Being provocative after 100 years of quantum mechanics

www.bgu.ac.il/atomchip  Ron Folman
Thanks:

• My host: Dima Budker
• The Miller team, and especially Kathy
• The coaching by Milo Lin and Xie Chen

Apologies:

• To the physicists: For not being technical enough
• To the non-physicists: For being too technical
• And to everyone for having to rush through the material

This talk will have two parts...
Views from the desert
Lots of history....
Examples of the Q tool box: 3 Quantum systems in our lab

Alkali vapor

Color centers in diamond

The Atom Chip

The best of two worlds: Quantum optics with an isolated system and accuracy/robustness of semi-conductor technology
Cold atoms behave as waves:
Atom Chip=Optics for matter waves: fibers, mirrors, etc.
Applications: clocks, acceleration sensors, gravitational sensors, magnetic sensors, quantum memory and communications, quantum computing

Fundamental science: Decoherence, interferometry, many body, atomic physics, low dimensional systems, atom-surface physics, surface physics, symmetries and fundamental constants

A quick view of what the atom chip is: “where material engineering meets quantum optics”
The Atom Chip definition is broadening

The atom chip technology is advancing very rapidly so that eventually, all the different particles such as Rydberg, molecules, atom-like (NV), ions, cold electrons, etc. may be put on the chip, including entanglement to a quantum surface.

The monolithic integration dream

More information on the atom chip in:

- new book on atom chips, RF, Philipp Treutlein and Joerg Schmiedmayer, (Eds: Jakob Reichel and Vladan Vuletic)
- special issue on QIP (Journal of Quantum Information Processing Editors :Howard Brandt & RF )

Ion and permanent magnet chips @ BGU for Mainz and Amsterdam

Highest temperature gradient known to mankind

Atom Chips: From 3 in 2000 to ~30 today,
The promise of AtomChips: miniaturization, integration, monolithic

- **Electronics**
- **Optics**
- **Matter waves**

→ Quantum scales (e.g. tunneling barriers), accuracy, complexity → novel functionality

e.g. Shimon Machluf, Yonathan Japha and RF, Nature Communications 2013.
The big challenge of Quantum Technology?

My answer:
The Tibetan monk
By the way, atom-chips are advantageous not only for matter waves:

Surface physics – use the atoms as a probe
e.g. Mesoscopic transport, Johnson noise, shot noise of fractional charge

Non-interferometric atom-chip measurements

Example: electron transport

I would have loved to stay in my comfort zone and talk about the atom chip....
...but I decided to be a little provocative

Back to our title:
After endless experiments confirming QM, What is there left to be provocative about?

Many names to our (psychological...?) discomfort:

- indeterminism (even philosophical implications e.g. quantum brain with freedom of thought?)
- non-locality (entanglement)
- reality is created by measurement
  Feynman's "if a tree falls in the forest and there is no one there to hear it, does it make a sound?", or Mermin's "is the moon there when nobody looks?"
  No reality independent of measurement (EPR, GHZ, Bell).
- quantization (the reason the atom does not collapse)
- uncertainty principle
- wave-particle duality
- superposition principle
First generation of fathers:

“God does not play dice with the universe.”

Albert Einstein
Nobel: 1921

“Will Quantum Physics Remain Indeterministic?”

Louis de-Broglie
Nobel: 1929

“I don’t like it and I’m sorry I ever had anything to do with it.”

Erwin Schrödinger
Nobel: 1933

“For those who are not shocked when they first come across quantum theory cannot possibly have understood it.”

Niels Bohr
Nobel: 1922
David Bohm
(Berkeley graduate, 1951 EPR experiment
1959 AB effect,
Spent most of his life
writing an alternative theory)

John Bell: 1964 B inequalities.
“QM carries within it the
seeds of its own destruction”

Is it all just the shock of
Boy meets new Girl?
First generation of sons: a lot of theoretical questions and ideas.

1957: Many Worlds, Everett

First generation of sons:

1990s

Objective/independent collapse models

e.g. gravitation/space-time (Penrose and others)

And many more.....
First generation of sons (21st century): Some (annoying?) people are still unhappy!

