment

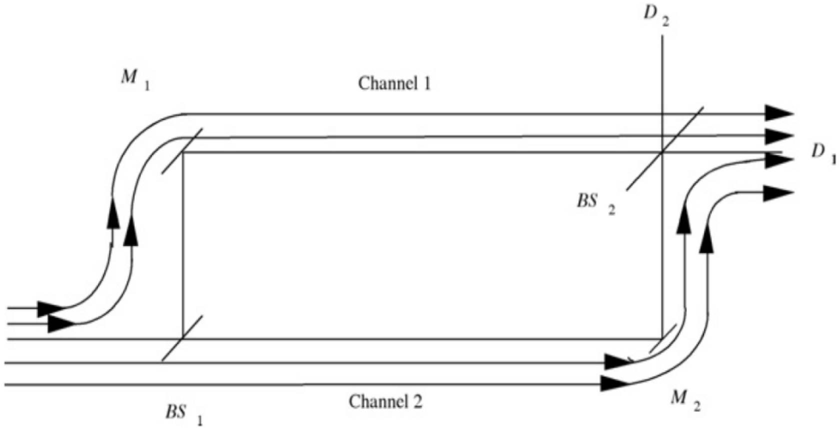




Wheeler, The past and the delayed-choice double-slit experiment, in *Mathematical Foundations of Quantum Theory*, Marlow (Ed.) (Academic Press, New York, 1978)



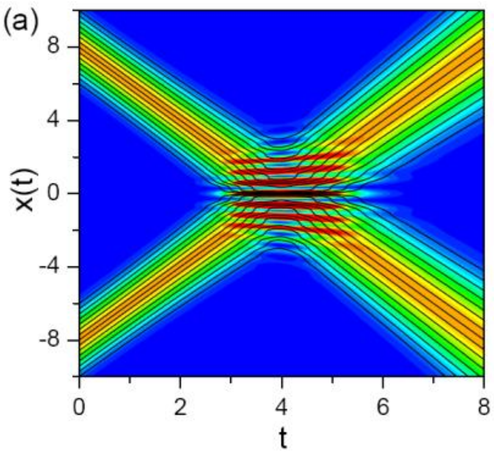


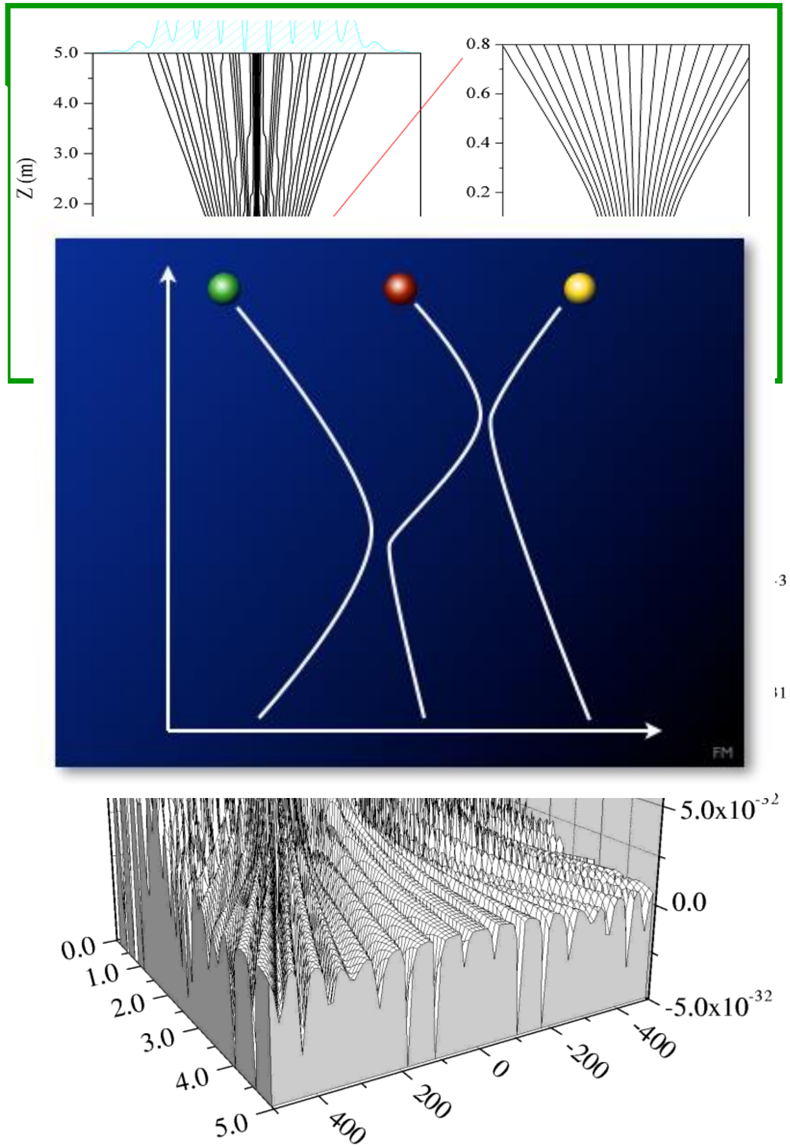


Hiley & Callaghan, *Phys. Scr.* **74**, 336 (2006)

Interference dynamics

Bohmian non-crossing = quantum dynamical noncrossing





AS & Miret-Artés, *Chem. Phys. Lett.* **445**, 350 (2007);

