Kvanttiteorian ontologinen tulkinta

Luonnonfilosofian seuran Kvantti-ilta, Helsinki, 2017-05-18

Paavo Pylkkänen

University of Helsinki, Finland and
University of Skövde, Sweden
E-mail: paavo.pylkkanen@helsinki.fi

- Traditionally quantum theory was not given an ontological interpretation
  - The wave function was seen as part of an algorithm for calculating probabilities of finding e.g. an electron at a given location.
  - QT was thought to concern our knowledge of the system, rather than the system itself
    - For a penetrating discussion of the traditional view, see Plotnitsky, A. (2010) *Epistemology and Probability. Bohr, Heisenberg, Schrödinger and the Nature of Quantum-Theoretical Thinking*. (Springer)

The comeback of ontology…

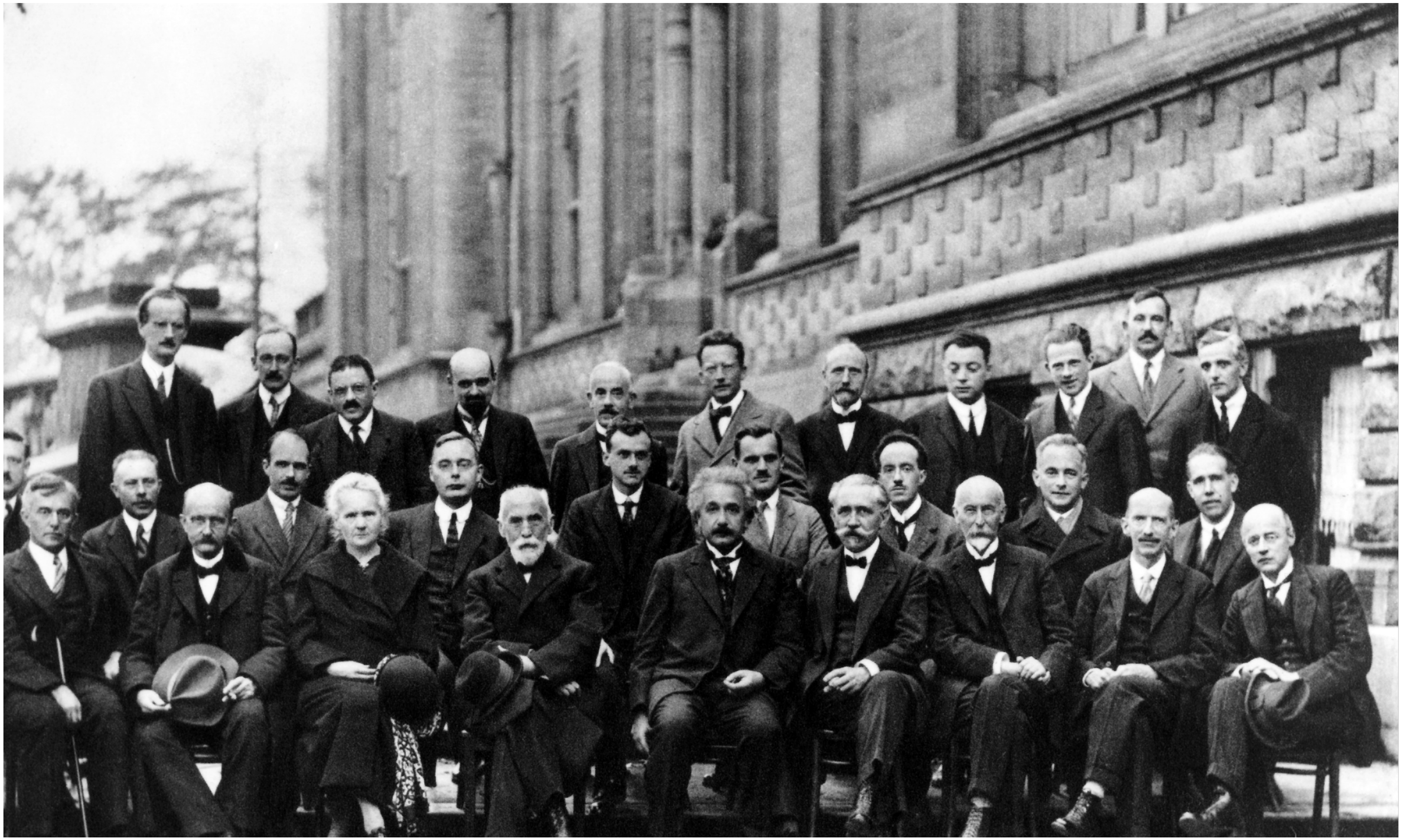
- However: in recent years much attention have been given to various ontological interpretations of QM, due to de Broglie (1927), Bohm (1952), Everett (1957), Ghirardi-Rimini-Weber (GRW, 1986) etc.
  - Saunders, S. et al. ed. (2010) *Many Worlds? Everett, Quantum Theory, & Reality*. Oxford University Press.
  - Albert, D. and Ney, A. ed. (2013) *The Wave Function: Essays on the Metaphysics of Quantum Mechanics*. Oxford University Press.

- My own long-term research interest: philosophical relevance of the ontological interpretation of Bohm & Hiley (1987, 1993)
  - Bohm, David and Hiley, Basil J. 1987. An Ontological Basis for Quantum Theory: I. Non-relativistic Particle Systems. *Physics Reports* **144** (6): 323-348.
  - Bohm, D. and Hiley, B. J. (1993) *The Undivided Universe: An Ontological Interpretation of Quantum Theory*. London: Routledge

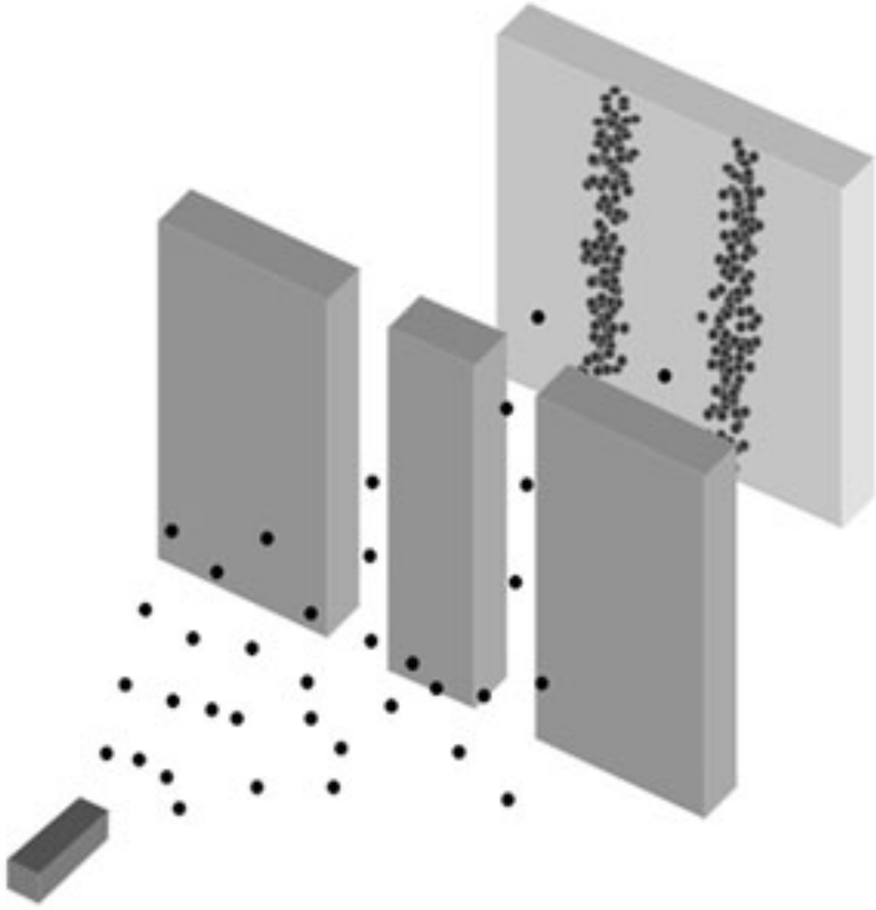
Recent papers

- Pylkkänen, P., Hiley, B.J. & Pättiniemi, I. (2017) Bohm's approach and individuality, in Guay, A. & Pradeu, T. eds. *Individuals Across Sciences*, Oxford University Press.
- Pylkkänen, P. (2017) Is there room in quantum ontology for a genuine causal role for consciousness, A. Khrennikov & Haven, E. (toim.) *The Palgrave Handbook of Quantum Models in Social Science: Applications and Grand Challenges.* London: Palgrave Macmillan, s. 293-317
- Pylkkänen, P. (2015) The quantum epoché, *Progress in Biophysics & Molecular Biology*. **119** (3), s. 332-340