Steven Weinberg
Nobel prize 1979
Unification of weak
and electro-magnetic
forces

Collapse of the state vector

Steven Weinberg*

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(Received 6 May 2012; published 20 June 2012)

Modifications of quantum mechanics are considered, in which the state vector of any system, large or small, undergoes a stochastic evolution. The general class of theories is described, in which the probability distribution of the state vector collapses to a sum of δ functions, one for each possible final state, with coefficients given by the Born rule.

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1. INTRODUCTION

There is now in my opinion no entirely satisfactory interpretation of quantum mechanics [1]. The Copenhagen
The Oxford Questions on the foundations of quantum physics

G. A. D. Briggs¹, J. N. Butterfield² and A. Zeilinger³

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The twentieth century saw two fundamental revolutions in physics—relativity and quantum. Daily use of these theories can numb the sense of wonder at their immense empirical success. Does their instrumental effectiveness stand on the rock of secure concepts or the sand of unresolved fundamentals? Does measuring a quantum system probe, or even create, reality or merely change belief? Must relativity and quantum theory just coexist or might we find a new theory which unifies the two? To bring...
After all these years:
Is it still just the shock
of Boy meets new Girl?
Second generation of sons: starting to think about experiments...

Towards Quantum Superpositions of a Mirror

William Marshall,¹ ² Christoph Simon,¹ Roger Penrose,³ ⁴ and Dik Bouwmeester¹ ²

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We propose an experiment for creating quantum superposition states involving of the order of $10^{14}$ atoms via the interaction of a single photon with a tiny mirror. This mirror, mounted on a high-quality mechanical oscillator, is part of a high-finesse optical cavity which forms one arm of a Michelson interferometer. By observing the interference of the photon only, one can study the creation and decoherence of superpositions involving the mirror. A detailed analysis of the requirements shows that the experiment is within reach using a combination of state-of-the-art technologies.

My main point: Very few examples of such experiments...!!

Why are we not teaching ideas of independent collapse in our universities?
(at least in advanced courses)
Second generation of sons:

The crux of our method is that the first measurement is performed in a gentle way through weak measurement.


Why are we not teaching weak measurement in our universities? (at least in advanced courses)
Why are we not teaching generalized versions of QM in our universities?
(at least in advanced courses)
Why are we not teaching BM in our universities? (at least in advanced courses)
Crash course in Bohmian mechanics

Many hints that information w/o energy can play a role: e.g. experiments on interaction free measurement Vaidman, Elitzur, Kwiat, Kasevich, Zeilinger...

-> You can detect an object even if it is destroyed by a single particle...!!!
(ask me later how it works)

One of the latest: Interaction free measurements with SC qubits, PRL 180406 (2006)

Orthodox QM:
No element of reality concerning particle position until it hits the screen.
Wave-particle duality forbids it!

Bohmian QM:
particle position always well defined.
Deterministic evolution.

Why are we not teaching interaction free measurements and the role of information in QM in our universities?
(at least in advanced courses)
Many of these theories could be tested: Example of my humble thoughts

**Bohm-Bub 1966:**
If QM is some “statistical equilibrium” state, short times will reveal deviations from QM. Measure 2 consecutive measurements showing, according to QM, no correlation (e.g. SG with 90 degree rotation) But with very short time delay.

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A SEARCH FOR HIDDEN VARIABLES IN THE DOMAIN OF HIGH ENERGY PHYSICS

**Ron Folman**

We consider the consecutive decays (prong-charged track):

- (I) $Z^0 \rightarrow \tau^+\tau^-$ (BR $3.32 \pm 0.04\%$)
- (II) $\tau^- \rightarrow \nu_\tau$  "1-prong" (a) (BR $85.82 \pm 0.25\%$)
  "3-prong" (b) (BR $14.06 \pm 0.25\%$)
  $e^-\nu_e\nu_\tau$ (c) (BR $17.93 \pm 0.26\%$)
  $\pi\nu_\tau$ (d) (BR $11.60 \pm 0.4\%$)

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1 February 1996

Test of the exponential decay law at short decay times using tau leptons

The OPAL Collaboration
There are many more examples of things related to thought and experiment concerning the fundamental rules of quantum mechanics which we don’t teach...