J. Phys. A **41**, 435303 (2008); *Am. J. Phys.* **80**, 525 (2012)

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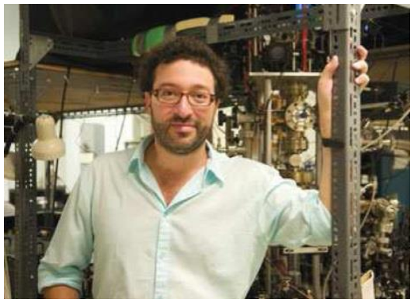
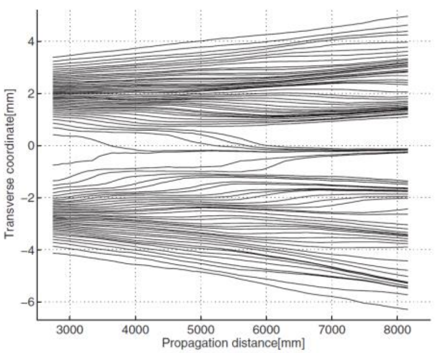
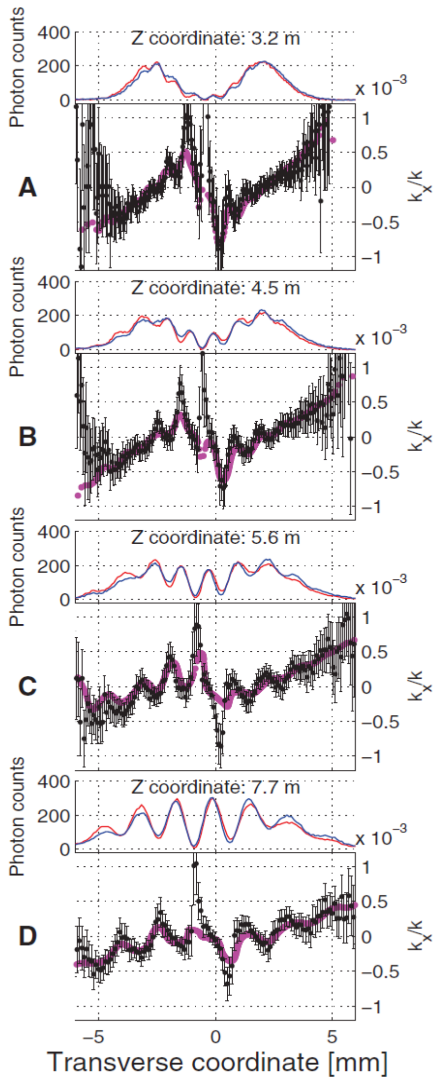
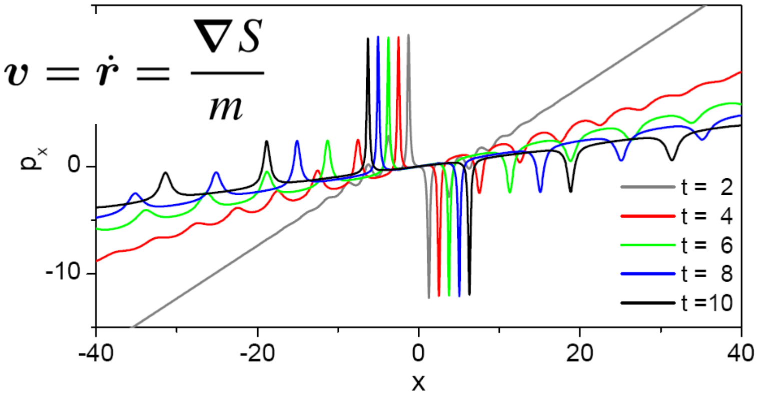




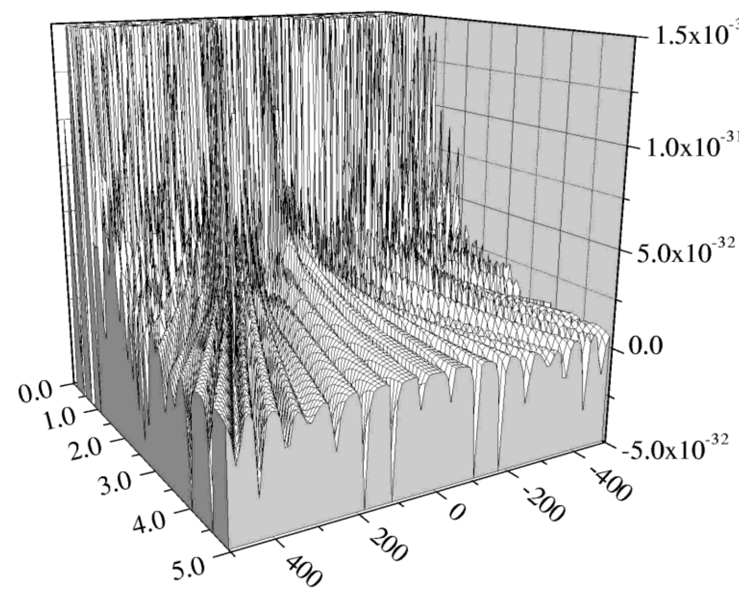


Kocsis et al., *Science* **332**, 1170 (2011)