The 5th Solvay conference, 1927

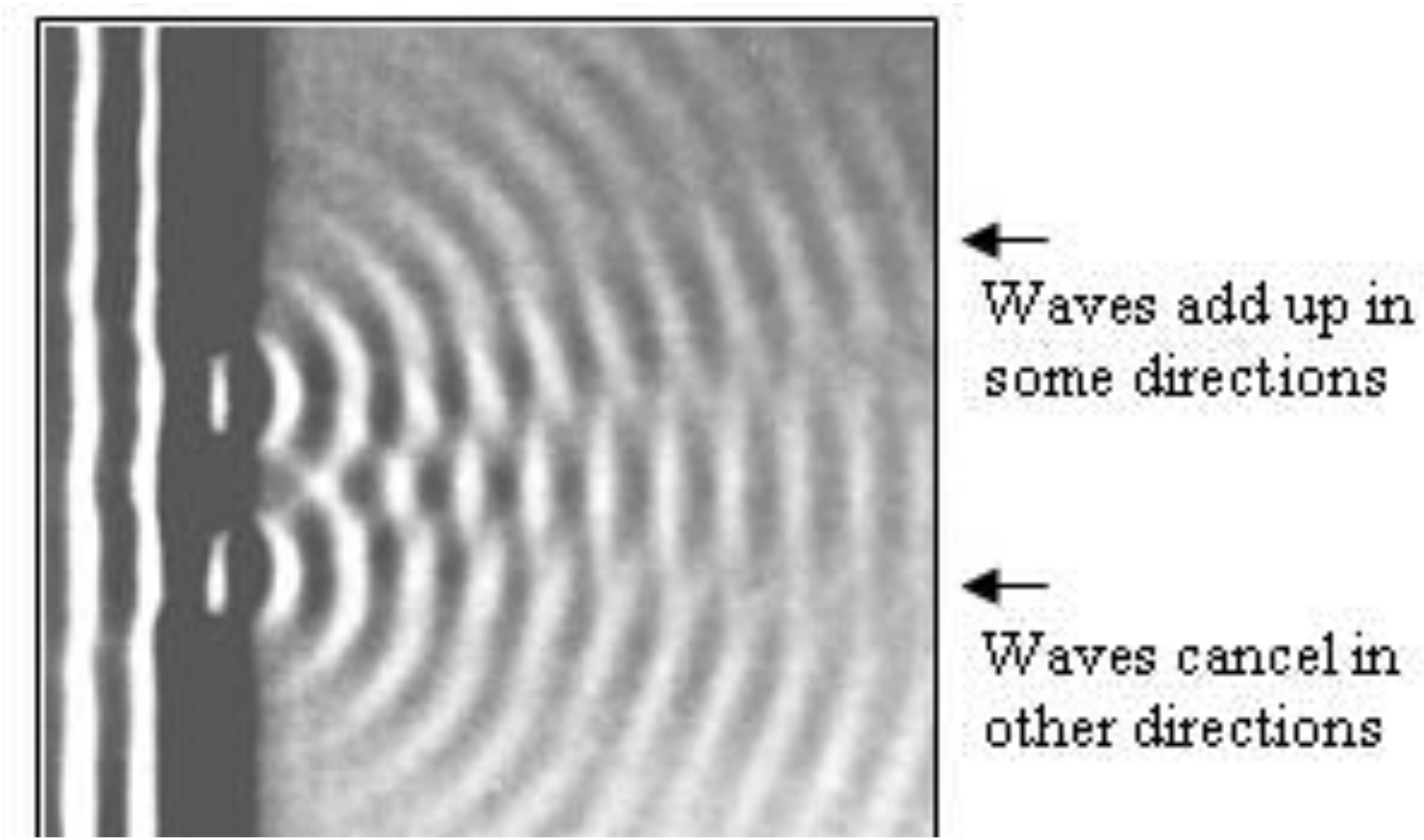


Two-slit experiment for particles

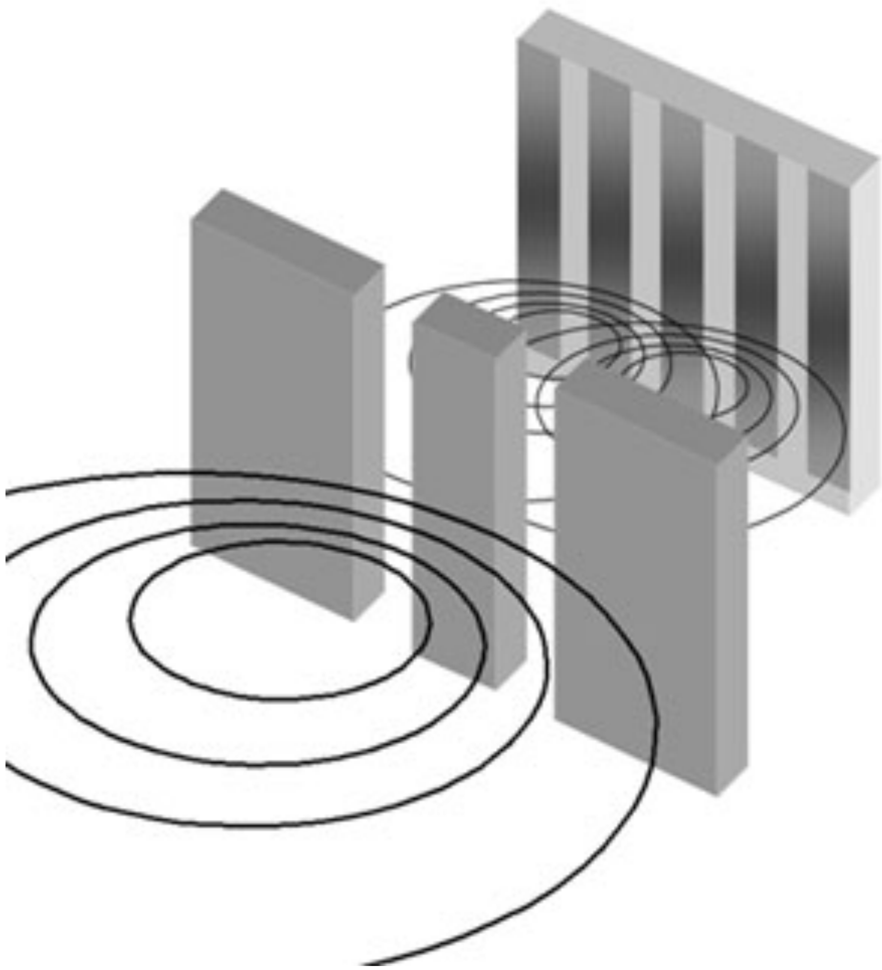


When waves meet they interfere (constructively and destructively)

Water waves in two slits

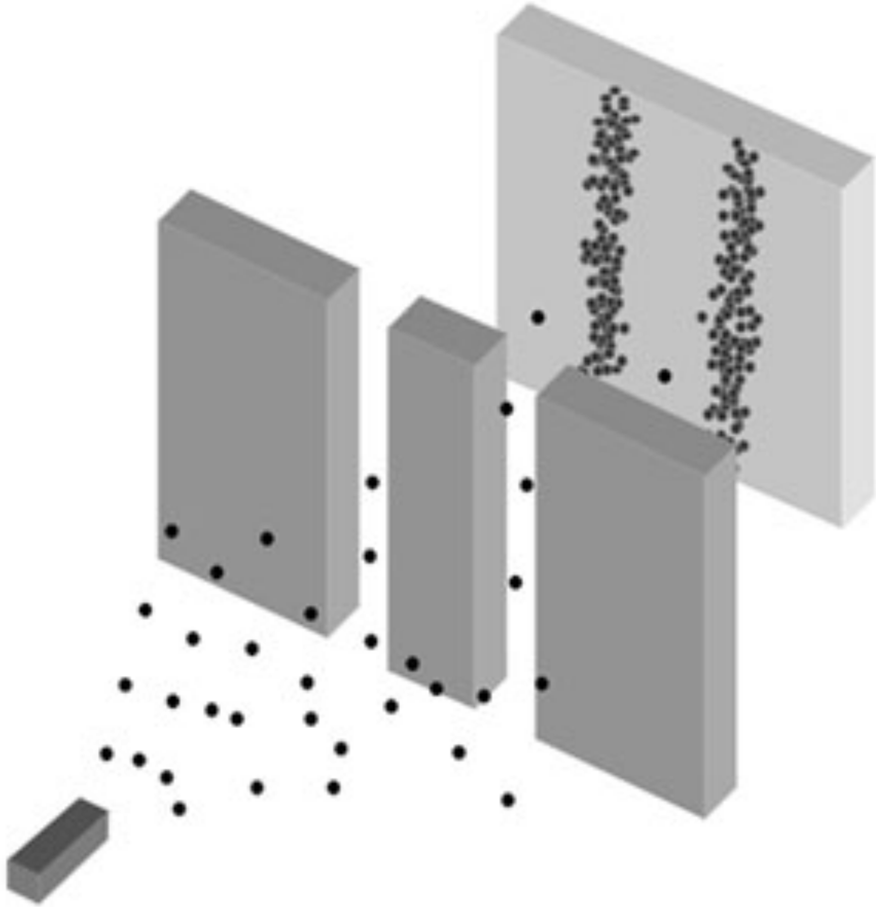


Note the interference fringes/pattern on the screen (interference = signature of a wave)



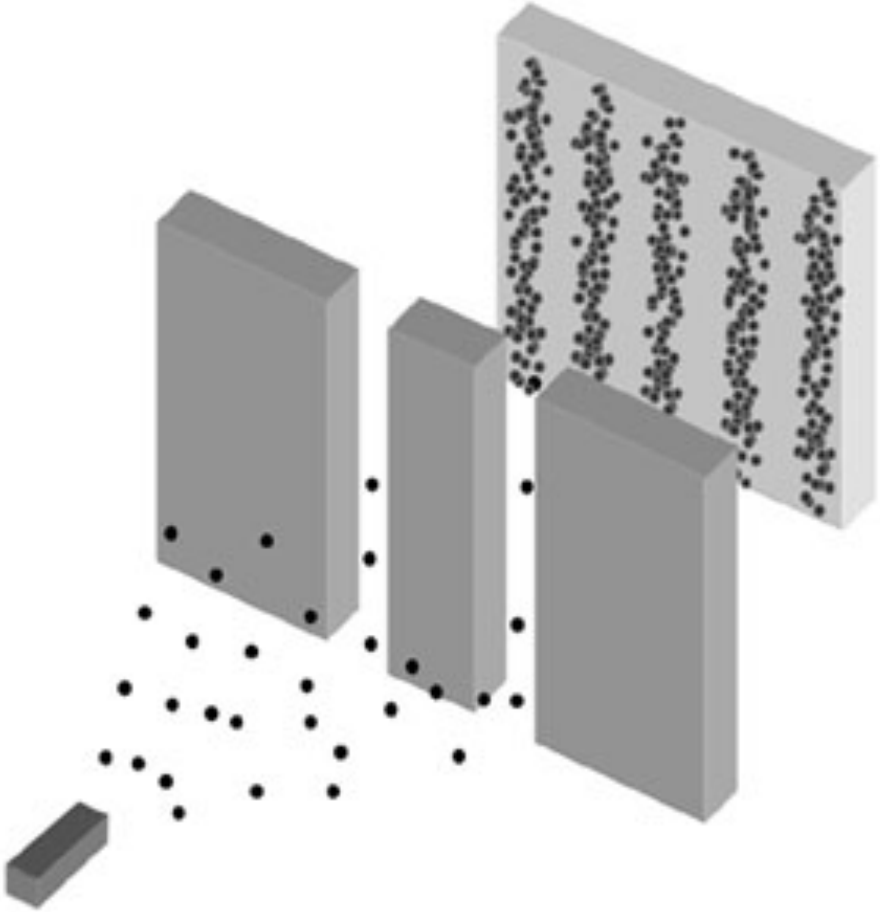
- What happens if you pass e.g. electrons through the 2-slits?
- The electron was initially assumed to be a particle (it has mass and charge)
  - so we expect that it should behave like a little bullet!

This is how physicists expected the electrons ought to behave…

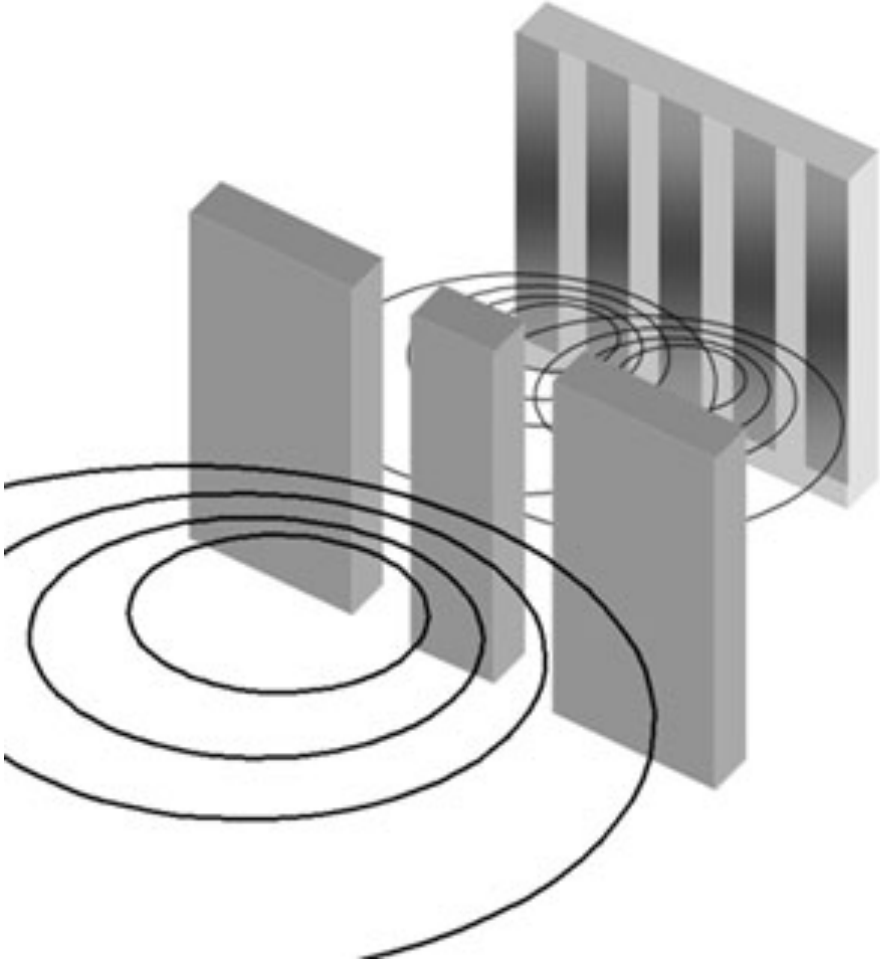


This is what the experiment shows!