Is it possible that we are having the quantum equivalent of the Nb syndrome?

In business schools it is called the Kodak effect

What could be done to get out of it?
What does philosophy of science have to say?

Thomas Kuhn (Princeton/MIT): Paradigm shifts!
(taught also at Berkeley)

The philosopher Thomas Kuhn once described science as "a series of peaceful interludes punctuated by intellectually violent revolutions." To Kuhn, scientific progress was never a gradual accumulation of knowledge, but an endlessly repeating battle between established theories, such as Newtonian gravity, and younger upstarts, such as Einstein’s general relativity.

Guided by the paradigm, normal science is also extremely productive: "when the paradigm is successful, the profession will have solved problems that its members could scarcely have imagined and would never have undertaken without commitment to the paradigm."

Will we live to see an extension to QM?
Many no-go theorems:

1. The most famous one is that of John Bell 1964: No local hidden variables! Lawrence Berkeley particle physicist Henry Stapp declared: “Bell’s theorem is the most profound discovery of science.” why?

2. Followed by the less known (but just as important) Kochen-Specker theorem 1967.

3. Followed by the GHZ state (1989) e.g. assuming for the spins of three particles a reality independent of measurement - directly leads to contradictions.

4. And more keep coming.....

John Bell: all we have proven is our lack of imagination
Let us make an outrageously unfounded assumption:

1. QM is not the end of the road even in the microscopic/low energy realm and more accurate descriptions of this realm are possible
2. Present experimental techniques are good enough to give a hint at this new description

**What should be the search strategy for the next say 20 years?**

Single particle physics or many body...?
Theories of independent decoherence?
Loopholes in previous tests? (e.g. of Bells’ inequalities)
The role of information? (non-local hidden variables)
What would suit a unification with Gravity?
Quantum effects in Biology? (dephasing is not what we thought)
Perhaps we should even check for correlations between random variables...?

What constitutes more of the same?
e.g. What will breaking records teach us about QM?

Violation of Bell’s inequality in Josephson phase qubits


systems may soon allow us to create superpositions of even larger objects, such as micro-sized mirrors or cantilevers (Marshall et al 2003 Phys. Rev. Lett. 91 130401; Kippenberg and Vahala 2008 Science 321 1172–6; Marquardt and Girvin 2009 Physics 2 40; Favery and Karrai 2009 Nature Photon. 3 201–5), and thus to test quantum mechanical phenomena at larger scales. Here we propose a method to cool down and create quantum superpositions of the motion of sub-wavelength, arbitrarily shaped dielectric objects trapped inside a high-finesse cavity at a very low pressure. Our method is ideally suited for the smallest living organisms, such as viruses, which survive under low-vacuum pressures (Rothschild and Mancinelli 2001 Nature 406 1092–101) and optically behave as dielectric objects (Askin and Dziedzic 1987 Science 235 1517–20). This opens up the possibility of testing the quantum nature of living organisms by...
There is a lot more to say….. but I need to conclude:

RF in his usual 
"why doesn’t it work" state....

1. At the beginning of the 21st century we have many new systems for quantum experiments in our labs. Specifically, the atom chip is a great new tool.

2. But what is our Q goal? Is it only technology and complexity (e.g. many body effects, solid state)

3. What do we do with the idea of extensions to QM? Are we intellectually stuck?

3. Should we start by enhancing our advanced university curriculum?

5. How do we theoretically and experimentally try and facilitate a search for a paradigm shift after 100 years of success?
I would like to end with one of my favorite Quantum quotes:

(Max Born - one of the fathers I have not mentioned yet...)

I believe that ideas such as absolute certitude, absolute exactness, final truth, etc. are figments of the imagination which should not be admissible in any field of science. On the other hand, any assertion of probability is either right or wrong from the standpoint of the theory on which it is based. This loosening of thinking (Locke, 1709) seems to me to be the greatest blessing which modern science has given to us. For the belief in a single truth and in being the possessor thereof is the root cause of all evil in the world.
My latest anti-gravity experiment....