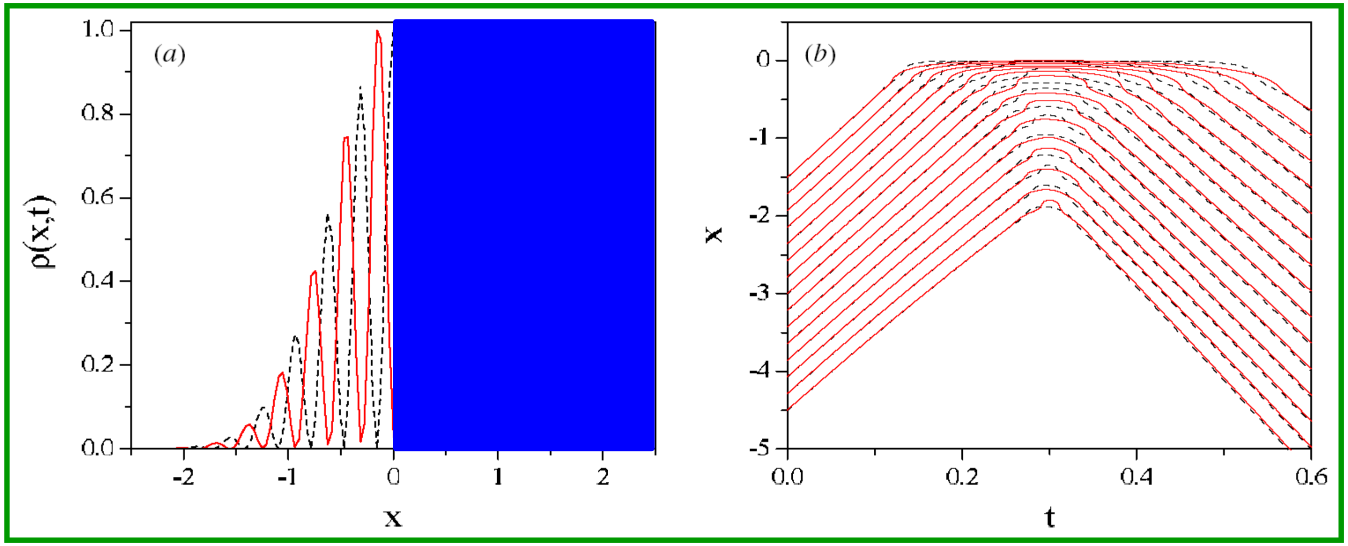
$$v = \dot{r} = \frac{\nabla S}{m}$$



$$Q \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}} = \frac{\hbar^2}{4m}\left[\frac{1}{2}\left(\frac{\nabla\rho}{\rho}\right)^2 - \frac{\nabla^2\rho}{\rho}\right]$$



“Effective” interference potential



AS & Miret-Artés, *J. Phys. A* **41**, 435303 (2008)

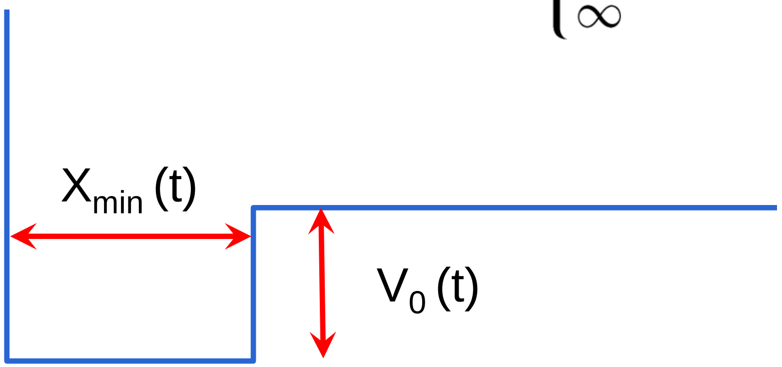
“Effective” interference potential

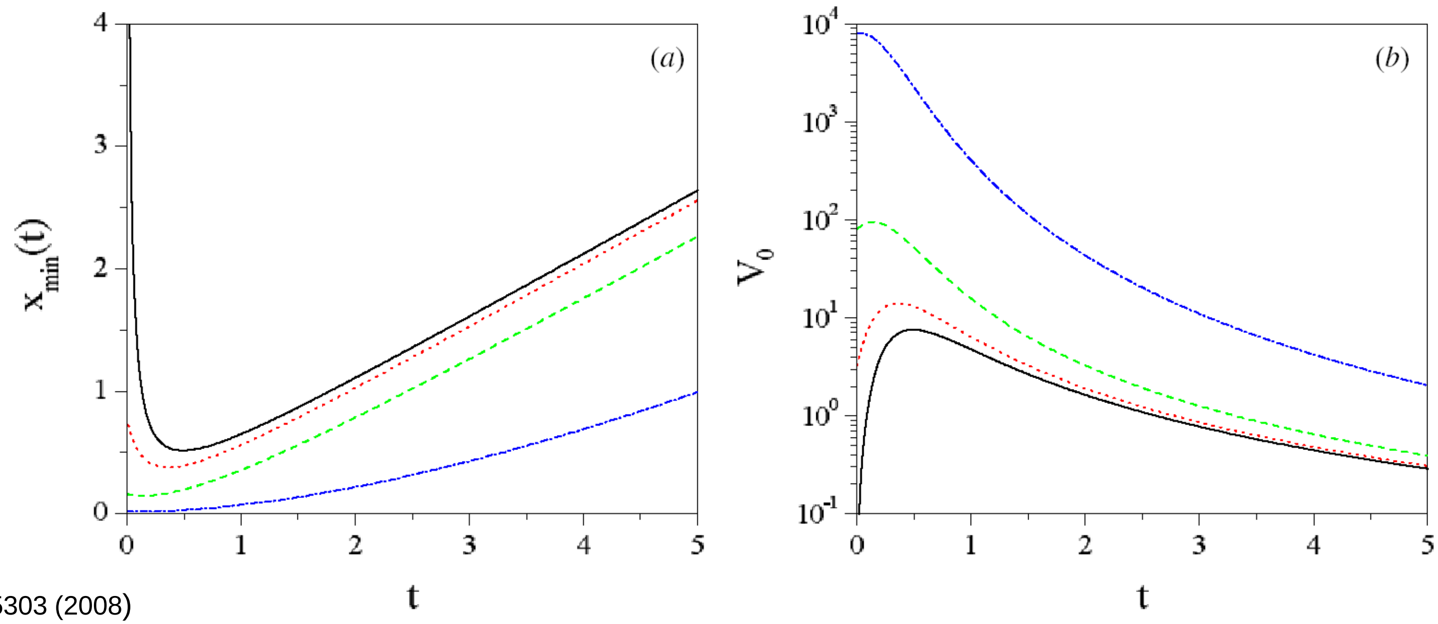
How does the effective “interference” potential look like?