(Note that we can only observe the dots in the screen, not the particles moving -> Heisenberg's uncertainty principle)

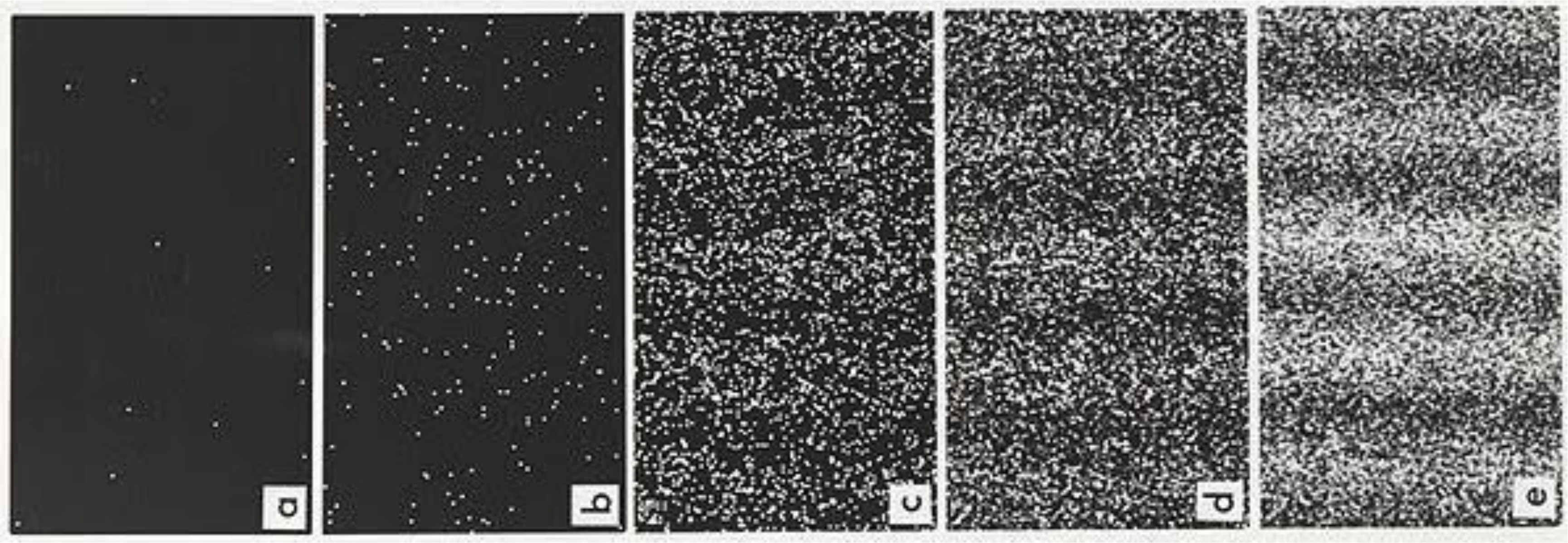


Compare the previous pattern with the wave pattern below

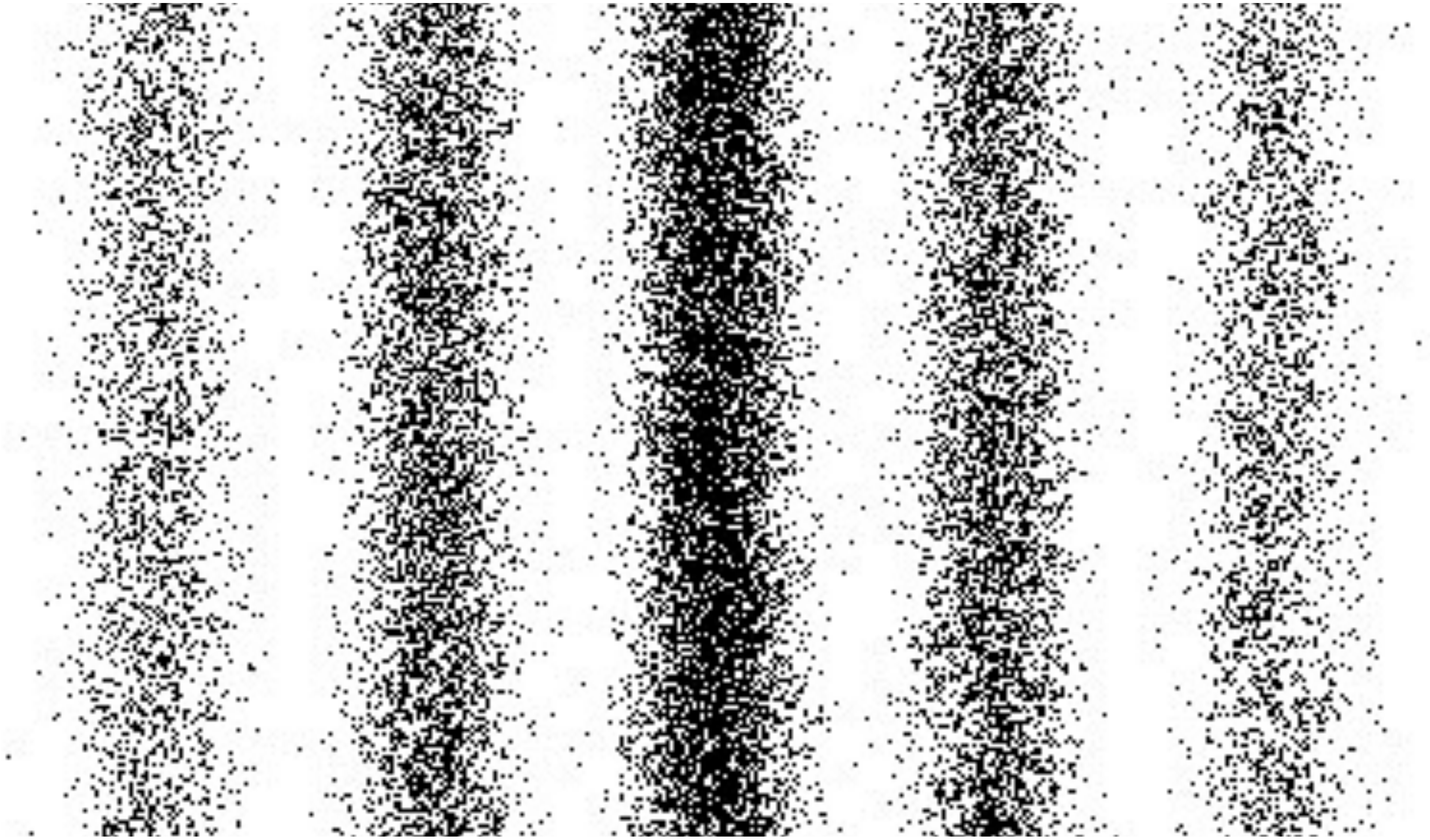


- Notice that we get an interference pattern even if the electrons enter the slit system one by one

Each electron arrives as a particle, but gradually these spots build up an interference pattern characteristic of waves



Wave interference pattern produced by many electrons



Wave-particle duality

- An individual system exhibits both
  - particle properties
    - it arrives at the detector at a single spot
- and
  - wave properties
    - the place where the spot appears is constrained by the mathematics of wave behaviour
    - how else would such individual particles build up a wave interference pattern?

- Note in particular: opening of 2^{nd} slit may prevent an electron reaching a point where it could arrive if only one slit were open.

- Natural to ask: how does the electron move through the slit system? How could a particle obey the mathematics of waves?
- The easiest way to answer these questions would be to make further experiments
  - “Let’s look what happens”

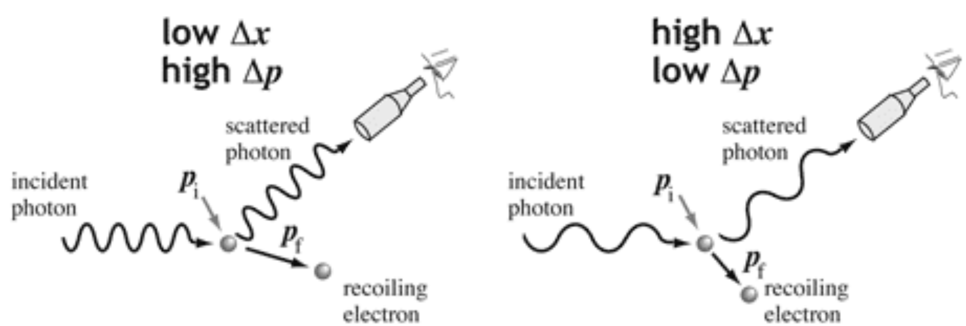
- Unfortunately we cannot observe the motion of an individual electron in detail!
  - This relates to the Heisenberg indeterminacy principle
  - "If we observe precisely where it is, we have no idea of where it is going" (and vice versa)

- Note especially: to predict the movement of an electron we should measure both position x (“where it is”) and momentum p (“where it is going”) at a single moment.
  - we cannot do this as long as we stay within current quantum theory!
  - without the initial conditions we cannot predict what the individual system does!
    - -> indeterminism, probability…

The Heisenberg Uncertainty Principle

$$\Delta x \, \Delta p \geq \hbar$$

Δx = uncertainty in position
Δp = uncertainty in momentum
$\hbar$ = $h / 2\pi$



A high frequency (short wavelength) photon gives a more accurate measurement of position, but it causes a greater uncertainty in the momentum of the recoiling electron. The act of measurement itself limits how well-defined the electron's position and momentum can be. The indeterminacy derives from the quantum wave nature of the electron itself.

Source: *WikiPremed, a trademark of Wisebridge Learning Systems LLC.*

"But you can't go through life applying Heisenberg's Uncertainty Principle to everything."

Summary…

- The mystery is this: the electrons leave as particles, and they arrive as particles, one by one, to the screen.
  - as a large number of them passes through the system, a pattern builds up.
  - what is this pattern?
  - it is an interference pattern!
  - interference is a signature of a wave.

Summary cont.

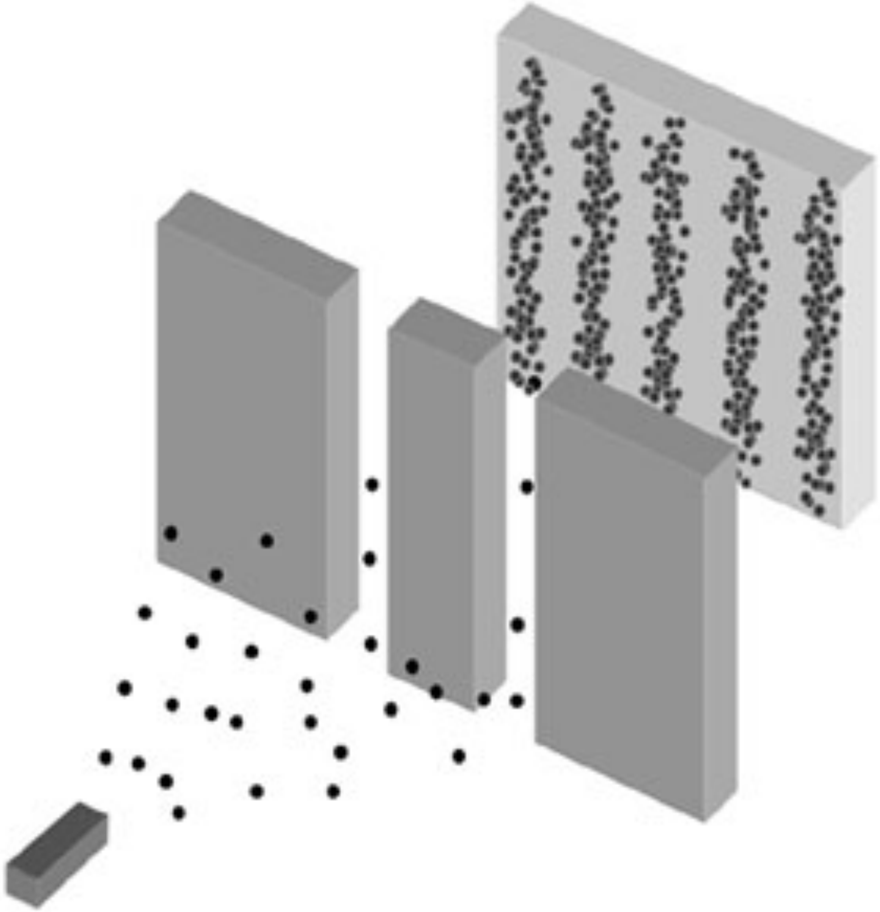
- But how can the particles, sent into the system one by one, collectively build up an interference pattern?
- Surely each individual “particle” must also have some wave property
  - how otherwise could such a “particle” obey the interference pattern (e.g. avoid certain classically allowed areas)?