Thanks for your attention
ON THE PHENOMENOLOGY OF TACHYON RADIATION

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Received August 22, 1994
On the possibility of a relativistic correction to the E and B fields around a current-carrying wire


On the possibility of a relativistic correction to the E and B fields around a current-carrying wire

Abstract

It is well known that electric and magnetic fields may change when they are observed from different frames of reference. For example, the motion of a charged probe particle moving parallel to a current-carrying wire would be described by utilizing different

References

Metrics

Related Articles

1. Electromagnetic properties of a toroidal solenoid
2. The Lorentz transformations of the vectors E, B, P, M and the external electric fields from a stationary superconducting wire with a steady current and from a stationary permanent magnet
3. A calculation of the surface charges and the electric field outside steady current carrying conductors

More
Quantum brain? Freedom of will?

Schroedinger in *Nature* 138, 13 (1936)

The Importance of Quantum Decoherence in Brain Processes

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*(Submitted to Phys. Rev. E July 2 1999, accepted October 25)*

Quantum mechanics in the brain

Does the enormous computing power of neurons mean consciousness can be explained within a purely neurobiological framework, or is there scope for quantum computation in the brain?

Christof Koch and Klaus Hepp

The relation between quantum mechanics and higher brain functions, including consciousness, is often discussed, but is far from being understood. Physicists, ignorant of modern neurobiology, are tempted to assume a formal or even dualistic view of the mind–brain problem. Meanwhile, cognitive neuroscientists and neurobiologists consider the quantum world to be irrelevant to their concerns and therefore do not attempt to understand its concepts. What can we confidently state about the current relationship between these two fields of scientific inquiry?

All biological organisms must obey the laws of physics, both classical and quantum. In contrast to classical physics, quantum mechanics is fundamentally indeterministic. The laws of quantum mechanics are therefore not predictive but rather prescriptive; what we observe in nature is the result of the quantum computation. Most quantum physicists view the brain as a classical instrument.

The critical question we are concerned with here is whether quantum computation seeks to exploit the parallelism inherent in entanglement by assuring that the system is observable.
The role of non-equilibrium vibrational structures in electronic coherence and recoherence in pigment–protein complexes

A. W. Chin¹,², J. Prior³, R. Rosenbach¹, F. Caycedo-Soler¹, S. F. Huelga¹ and M. B. Plenio¹*

Recent observations of oscillatory features in the optical response of photosynthetic complexes have revealed evidence for surprisingly long-lasting electronic coherences which can coexist with energy transport. These observations have ignited multidisciplinary interest in the role of quantum effects in biological systems, including the fundamental question of how electronic coherence can survive in biological surroundings. Here we show that the non-trivial spectral structures of protein fluctuations can generate non-equilibrium processes that lead to the spontaneous creation and sustenance of electronic coherence, even at physiological temperatures. Developing new advanced simulation tools to treat these effects, we provide a firm microscopic basis to successfully reproduce the experimentally observed coherence times in the Fenna-Matthews-Olson complex, and illustrate how detailed quantum modelling and simulation can shed further light on a wide range of other non-equilibrium processes which may be important in different photosynthetic systems.
Interaction free measurement – using the duality or the non local nature of the photon particle (A. Elitzur & L. Vaidman) to measure things without interacting with them!

Problem: you want to verify that you have a certain photosensitive material in your bottle. Note that its so small that only light can see it, but since its photosensitive, and light will destroy it!

Prove that we can detect the presence of the photosensitive material without destroying it!! what maximal percentage will we be able to detect without destruction? 
Local realism is the idea that objects have definite properties whether or not they are measured, and that measurements of these properties are not affected by events taking place sufficiently far away. Einstein, Podolsky and Rosen used these reasonable assumptions to conclude that quantum mechanics is incomplete. Starting in 1965, Bell and others constructed mathematical inequalities whereby experimental tests could distinguish between quantum mechanics and local realistic theories. Many experiments have since been done that are consistent with quantum mechanics and inconsistent with local realism. But these conclusions remain the subject of considerable interest and debate, and experiments are still being refined to overcome ‘loopholes’ that might allow a local realistic interpretation. Here we have measured correlations in the classical properties of massive entangled particles ($^9$Be$^+$ ions): these correlations violate a form of Bell’s inequality. Our measured value of the appropriate Bell’s ‘signal’ is $2.25 \pm 0.03$, whereas a value of 2 is the maximum allowed by local realistic theories of nature. In contrast to previous measurements with massive particles, this violation of Bell’s inequality was obtained by use of a complete set of measurements. Moreover, the high detection efficiency of our apparatus eliminates the so-called ‘detection’ loophole.