$$V_0 a^2 = n\frac{\hbar^2}{2m} \longrightarrow V(t) = \begin{cases} 0 & x < x_{\min}(t) \\ -V_0[x_{\min}(t)] & x_{\min}(t) \leqslant x \leqslant 0 \\ \infty & 0 < x. \end{cases}$$

$$x_{\min}(t) = \frac{\pi \sigma_t^2}{\frac{2p\sigma_0^2}{\hbar} + \frac{\hbar t}{2m\sigma_0^2} x_0}$$

$$V_0[x_{\min}(t)] = \frac{2\hbar^2}{m}\frac{1}{x_{\min}^2(t)}$$





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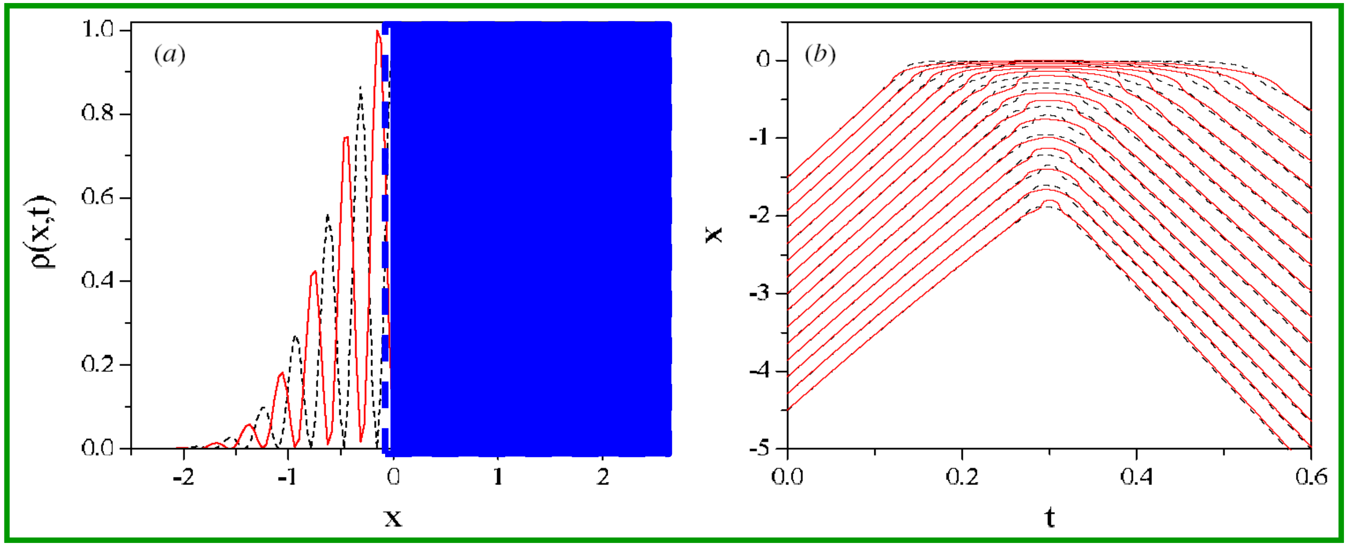