The situation has given rise to many different interpretations

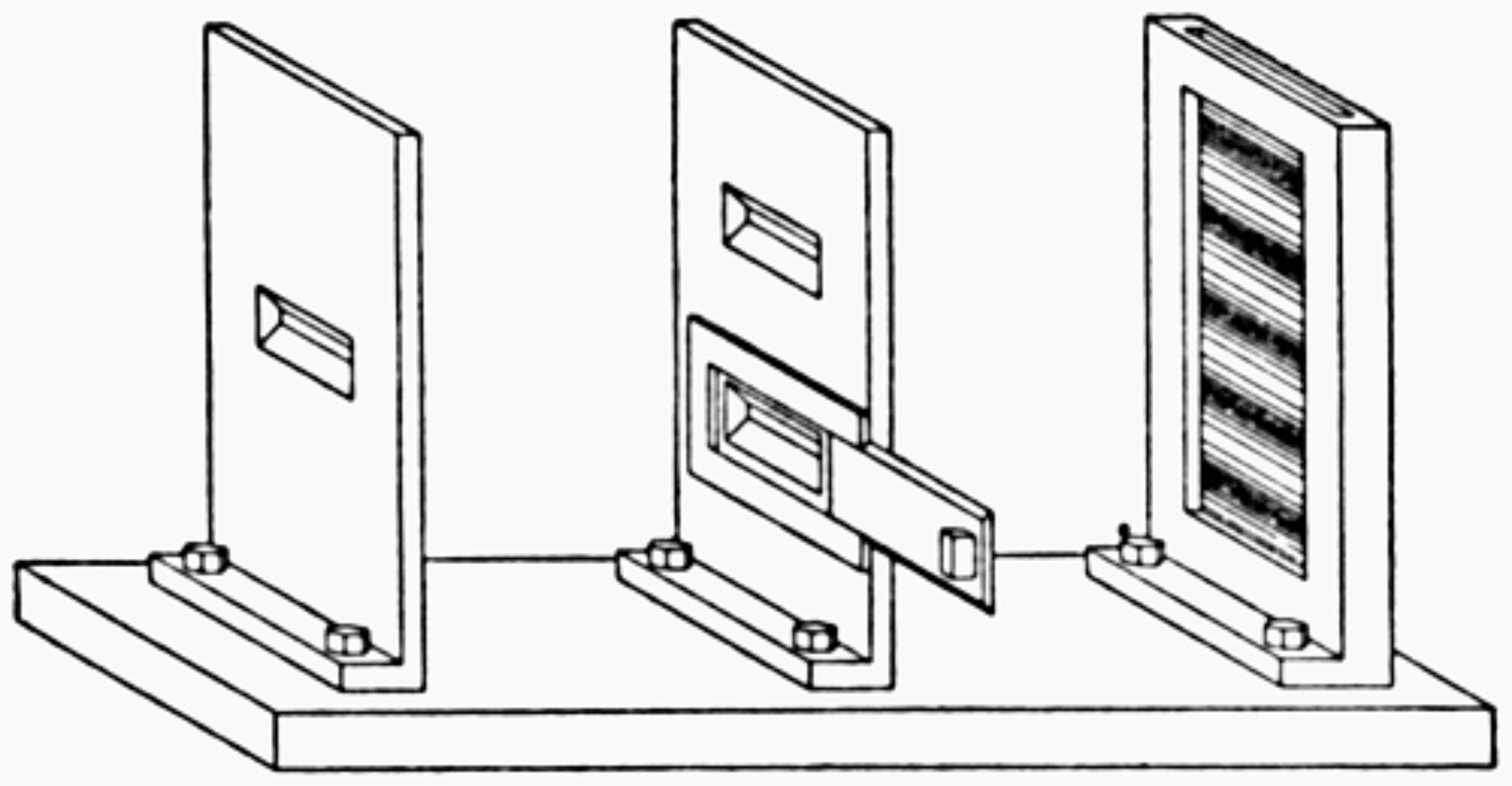
- Bohr
- Von Neumann (collapse interpretations)
- “many worlds”
- deBroglie-Bohm
- etc.

Bohr: it is meaningless to talk about the electrons moving (because we cannot observe the movement). Wave and particle models are complementary.

(The picture below is misleading because it shows the electrons as particles that move)

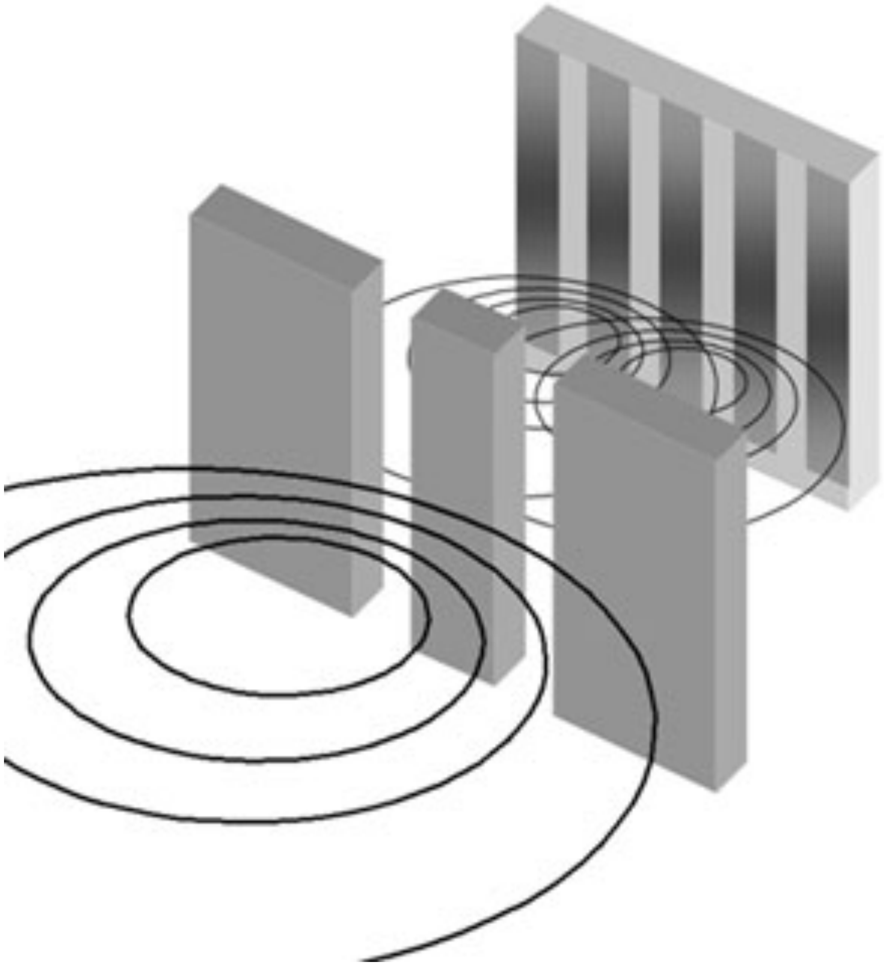


A double-slit apparatus suggested by Niels Bohr to demonstrate the wave-particle dualism

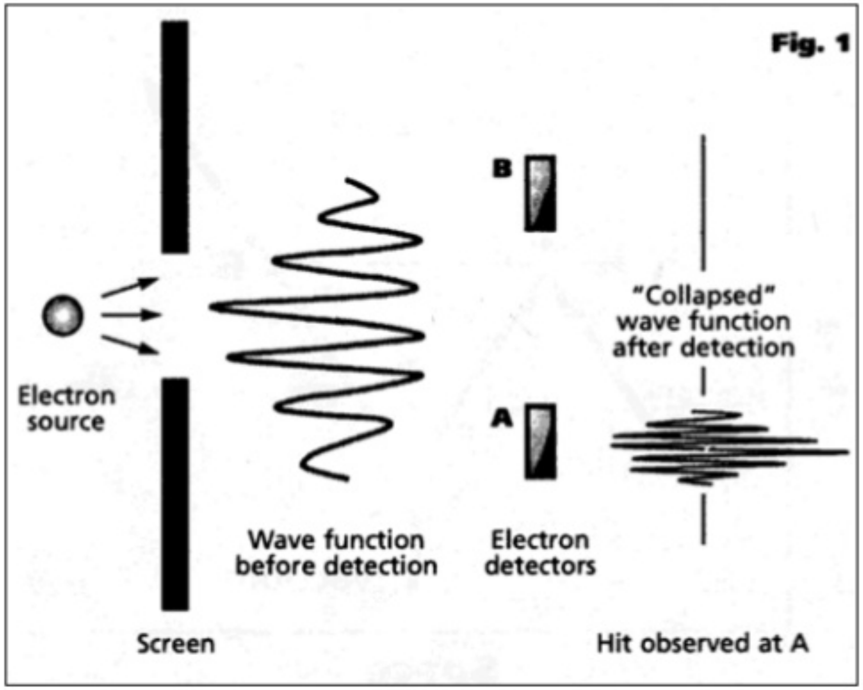


From N. Bohr 1949/1983: Discussions with Einstein on Epistemological Problems in Atomic Physics, p. 27.

Von Neumann: the electron is a wave when it moves, but the wave "collapses" into a particle at the screen