Early experiments to test Bell’s inequalities were subject to two primary, although seemingly implausible, loopholes. The first might be termed the locality or ‘lightcone’ loophole, in which the correlations of apparently separate events could result from unknown subluminal signals propagating between different regions of the apparatus. Aspect has given a brief history of this issue, starting with the experiments of ref. 8 and highlighting the strict relativistic separation between measurements reported by the Innsbruck group. Similar results have also been reported for the Geneva experiment. The second loophole is usually referred to as the detection loophole. All experiments up to now have had detection efficiencies low enough to allow the possibility that the subensemble of detected events agrees with quantum mechanics even though the entire ensemble satisfies Bell’s inequalities. Therefore it must be assumed that the detected events represent the entire ensemble; a fair-sampling hypothesis. Several proposals for closing this loophole have been made; we believe the experiment that we
Testing the speed of ‘spooky action at a distance’

Daniel Salart\textsuperscript{1}, Augustin Baas\textsuperscript{1}, Cyril Branciard\textsuperscript{1}, Nicolas Gisin\textsuperscript{1} & Hugo Zbinden\textsuperscript{1}

Correlations are generally described by one of two mechanisms: either a first event influences a second one by sending information encoded in bosons or other physical carriers, or the correlated events have some common causes in their shared history. Quantum physics predicts an entirely different kind of cause for some correlations, named entanglement. This reveals itself in correlations that violate Bell inequalities (implying that they cannot be described by common causes) between space-like separated events (implying that they cannot be described by classical communication). Many Bell tests have been performed\textsuperscript{1}, and loopholes related to locality\textsuperscript{2,4} and detection\textsuperscript{5,6} have been closed in several independent experiments. It is still possible that a first event could influence a second, but the speed of this hypothetical influence (Einstein’s ‘spooky action at a distance’) would need to be defined in some universal privileged reference frame and be greater than the speed of light. Here we put stringent experimental bounds on the speed of all such hypothetical influences. We performed a Bell test over more than 24 hours between two villages separated by 18 km and approximately east–west oriented, with the source located precisely in the middle. We continuously observed two-photon interferences well above the Bell inequality threshold. Taking advantage of the Earth’s rotation, the configuration of our experiment allowed us to determine, for any hypothetically privileged frame, a lower bound for the speed of the influence. For example, if such a privileged reference frame exists and is such that the Earth’s speed in this frame is less than $10^{-3}$ times that of the speed of light, then the speed of the influence would have to exceed that of light by at least four orders of magnitude.
Experimental Realization of Wheeler’s Delayed-Choice Gedanken Experiment

Vincent Jacques, E Wu, Frédéric Grosshans, François Treussart, Philippe Grangier, Alain Aspect, Jean-François Roch

Wave-particle duality is strikingly illustrated by Wheeler’s delayed-choice gedanken experiment, where the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: Either the interferometer is closed (that is, the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that gedanken experiment with single photons allowing unambiguous which-way measurements. The choice between open and closed configurations, made by a quantum random number generator, is relativistically separated from the entry of the photon into the interferometer.

wave-particle duality of the light field. To understand their meaning, consider the single-photon interference experiment sketched in Fig. 1. In the closed interferometer configuration, a single-photon pulse is split by a first beamsplitter $BS_{input}$ of a Mach-Zehnder interferometer and travels through it until a second beamsplitter $BS_{output}$ recombines the two interfering arms. When the phase shift $\Phi$ between the two arms is varied, interference appears as a modulation of the detection probabilities at output ports 1 and 2, respectively, as $\cos^2 \Phi$ and $\sin^2 \Phi$. This result is the one expected for a wave, and as Wheeler pointed out, “[this] is evidence … that each ar-