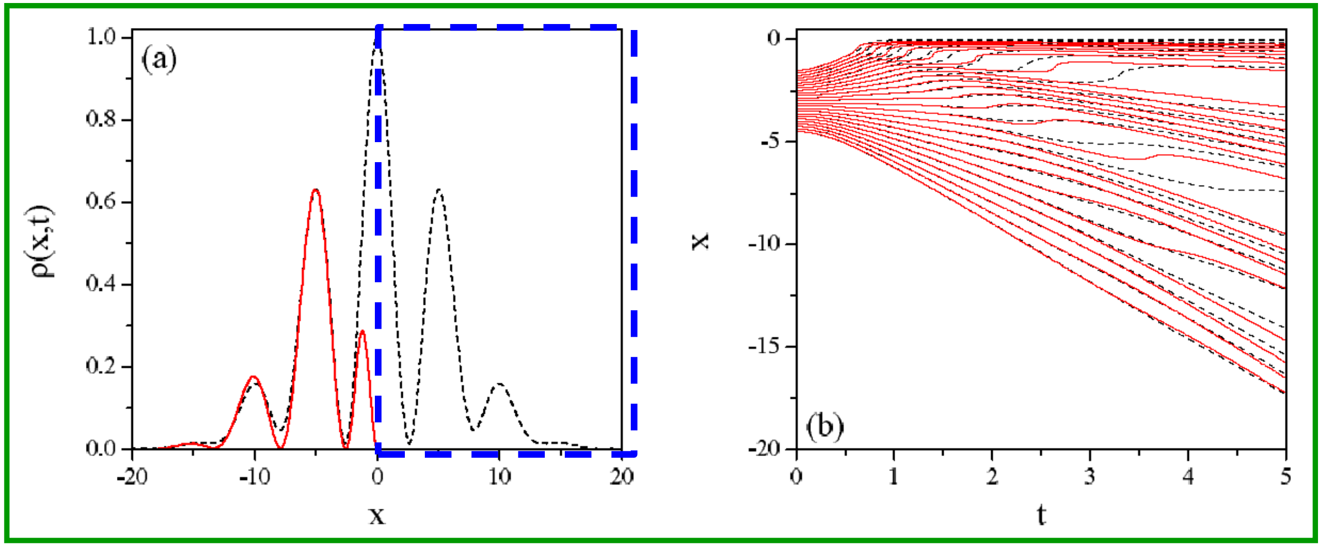

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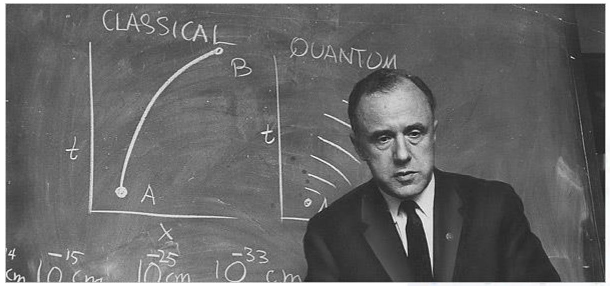
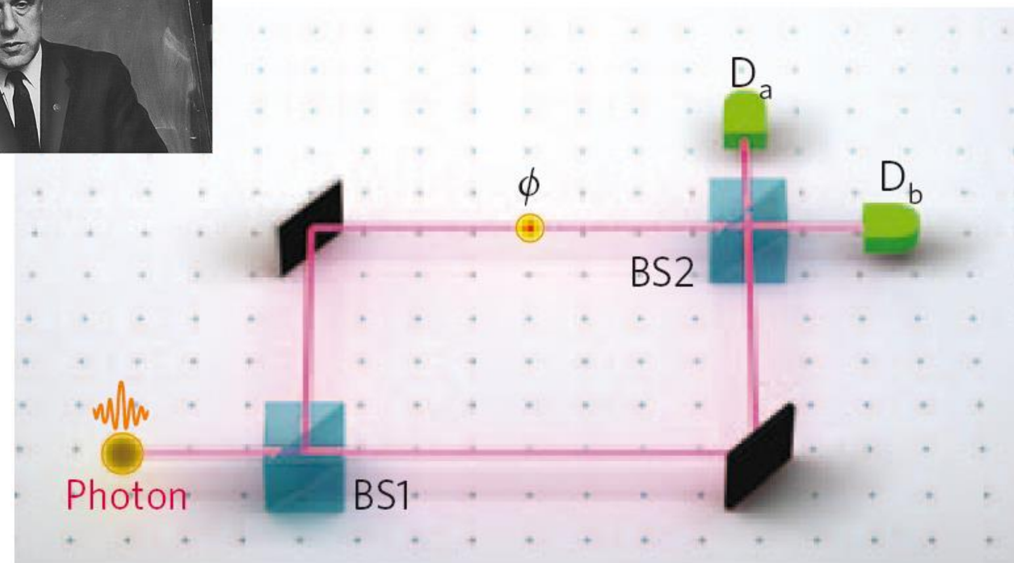
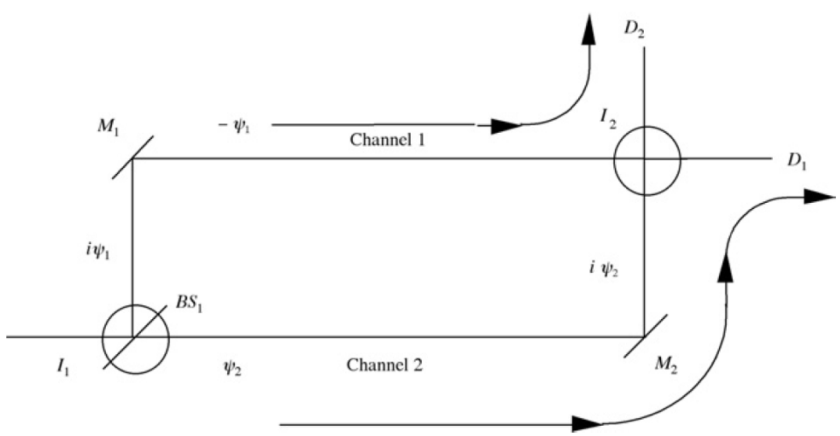
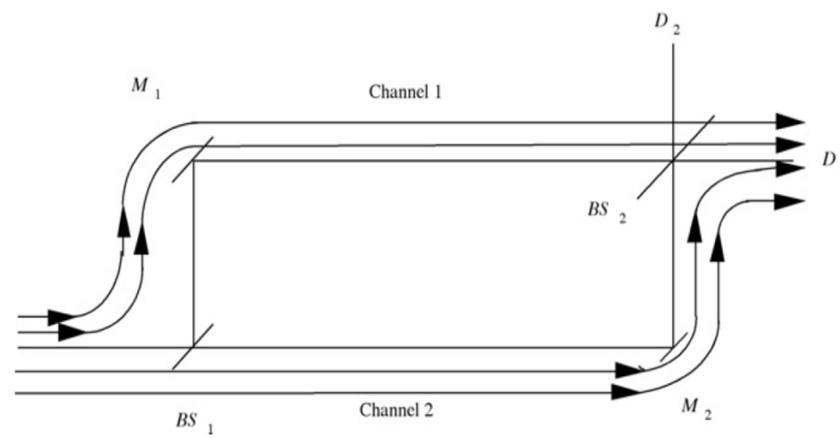
Wheeler’s delayed-choice experiment