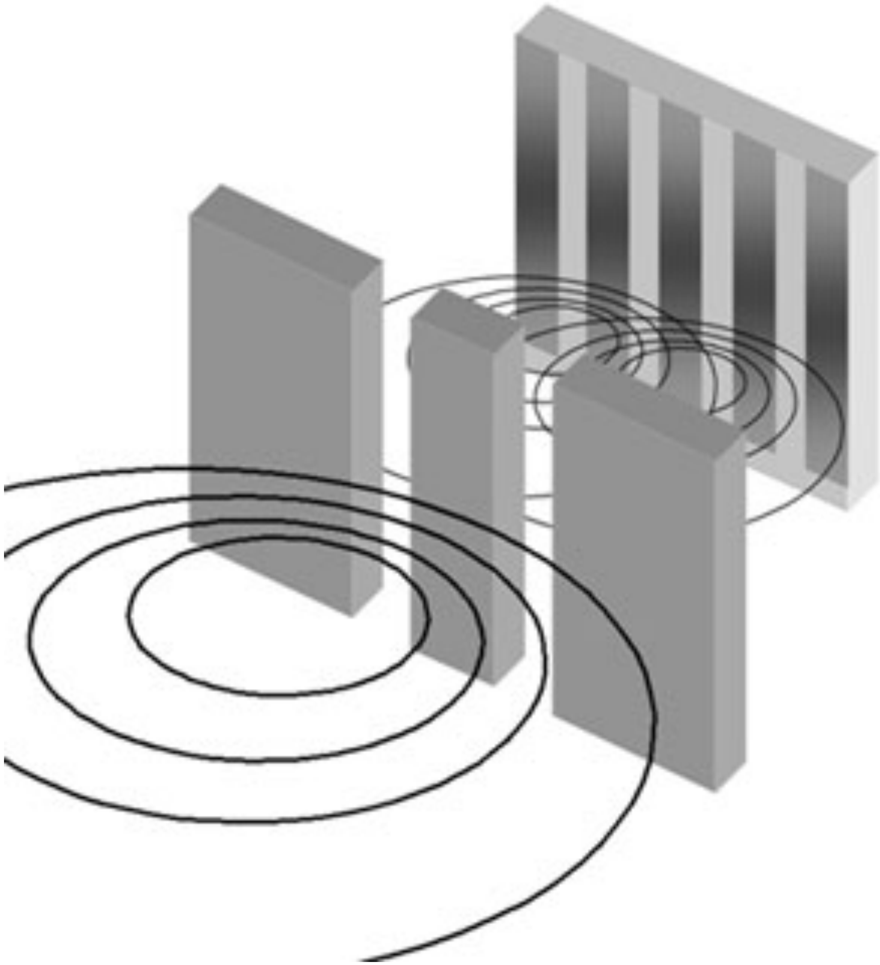


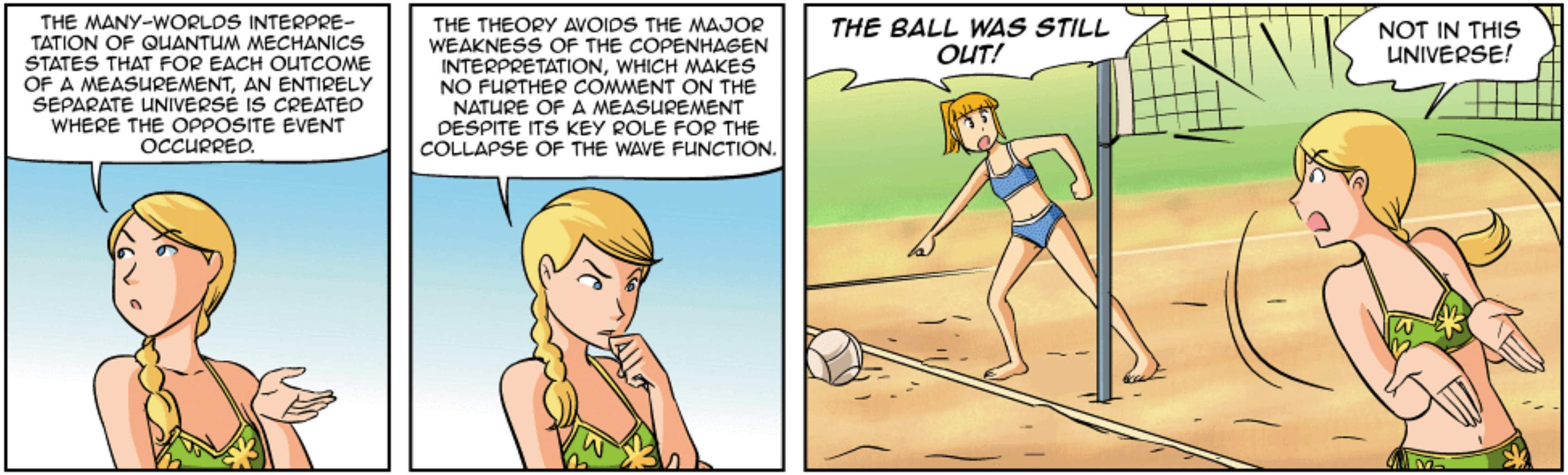
Wave-function Collapse



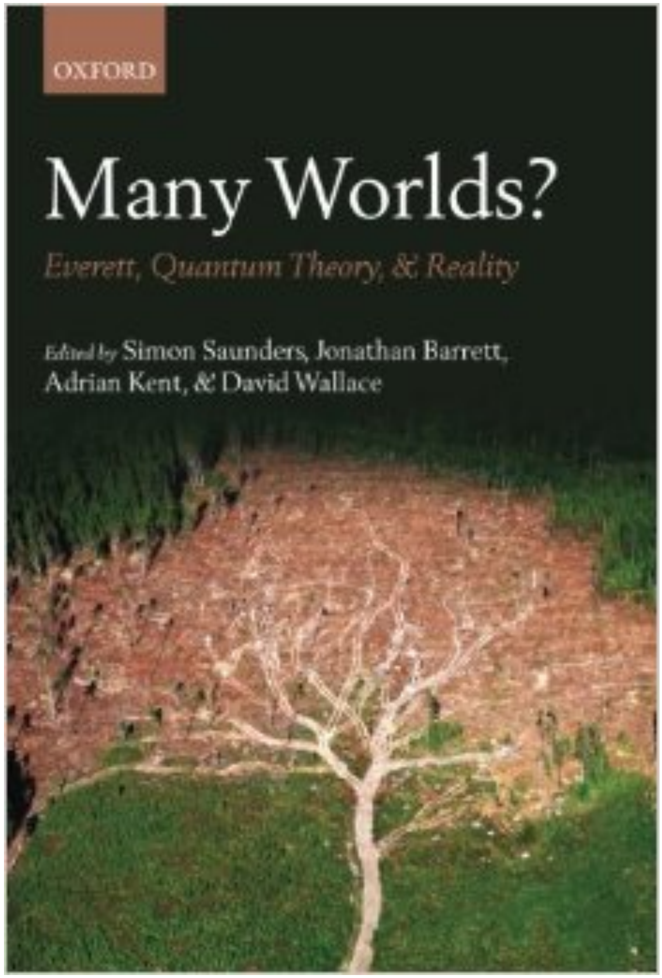
"Many worlds": only the wave is real but there is no collapse. The total wavefunction "branches" in each measurement

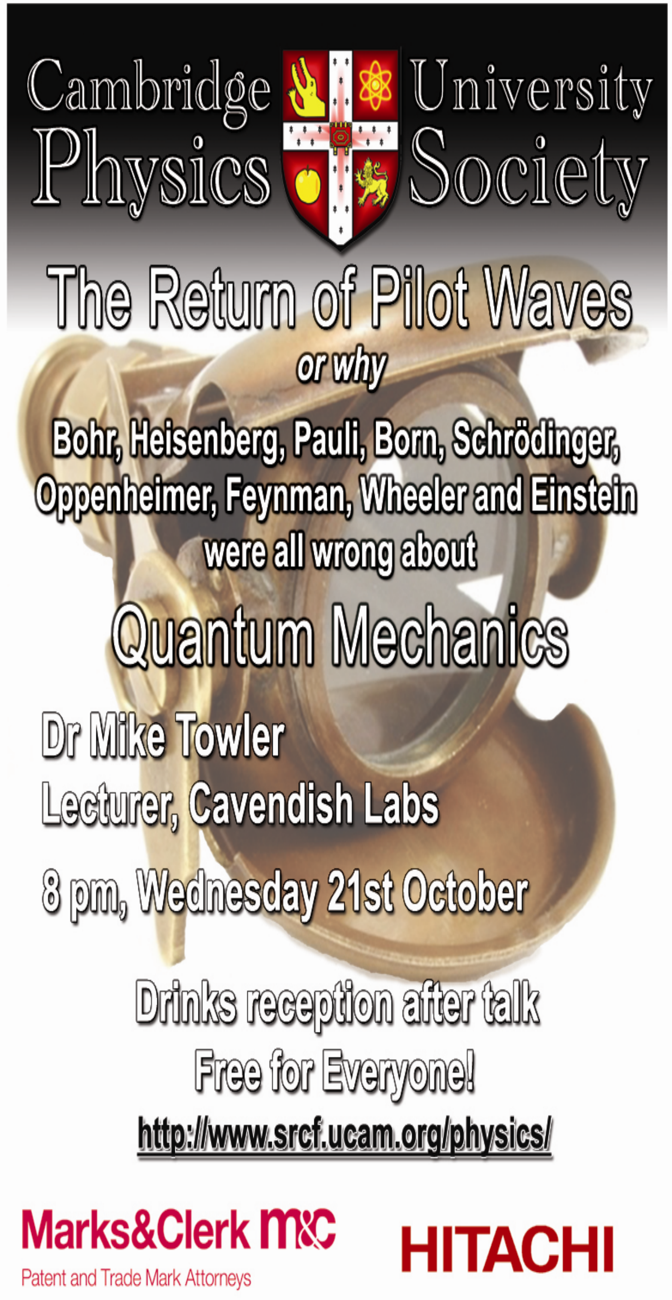
(Wallace: the world at the macroscopic level is constantly branching into copies)





Sandra and Woo by Oliver Knörzer (writer), Powree (artist) and Lisa Moore (colorist) - www.sandraandwoo.com


OXFORD
Many Worlds?
Everett, Quantum Theory, & Reality
Edited by Simon Saunders, Jonathan Barrett,
Adrian Kent, & David Wallace

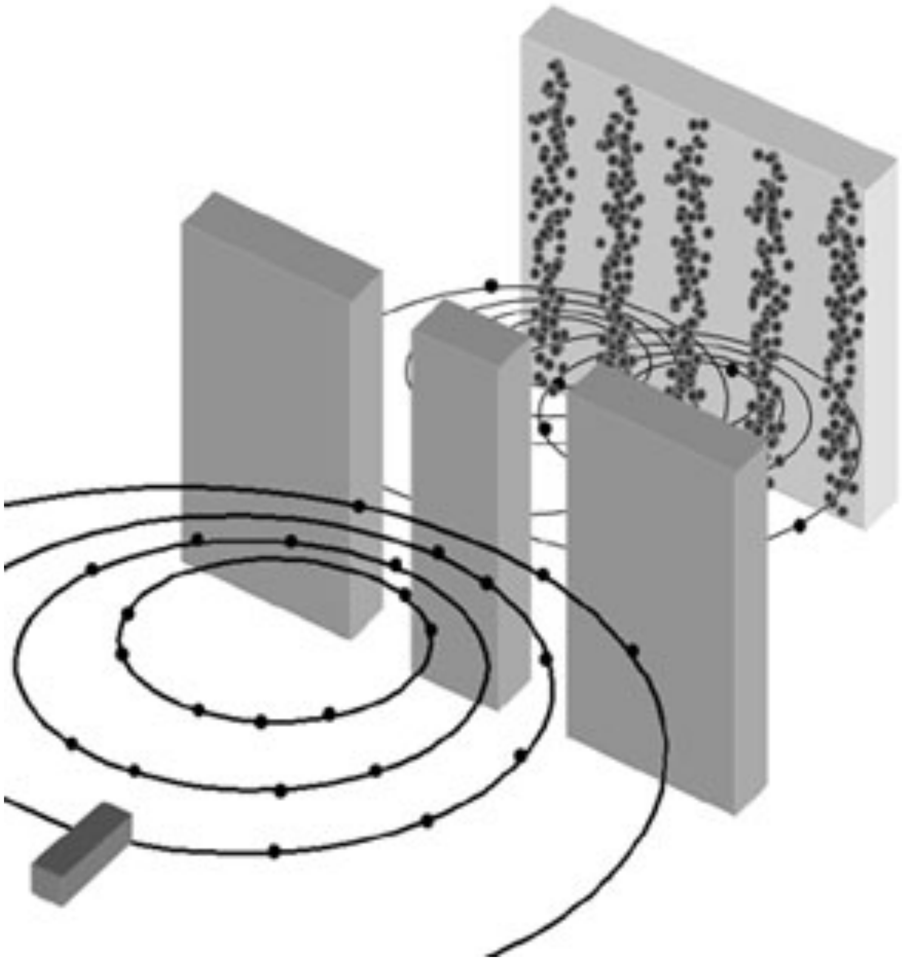

Cambridge University
Physics Society
The Return of Pilot Waves
or why
Bohr, Heisenberg, Pauli, Born, Schrödinger,
Oppenheimer, Feynman, Wheeler and Einstein
were all wrong about
Quantum Mechanics
Dr Mike Towler
Lecturer, Cavendish Labs
8 pm, Wednesday 21st October
Drinks reception after talk
Free for Everyone!
http://www.srcf.ucam.org/physics/
Marks&Clerk m&c
Patent and Trade Mark Attorneys
HITACHI

Enter Bohm

deBroglie-Bohm: the electron is a particle, accompanied with a new type of quantum field which guides it ("pilot wave")

Bohm: the field has some exotic new properties and must not be thought of pushing and pulling the

particle mechanically.



The ontological interpretation of quantum theory (Bohm and Hiley)

- It is assumed that, say, an electron is a particle which has a well-defined position and momentum and is accompanied and guided by a field ψ which satisfies the Schrödinger equation

$$i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \nabla^2 \psi + V(\mathbf{r})\,\psi.$$

Got it?

- It is not particle OR field
- It is not a field which collapses into a particle
- It is not a field which branches into "many worlds"
- It is **particle AND field**
  - "an inseparable union of a particle and a field"

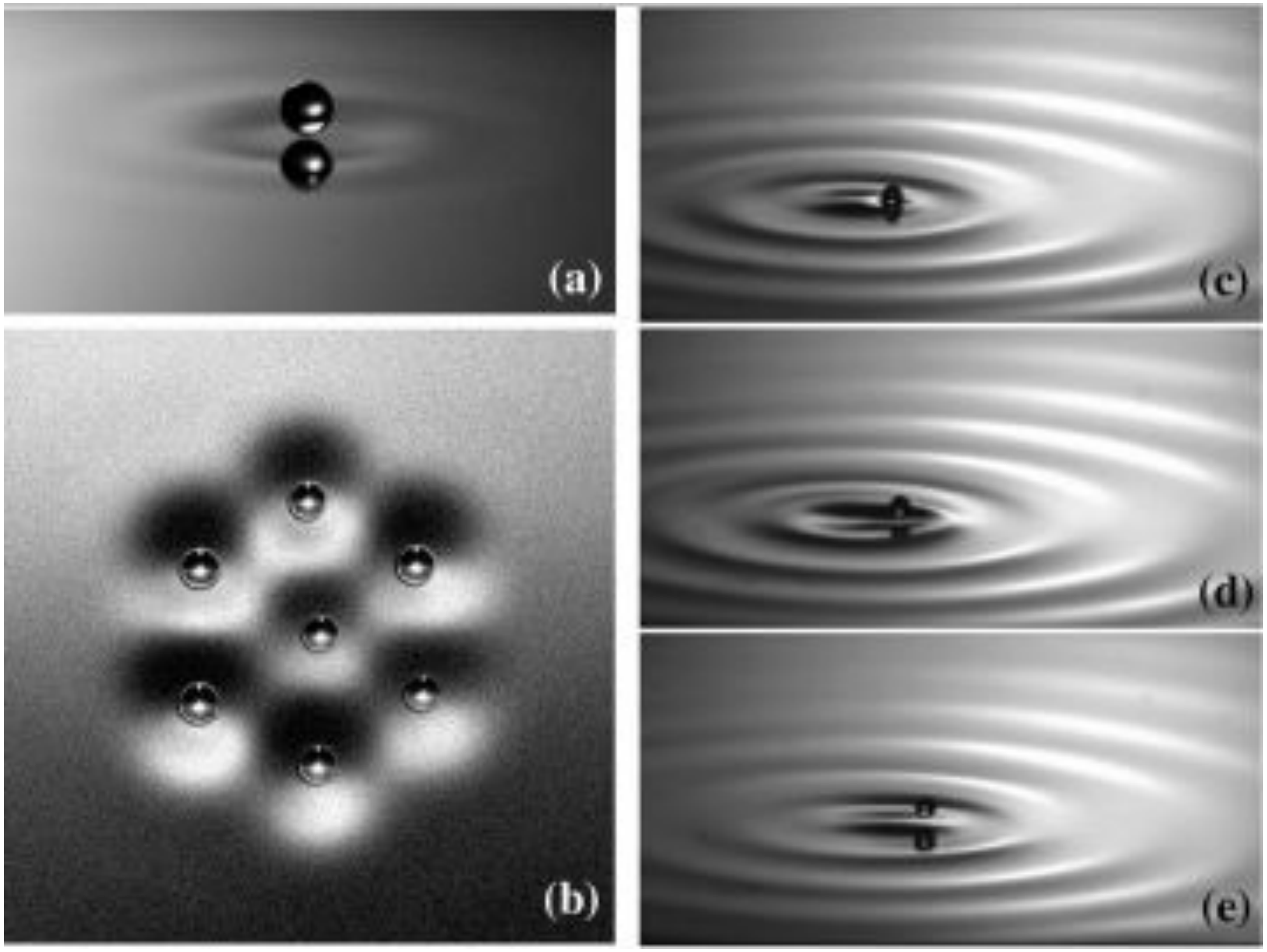
- In the two-slit experiment the particle goes through one of the slits, and then appears at a point in a photographic place
  - this explains why we see the appearance of a spot
  - note especially that there is no need to assume a collapse of the wave function
- The accompanying field goes through both slits, interferes afterwards, and guides the movement of the particle so that the particles collectively, spot by spot, build up an interference pattern.

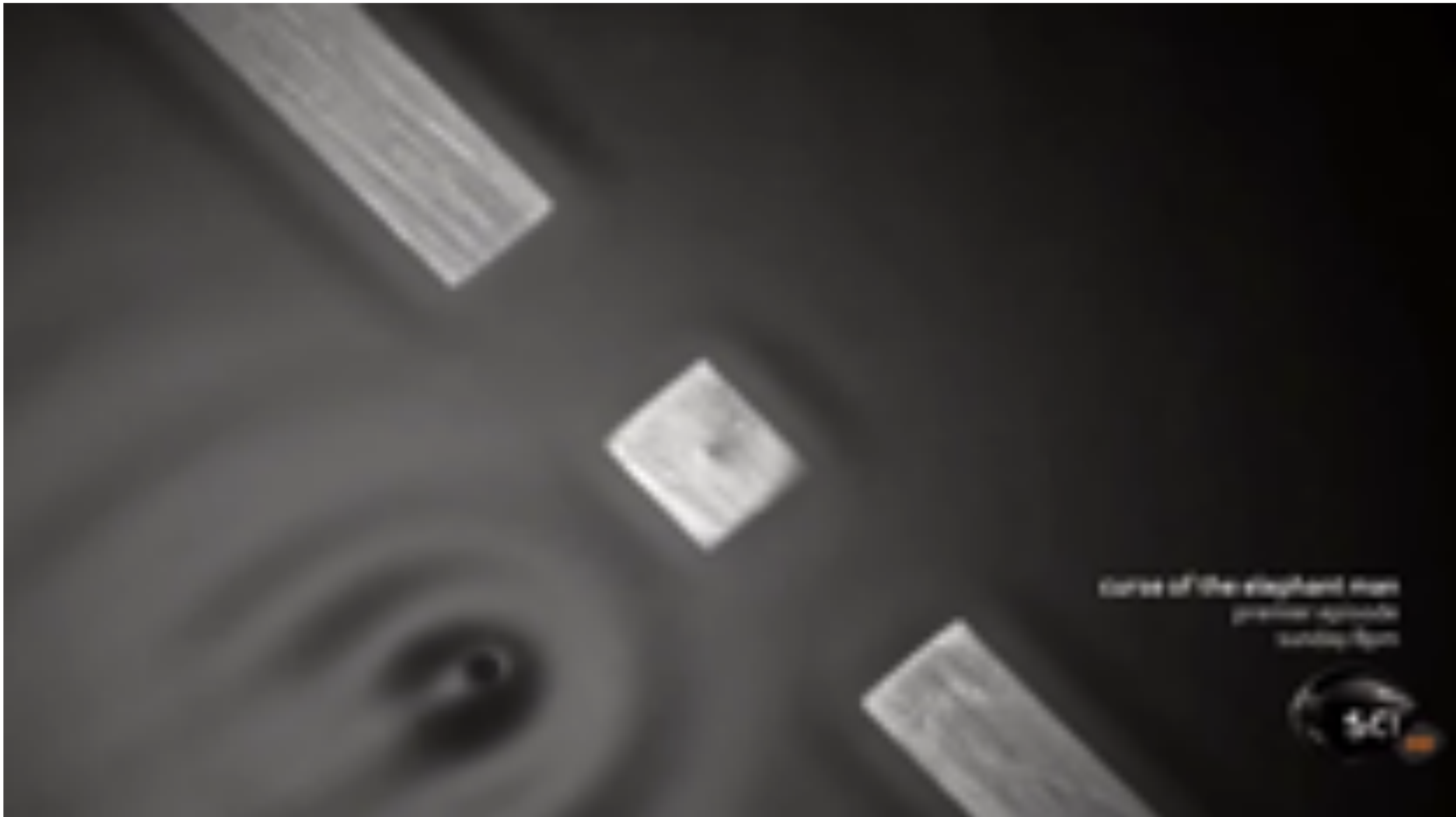
- In order to obtain some intuitive understanding of a system where a wave guides a particle, let us examine a classical analogue.
  - But remember: what follows is merely a limited, mechanical analogy, the quantum case is radically different in some key ways.
    - This therefore also helps to understand the difference between classical and quantum.

Yves Couder: 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.

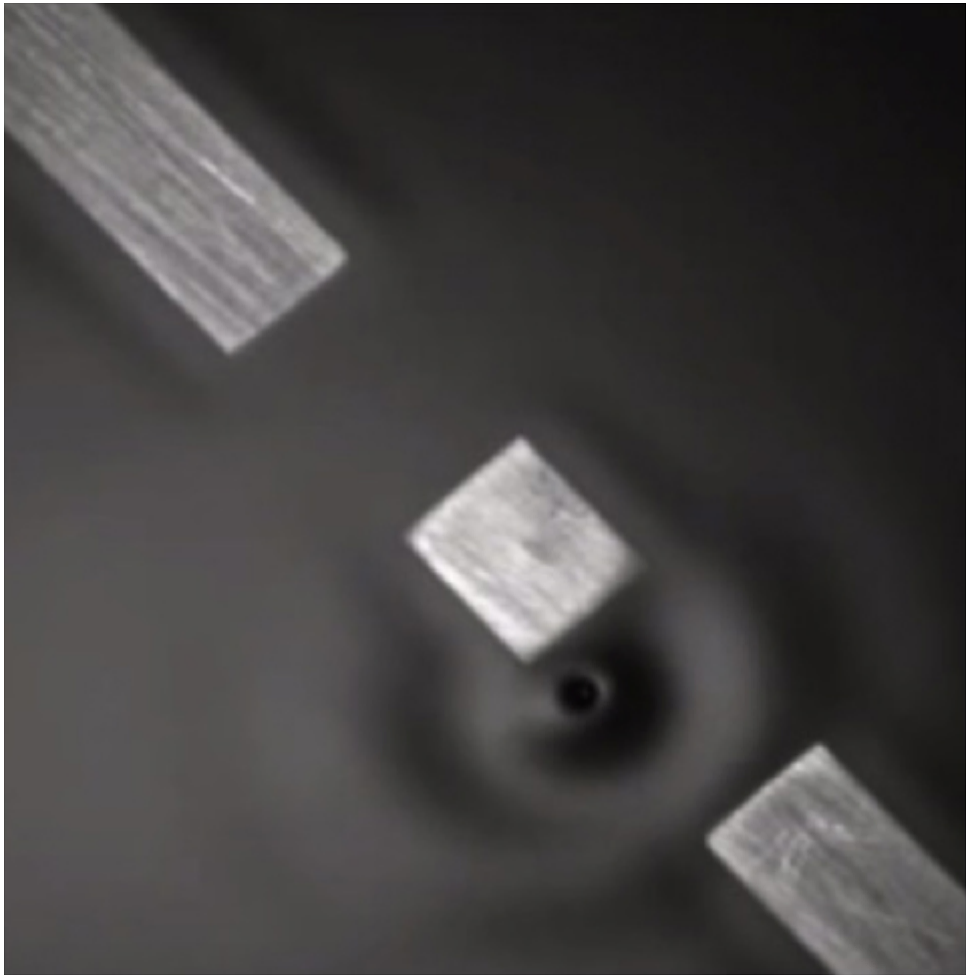
Couder & Fort: Single-Particle Diffraction and Interference at a Macroscopic Scale

The drop becomes spontaneously self-propelled and moves on the liquid surface at constant velocity. This occurs when there is a locking phenomenon so that the drop falls systematically on the forward front of the wave generated by its previous bouncings




curse of the elephant man

When a droplet bounces along the surface of a liquid toward a pair of openings in a barrier, it passes randomly through one opening or the other while its "pilot wave," or the ripples on the liquid's surface, passes through both. After many repeat runs, a quantum-like interference pattern appears in the distribution of droplet trajectories.



Yves Couder et al.

- The bouncing droplet is a fascinating <u>classical analogue</u> of the deBroglie-Bohm theory
- However: the genuine quantum case has some radically different features
  - non-locality, active information, the guiding field lives in a non-manifest, implicate, multi-dimensional configuration space…

How to calculate quantum 'trajectories'.

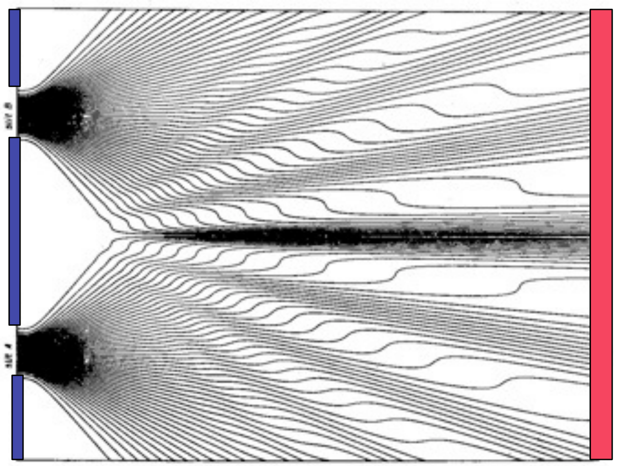
Insert the wave function $\psi(x,t) = R(x,t)e^{-iS(x,t)}$ into the Schrödinger equation.

Real part gives: $$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + Q + V = 0$$ Quantum Hamilton-Jacobi.

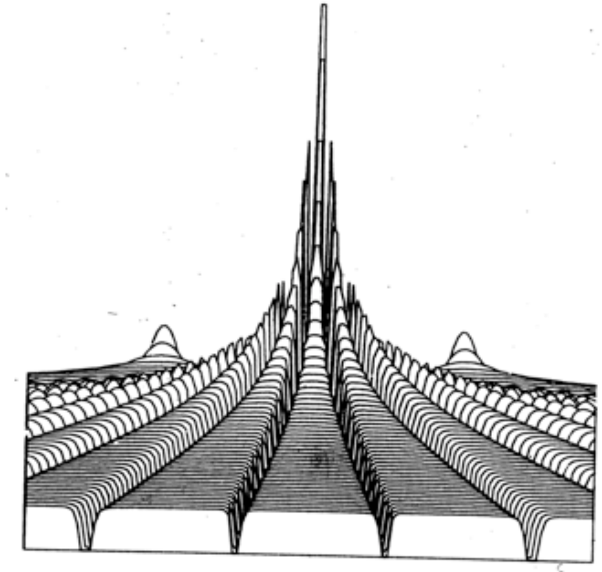
$$E_B = -\frac{\partial S}{\partial t} \qquad P_B = \nabla S$$

Quantum Potential = $Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}$

[Bohm & Hiley, The Undivided Universe, 1993]



Schrödinger trajectories



Quantum Potential

[Philippidis, Dewdney and Hiley, Nuovo Cimento **52B**, 15-28 (1979)]

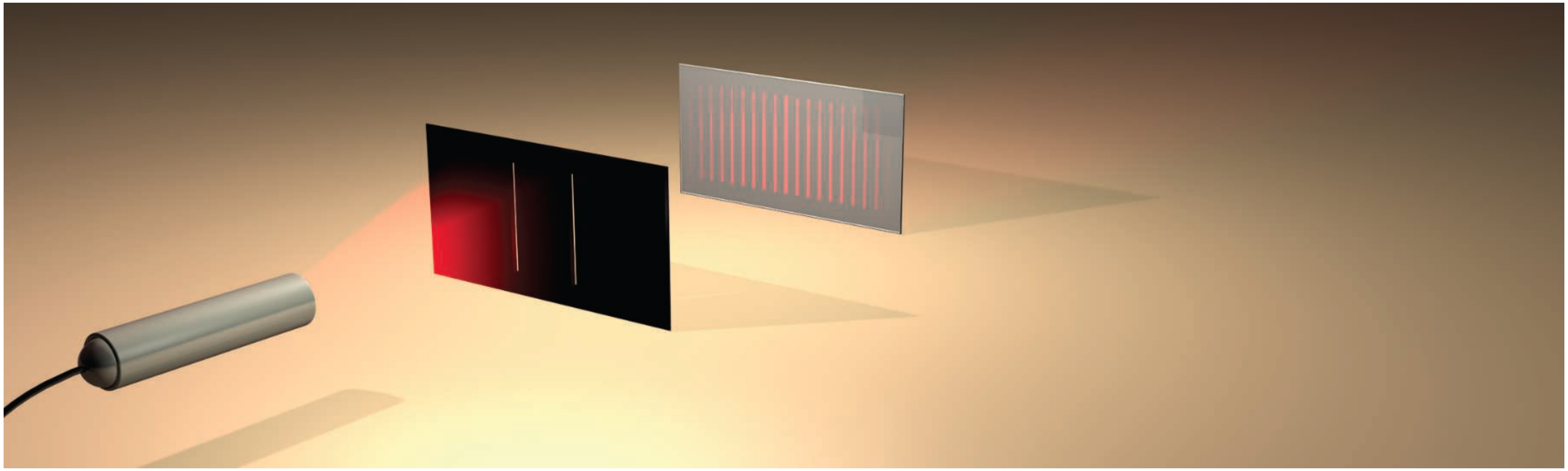
[Slide made by B.J. Hiley]

- De Broglien-Bohmin ehdotus elektronien liikeradoista on hypoteesi, jota ei ole voitu testata kokeellisesti
- Epätarkkuusperiaate estää havaitsemasta, kulkevatko elektronit pitkin tulkinnan ehdottamia liikeratoja
  - kvanttiteorian havaintoaineisto on yhteensopiva monien eri tulkintojen kanssa
  - kvanttiteoria tarjoaa hyvän esimerkin teorioiden ja tulkintojen empiirisestä alimääräytyneisyydestä.