Wheeler, The past and the delayed-choice double-slit experiment, in *Mathematical Foundations of Quantum Theory*, Marlow (Ed.) (Academic Press, New York, 1978)







Hiley & Callaghan, *Phys. Scr.* **74**, 336 (2006)

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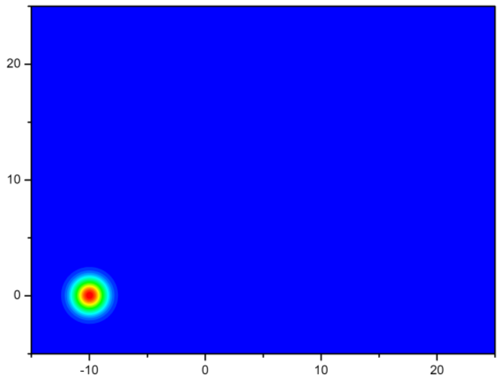
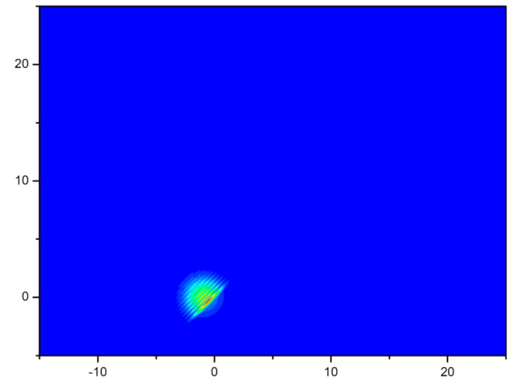
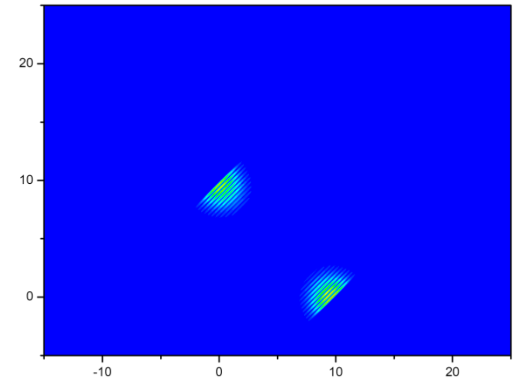
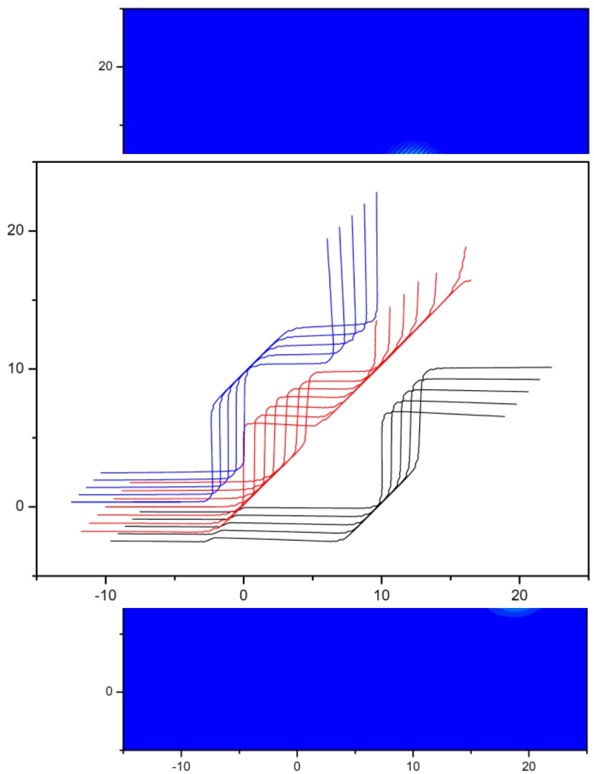
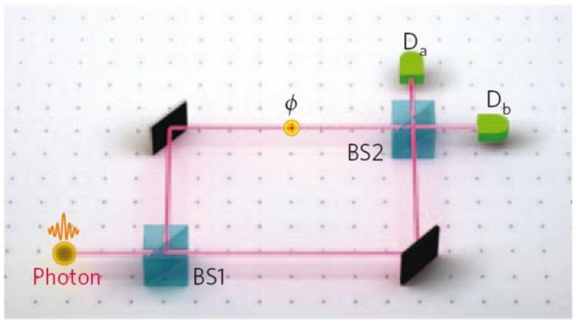
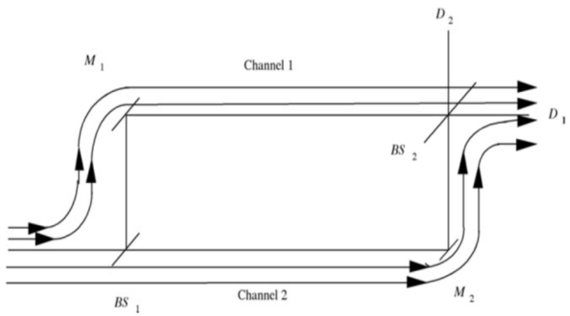


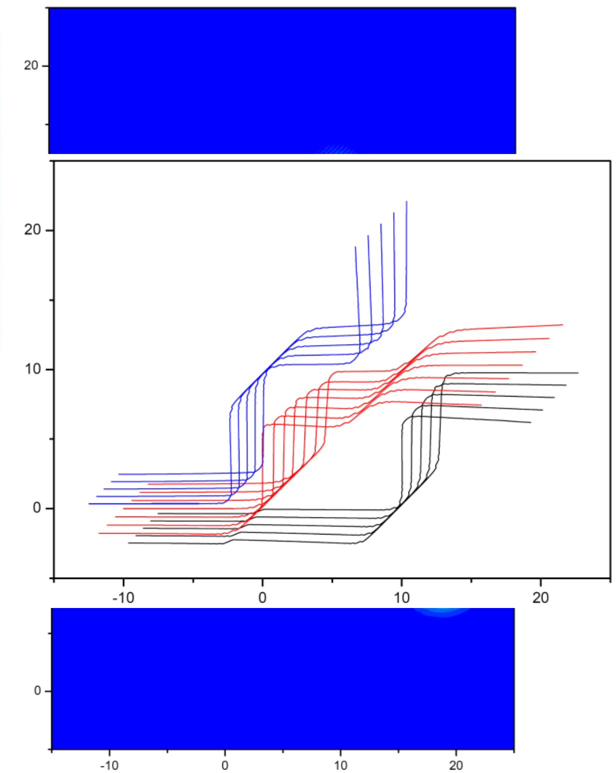






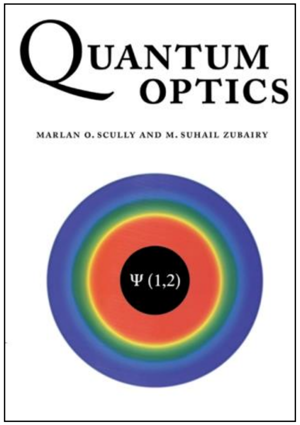






Choque & AS, in preparation

Rays and waves can coexist



Classical	**Geometrical optics rays** **Fermat's principle**	**Classical trajectories** **Hamilton's principle**

	Light	Matter
Semiclassical	$\mathbf{E}(\mathbf{r},t)$ $\Box^2\mathbf{E} = -\mu_0\mathbf{P}$ Maxwell	$\psi(\mathbf{r},t)$ $\dot{\psi}(\mathbf{r},t) = -\frac{\mathrm{i}}{\hbar}\mathcal{H}\psi(\mathbf{r},t)$ Schrödinger
Quantum field	$\vert\dot{\psi_f}\rangle = -\frac{\mathrm{i}}{\hbar}\mathcal{H}_f\vert\psi_f\rangle$ $\mathbf{E}(\mathbf{r},t) = \sum_{\mathbf{k}}\alpha_{\mathbf{k}}(t)U_{\mathbf{k}}(\mathbf{r})$ Dirac	$\vert\dot{\psi_m}\rangle = -\frac{\mathrm{i}}{\hbar}\mathcal{H}_m\vert\psi_m\rangle$ $\hat{\psi}(\mathbf{r},t) = \sum_{\mathbf{p}}\hat{c}_{\mathbf{p}}(t)\phi_{\mathbf{p}}(\mathbf{r})$ Schwinger

Rays and waves can coexist

There are no particles, there are only fields

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(Received 18 April 2012; accepted 15 January 2013)

Quantum foundations are still unsettled, with mixed effects on science and society. By now it should be possible to obtain consensus on at least one issue: Are the fundamental constituents fields or particles? As this paper shows, experiment and theory imply that unbounded fields, not bounded particles, are fundamental. This is especially clear for relativistic systems, implying that it's also true of nonrelativistic systems. Particles are epiphenomena arising from fields. Thus, the Schrödinger field is a space-filling physical field whose value at any spatial point is the probability amplitude for an interaction to occur at that point. The field for an electron *is* the electron; each electron extends over both slits in the two-slit experiment and spreads over the entire pattern; and quantum physics is about interactions of microscopic systems with the macroscopic world rather than just about measurements. It's important to clarify this issue because textbooks still teach a particles- and measurement-oriented interpretation that contributes to bewilderment among students and pseudoscience among the public. This article reviews classical and quantum fields, the two-slit experiment, rigorous theorems showing particles are inconsistent with relativistic quantum theory, and several phenomena showing particles are incompatible with quantum field theories.
[http://dx.doi.org/10.1119/1.4789885]