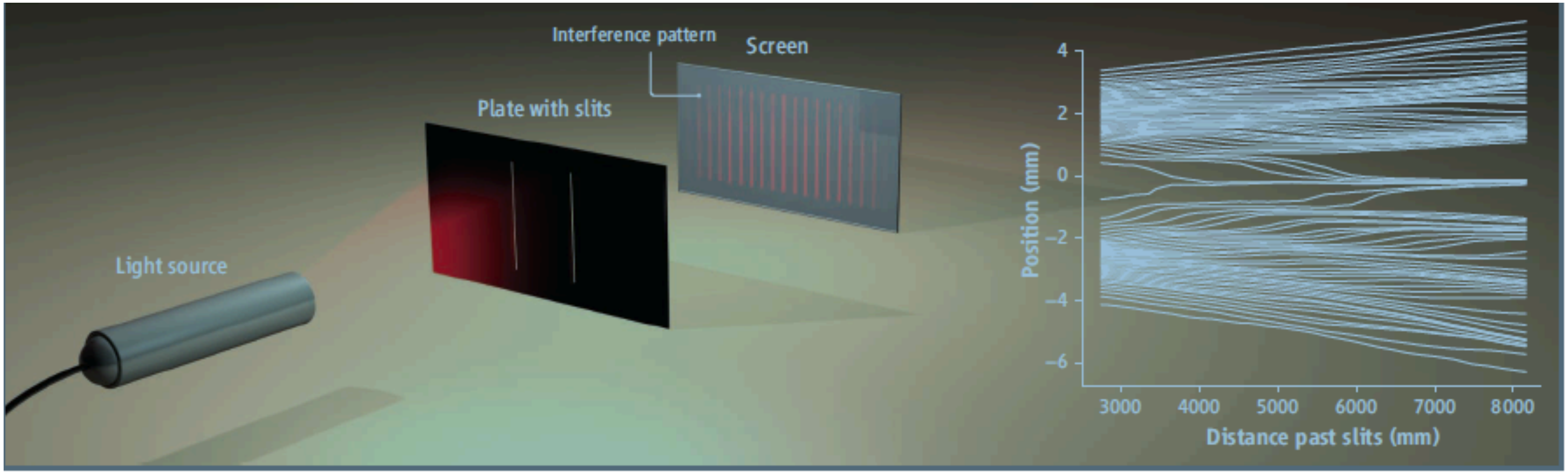
- Viime vuosina on kuitenkin tapahtunut kehitystä, joka saattaa tuoda uutta valoa näihin kysymyksiin.
  - vuonna 2011 arvovaltaisen brittiläisen Institute of Physics –järjestön lehden *Physics Worldin* "vuoden läpimurto" –huomionosoitus myönnettiin Aephraim Steinbergille ja tämän ryhmälle Toronton yliopistossa.

Kocsis, S. et al. (2011), Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer, *Science*, vol. 332, 1170-73.

- Käyttämällä kehittyvää tekniikkaa, jota kutsutaan ”heikoksi mittaukseksi”, ryhmä pystyi määrittämään Youngin 2-rakokokeessa yksittäisten fotonien keskimääräisiä liikeratoja, jotka vastasivat de Broglie–Bohmin tulkinnan liikeratoja.
    - vaikka kyse on vain keskimääräisistä liikeradoista, se että ylipäätään puhutaan fotonin liikeradasta (mikä tarkoittaa sitä, että fotonilla olisi hyvin määritelty paikka ja liikemäärä samanaikaisesti) sotii ainakin ensi näkemältä vahvasti Bohrin ja Heisenbergin tulkintaa vastaan.



You cannot measure a quantum particle without disturbing it. Or can you? Weird "weak measurements" are opening new vistas in quantum physics.



Two-slit redux. Each photon goes through both slits and has no trajectory, yet weak measurements trace the photons' average trajectories (graph, *right*).

5 AUGUST 2011 VOL 333 SCIENCE

Jean Bricmont heikoista mittauksista

- Nopeuksien heikosta mittauksesta voidaan rekonstruoida liikeratoja
- Jotta saavutetaan nopeuden heikko mittaus täytyy ensiksi mitata hiukkasen paikka “heikosti”
  - tämä tarkoittaa, ettei aaltofunktiota häiritä paljoa
- Mutta tällöin ei saada hiukkaselle tarkkaa paikkaa.

Bricmont, J. (2016) *Making Sense of Quantum Mechanics.* Berlin: Springer.

- Koska ensimmäinen mittaus on heikko, voidaan tehdä “vahva” (s.o. tavallinen) mittaus hieman myöhemmin, ja tällä kertaa saadaan tarkka paikka.
- Toistamalla operaatio monta kertaa, saadaan tilastollinen paikkajakauma, ja ottamalla sen keskiarvo, saadaan paikka ensimäisessä sijainnissa.

Bricmont, J. (2016) *Making Sense of Quantum Mechanics.*

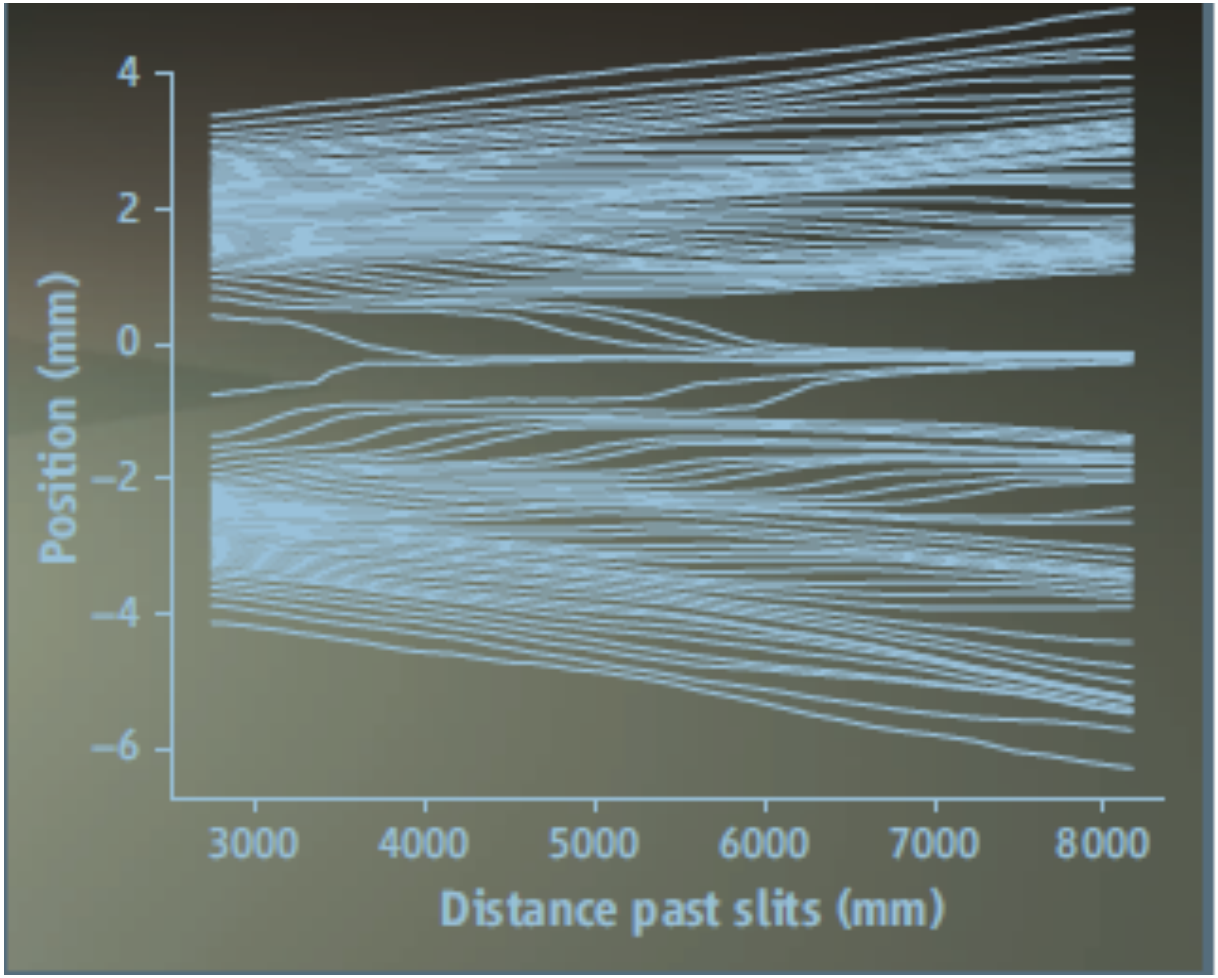
- Nyt on mitattu kaksi paikkaa peräjälkeen ja niiden välinen aikaintervalli, joten voidaan laskea nopeus joka voidaan liittää ensimmäiseen paikkaan
  - tämä ei ole ristiriidassa epätarkkuusperiaatteen (EP) kanssa, sillä meidän pitää tehdä monta operaatiota ja laskea keskiarvo saadaksemme tuloksen.
  - EP pätee vain vahvojen (tavallisten) mittausten tuloksiin.

Bricmont, J. (2016) *Making Sense of Quantum Mechanics*.

- Toistamalla “heikkoa mittausta” eri paikoissa saadaan nopeuskenttä (s.o. jokaiseen avaruuden pisteeseen voidaan liittää nopeus)
  - tästä kentästä voidaan rekonstruoida liikeratoja piirtämällä viivat, joiden tangentit saadaan nopeuskentästä.

Bricmont, J. (2016) *Making Sense of Quantum Mechanics.*

`Observing the average trajectories of single photons in a two-slit interferometer'



Bricmont:

- “Edellinen ei ‘todista’ että de Broglie-Bohmin teoria on tosi, sillä on muita teorioita, jotka antavat samat empiiriset ennustukset
  - esim. Fenyes & Nelson; Deotto & Ghirardi.
  - tulos on silti suggestiivinen, sillä de Broglie-Bohmin teorian tässä yhteydessä tekemät ennustukset ovat luontevia teorian näkökulmasta, ja havainnot konfirmoivat ne.”

Bricmont, J. (2016) *Making Sense of Quantum Mechanics.* Berlin: Springer.