Quantum mechanics should be harder pushed

Schrödinger's kit: Tools that are in two places at once

New Scientist
- 28 June 2010 by **Michael Brooks**
- Magazine issue 2766. **Subscribe and save**
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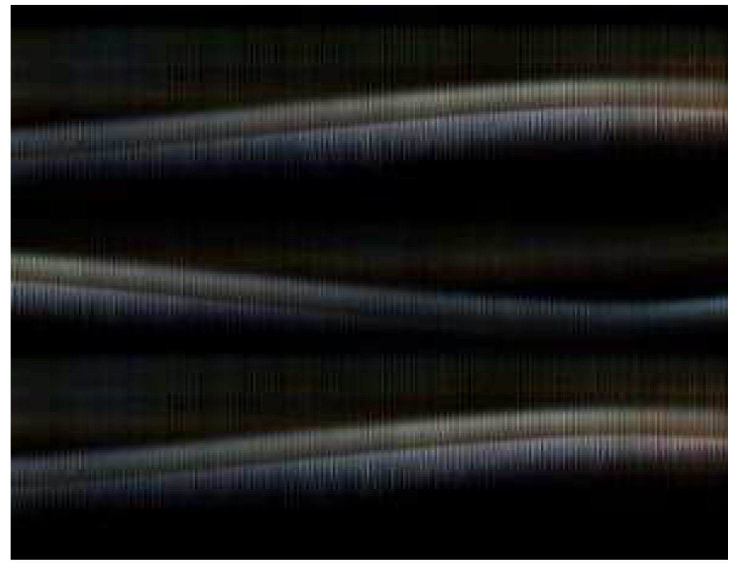
Quantum theory is our most successful theory of physics. There is not one shred of experimental evidence that doesn't fit with its predictions. So why, if it ain't broke, is a growing number of researchers expressing a desire to fix it?

"Everything depends on whether you believe quantum mechanics is going to go on describing the physical world perfectly to whatever level you push it," says Nobel laureate Anthony Leggett, who studies the quantum world at the University of Illinois at Urbana-Champaign.

Leggett thinks it won't, that there are too many issues with quantum theory to think it anything more than an approximation of reality. "I'm inclined to put my money on the idea that if we push quantum mechanics hard enough it will break down and something else will take over - something we can't envisage at the moment," he says.



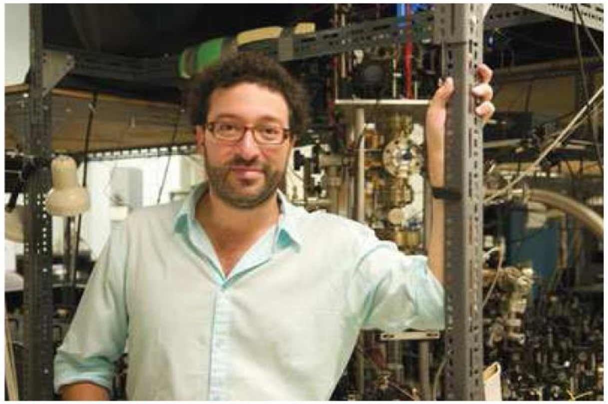
Probing the weird quantum world (Image: Hiroshi Watanabe/Getty)

- 1 more image

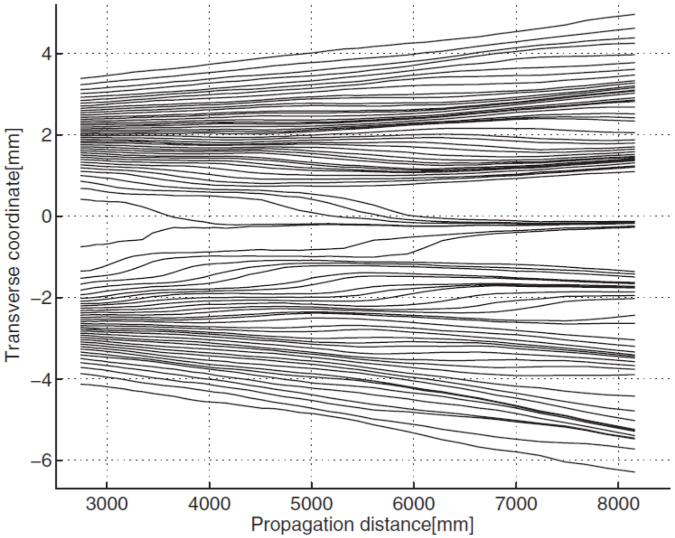
Quantum mechanics should be harder pushed

***Physics World* reveals its top 10 breakthroughs for 2011**

Dec 16, 2011 13 comments



Aephraim Steinberg wants you to throw off your quantum biases



The experiment reveals, for example, that a photon detected on the right-hand side of the diffraction pattern is more likely to have emerged from the optical fibre on the right than from the optical fibre on the left. While this knowledge is not forbidden by quantum mechanics, Steinberg says that physicists have been taught that "asking where a photon is before it is detected is somehow immoral".

"Little by little, people are asking forbidden questions," says Steinberg, who adds that his team's experiment will "push [physicists] to change how they think about things".

Большое спасибо!

1. How can the symmetry be “sponteneouly” broken?
2. What is the role of vacuum and what is the stuff it is made of?
3. Is there any underneath mechanism beyond the Higgs?
4. Can also space-time be related to a fundamental particle?
5. Is quantum theory (QFT included) our final theory?