- Ongelma: Steinbergin ryhmän kokeet on tehty fotoneilla, mutta esim. Bohm & Hileyn tulkinnan mukaan fotonilla (toisin kuin esim. elektronilla) ei ole liikeratataa.
  - siksi olisi mielekästä tehdä “heikot mittaukset” fermioneilla (esim. elektroneilla tai atomeilla)
  - Flack, Hiley & Barker, ongoing

vrt. D. Marian, N. Zanghì, and X. Oriols, 2016, Weak Values from Displacement Currents in Multiterminal Electron Devices

University College, London
Foundations of quantum mechanics: experiment and theory

- Toistaiseksi heikkojen mittausten tekniikkaa on käytetty vain optisissa kokeissa
  - ei ole kuitenkaan tehty heikkoja mittauksia hiukkasilla, joilla on ei-nolla lepomassa ja jotka tottelevat Schrödingerin yhtälöä.
  - siksi aiomme tehdä kaksi koetta, joissa mitataan atomin spinin ja liikemäärän heikot arvot.
- Tämä on ensimmäinen kerta kun heikkojen mittausten tekniikkaa sovelletaan hiukkasiin, joilla on ei-nolla lepomassa
  - tämä voi avata mahdollisuuksia uuden typpisten mittausten tekemiseen.
  - nyt on selkeitä teorian antamia ennusteita joita voidaan verrata koehavaintoihin."

Flack, Hiley & Barker, in progress
https://www.hep.ucl.ac.uk/qupot/

- Kvanttimekaniikassa on kyse havaittavuuden rajoista
- Pitkään on uskottu, että esim. kvanttiobjektien liikeradoista puhuminen on puhdasta “metafysiikkaa”
- Heikot mittaukset tuovat liikeradan käsitteen havaittavuuden piiriin
  - mutta kyse on vain keskimääräisistä liikeradoista, eikä ole selvää miten nämä pitäisi tulkita

Viimeisin huuto: “Weak-value amplification of the nonlinear effect of a single photon”

nature physics
LETTERS
PUBLISHED ONLINE: 27 FEBRUARY 2017 | DOI: 10.1038/NPHYS4040

Weak-value amplification of the nonlinear effect of a single photon

Matin Hallaji[1]*, Amir Feizpour[1], Greg Dmochowski[1], Josiah Sinclair[1] and Aephraim M. Steinberg[1,2]

In quantum mechanics, the concept of weak measurements allows for the description of a quantum system both in terms of the initial preparation and the final state (post-selection)[1]. This paradigm has been extensively studied theoretically and experimentally, but almost all of weak-measurement experiments carried out to date can be understood in terms of the classical (electromagnetic wave) theory of optics. Here, we present a quantum version in which the measurement apparatus deterministically entangles two distinct optical beams. We show that a single photon, when properly post-selected, can have an effect equal to that of eight photons: that is, in a system where a single photon has been calibrated to write a nonlinear phase shift of ϕ_0 on a probe beam, we measure phase shifts as large as $8\phi_0$ for appropriately post-selected single photons. This opens up a new regime for the study of entanglement of optical beams, as well as further investigations of the power of weak-value amplification for the measurement of small quantities.

Measurement of a property of a system generally proceeds by coupling the system to a probe in such a way that the change of state of the probe depends on the value of this property. For example, a galvanometer is constructed so that its needle deflects by an amount proportional to the potential difference across the system being studied. A subsequent observation of the final state of the probe provides information (often incomplete) about the value of the observable. In quantum mechanics, this information is gained at the price of disturbing the system through the interaction. There is a strict trade-off between the minimum disturbance and the amount of information which can be gained[2–4]. In weak measurement, the disturbance to the system is reduced at the cost of a similar reduction in the amount of information provided by the measurement. This minimal disturbance makes it reasonable to consider conditioning the read-out of the probe on finding the system in a particular final state after the interaction (post-selection). In this case, the pointer shift, averaged over many measurement repetitions, has been shown[1] to have a magnitude which would correspond to what is termed the ‘weak value’ of the observable: $\langle f|\hat{A}|i\rangle/\langle f|i\rangle$, where $\hat{A}$ is the observable, and $|i\rangle$ and $|f\rangle$ are the pre- and post-selected states of the system, respectively. Evidently, the weak value depends equally on both pre-selected (initial) and post-selected (final) states. This feature of weak measurement makes it a powerful tool for exploring fundamental questions in quantum mechanics[3,5–16], specifically the properties of post-selected subensembles ranging from particles transmitted through tunnel barriers to measurement-based quantum-computing systems[17–19].

Strangely, the weak value is not constrained to be within the eigenvalue spectrum of the observable $\hat{A}$, and is not even in general a real number. In particular, as the overlap between the initial and final states becomes very small, $\langle f|i\rangle \to 0$, the weak value can become (almost) arbitrarily large (as long as the post-selection success is dominated by the overlap of pre- and post-selected states and not the measurement back-action; see the Supplementary Information.) Indeed, the founding paper of the field[1] appeared under the unwieldy but provocative title ‘How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100’. This has led to the idea of using ‘weak-value amplification’ (WVA) to improve the detection or measurement of small effects[20–26]. Interest in this application of weak measurement has grown in the past few years alongside an ongoing debate on the usefulness of WVA[27–31]. Even the quantum mechanical nature of WVA has been challenged[32], and attempts have been made to describe the effect classically based on measurement disturbance. In 2011, we proposed that WVA of the small optical nonlinearity at the single-photon level[33] was possible and could, under some conditions, improve the signal-to-noise ratio. Here, we present an experiment implementing this idea, asking a question directly analogous to that of the original Aharonov, Albert and Vaidman paper: In a two-arm interferometer containing one photon in total, can the result of a measurement of the photon number in one arm turn out to be greater than 1? We find the answer is yes.

Anomalous weak values observed to date[20,21] have typically utilized two different degrees of freedom (such as polarization and propagation direction) of a photon as the ‘system’ and the ‘probe’, obviating the need for any inter-photon interaction; the effects can thus be explained perfectly in terms of linear optics, without resorting to quantum theory. There have been two exceptions. In one, a probabilistic quantum logic gate was implemented, so that although there was no deterministic entanglement of system and probe, an additional post-selection step projected the system onto an entangled state some fraction of the time[14,34]. In the other, deterministic WVA was implemented in a transmon

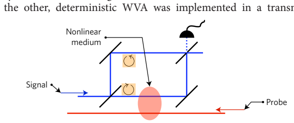


Figure 1 | Conceptual schematic of the interferometer. The signal beam is split into two paths, labelled ⟲ and ⟳ (to make a connection with the actual, polarization-based, interferometer shown in Fig. 2). A probe beam measures the number of photons in one path through a nonlinear interaction. The interferometer is made slightly imbalanced so that there is a small chance for a signal photon to be detected in the nearly dark port.

[1]Centre for Quantum Information and Quantum Control and Institute for Optical Sciences, Department of Physics, University of Toronto, 60 St George Street, Toronto, Ontario M5S 1A7, Canada. [2]Canadian Institute For Advanced Research, 180 Dundas Street W., Toronto, Ontario M5G 1Z8, Canada.
*e-mail: mhallaji@physics.utoronto.ca

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.

- …almost all of weak-measurement experiments carried out to date can be understood in terms of the classical (electromagnetic wave) theory of optics.
- Here, we present a quantum version in which the measurement apparatus deterministically entangles two distinct optical beams.
- We show that a single photon, when properly post-selected, can have an effect equal to that of eight photons.

Matin Hallaji et. al, *Nature Physics* PUB. ONLINE: 27 FEB 2017 | DOI: 10.1038/NPHYS4040

- In a two-arm interferometer containing one photon in total can the result of a measurement of the photon number in one arm turn out to be greater than 1?
- We find the answer is yes.

Kirjallisuutta

- Aharonov, Albert & Vaidman (1988). "How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100". *Physical Review Letters*. **60** (14): 1351–1354.
- Bricmont, J. (2016) *Making Sense of Quantum Mechanics.* Berlin: Springer.
- Bohm, D. ja Hiley, B.J. (1993) *The Undivided Universe. An Ontological Interpretation of Quantum Theory.* London: Routledge.
- Flack R. ja Hiley B. J. (2014) Weak Measurement and its Experimental Realisation, *J.Phys: Conference Series*, **50**. arXiv:1408.5685
- Johnston, H. (2011) "Physics world reveals its top 10 breakthroughs for 2011". *IOP Physics world,* Dec 16, 2011. http://physicsworld.com/cws/article/news/2011/dec/16/physics-world-reveals-its-top-10-breakthroughs-for-2011
- Kocsis, S., Braverman, B., Ravets, S., Stevens, M. J., Mirin, R. P., Shalm, L.K., Steinberg, M. A. (2011), Observing the Average Trajectories of Single Photons in a Two-Slit Interferometer, *Science*, vol. 332, 1170-73.
- Plotnitsky, A. (2010) *Epistemology and Probability. Bohr, Heisenberg, Schrödinger and the Nature of Quantum-Theoretical Thinking.* Heidelberg and New York: Springer.

Suomeksi

- Pylkkänen, P. (2016) Aaltofunktio ja mahdollisuus kvanttimekaniikassa, teoks. I.Niiniluoto, T. Tahko ja T.Toppinen (toim.) *Mahdollisuus.* SFY
  - https://www.filosofinenyhdistys.fi/wp-content/uploads/2016/12/Mahdollisuus-2.pdf
- Pylkkänen, P. (2015) Kvanttiteoria filosofian innoittajana. *Niin & Näin* 3/2015*.*
  - http://netn.fi/artikkeli/kvanttiteoria-filosofian-innoittajana
- Pylkkänen, P. (2015) Fysiikka, taide ja todellisuuden rakenne, teoks. P. Limnell, P. & Kunnas-Holmström, K. (toim.). *Taiteen ja tieteen järjestykset sekä luovat prosessit.* Pori: Porin taidemuseo, s. 89-97


ANGRY FLOWER
angryflower.com
SCHRÖDINGER'S FRIDGE
HEY, IS THERE ANY BEER IN THE FRIDGE?
INDETERMINATE!
I MAY HAVE DRUNK THEM ALREADY - BUT MAYBE I DIDN'T! THUS THE FRIDGE CONTAINS THE POSSIBILITIES OF NO BEERS AND SOME BEERS EXISTING IN SIMULTANEOUS SUPER-POSITION!
THE ONLY WAY TO MAKE THEM REAL IS TO OPEN THE FRIDGE!
OPEN IT!
YEAH!
WHOOSH!
HOLY BLAP!
THE WAVEFORM ISN'T COLLAPSING!
WOM WOM WOM
I'M OBSERVING MY FRICKIN' HEAD OFF, HERE, BUT THEY'RE JUST NOT ACTUALIZING!
I CAN'T DRINK POSSIBLE BEERS!
I NEED ACTUAL BEERS!!!
DAMN YOU, QUANTUM PHYSICS!!!
NEXT WEEK: THE DOUBLE-SLIT EXPERIMENT...

Literature

- Albert, D. and Ney, A. ed. (2013) *The Wave Function: Essays on the Metaphysics of Quantum Mechanics*. Oxford University Press.
- Bohm, David and Hiley, Basil J. (1987) An Ontological Basis for Quantum Theory: I. Non-relativistic Particle Systems. Phys. Rep. 144 (6): 323-348.
- Bohm, D. and Hiley, B. J. (1993) *The Undivided Universe: An Ontological Interpretation of Quantum Theory*. London: Routledge
- Dürr, D., Goldstein, S. and Zanghi, N. (2013) *Quantum Physics Without Quantum Philosophy*. Berlin: Springer.
- Floridi, Luciano, "Semantic Conceptions of Information", *The Stanford Encyclopedia of Philosophy* (Spring 2015 Edition), Edward N. Zalta (ed.), forthcoming URL = http://plato.stanford.edu/archives/spr2015/entries/information-semantic/
- Goldstein, Sheldon, "Bohmian Mechanics", *The Stanford Encyclopedia of Philosophy* (Spring 2013 Edition), Edward N. Zalta (ed.), URL = http://plato.stanford.edu/archives/spr2013/entries/qm-bohm/
- Pylkkänen, P. (2007) *Mind, Matter and the Implicate Order*. Berlin and New York: Springer Frontiers Collection.
- Pylkkänen, P., Hiley, B.J. and Pättiniemi, I., (forthcoming) Bohm's approach and individuality. To appear in Guay, A. and Pradeu, T. eds. *Individuals Across Sciences: A Revisionary Metaphysics?*, Oxford University Press. http://arxiv.org/abs/1405.4772
- Riggs, P. (2009) *Quantum Causality: Conceptual Issues in the Causal Theory of Quantum Mechanics*. Heidelberg and New York: Springer.
- Saunders, S. et al. ed. (2010) *Many Worlds? Everett, Quantum Theory, & Reality*. Oxford University Press.
- Towler, M. (2009) Pilot-wave theory, Bohmian metaphysics, and the foundations of quantum mechanics, a graduate course at the Cavendish Laboratory, University of Cambridge
- http://www.tcm.phy.cam.ac.uk/~mdt26/pilot_waves.html
- Wallace , D. (2012) *The Emergent Multiverse. Quantum Theory according to the Everett Interpretation.* Oxford University Press.