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Examples of the work we do: Atomic vapor (on the interaction of light and matter)

Synopsis: A “Magic Frequency” for Atomic Spectroscopy

Magic Frequencies in Atom-Light Interaction for Precision Probing of the Density Matrix
Menachem Givon, Yair Margalit, Amir Waxman, Tal David, David Groswasser, Yonathan Japha, and Ron Folman
Published August 1, 2013

Physicists use lasers to track the quantum evolution of atomic states, but interpreting the measurements can be tricky when the light absorption depends on the orientation of the atom’s internal angular momentum. Menachem Givon at Ben-Gurion University...
NV Diamond atom-like system

Room temperature Rabi oscillations in a solid!!

Archive 2013
Last example: Atom chips

Coherent Stern-Gerlach momentum splitting on an atom chip

Shimon Machluf¹, Yonathan Japha¹ & Ron Folman¹,²

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Observed interference pattern

Norman F. Ramsey Nobel prize 1989

Isidor Isaac Rabi Nobel prize 1944

Pieter Zeeman Nobel 1902
“For those who are not shocked when they first come across quantum theory cannot possibly have understood it.”

Niels Henrik David Bohr

The Nobel Prize in Physics 1922 was awarded to Niels Bohr “for his services in the investigation of the structure of atoms and of the radiation emanating from them.”
“God does not play dice with the universe.”

Albert Einstein

The Nobel Prize in Physics 1921 was awarded to Albert Einstein “for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect”.

Albert Einstein received his Nobel Prize one year later, in 1922. During the selection process in 1921, the Nobel Committee for Physics decided that none of the year’s nominations met the criteria as outlined in the will of Alfred Nobel. According to the Nobel Foundation’s statutes, the Nobel Prize can in such a case be reserved until the following year, and this statute was then applied. Albert Einstein therefore received his Nobel Prize for 1921 one year later, in 1922.
Will Quantum Physics Remain Indeterministic?

Prince Louis-Victor Pierre Raymond de Broglie

The Nobel Prize in Physics 1929 was awarded to Louis de Broglie "for his discovery of the wave nature of electrons".

Photos: Copyright © The Nobel Foundation

TO CITE THIS PAGE:
"I don't like it and I'm sorry I ever had anything to do with it."
DAVID J. BOHM (*center*) is escorted to the House Un-American Activities Committee hearing room by Donald Appel, a staff investigator, on May 25, 1949.
Creator of a Brave, New Quantum World

David Joseph Bohm was born in 1917 in Wilkes-Barre, Pa. After studying physics at Pennsylvania State College, he pursued graduate studies at the University of California at Berkeley. There, during World War II, he investigated the scattering of nuclear particles under the supervision of J. Robert Oppenheimer. After receiving his degree from Berkeley, Bohm became an assistant professor at Princeton University in 1946.

It was during those years that Bohm wrote his now classic defense of the Copenhagen interpretation, *Quantum Theory*. At the same time, however, Bohm’s doubts about the adequacy of that interpretation were becoming more acute. His own alternative emerged in published form shortly thereafter, in 1952.

By then, Princeton had forced him from its faculty. During the McCarthy era, Bohm had been called before the House Un-American Activities Committee in connection with completely unsubstantiated allegations that he and some former colleagues at the radiation laboratory at Berkeley were communist sympathizers. (During World War II, Oppenheimer began turning in to the Federal Bureau of Investigation names of friends and acquaintances who he thought might be communist agents. Bohm apparently was one of the accused.) A passionate believer in liberty, Bohm refused to testify as a matter of principle. As a result, the committee found him to be in contempt of Congress.

The incident proved disastrous to Bohm’s professional career in the U.S. Princeton refused to renew his contract and told him not to set foot on the campus. Unable to find employment at any other university, Bohm left the country in 1951 to take a position at the University of São Paulo in Brazil. There he was asked by U.S. officials to give up his passport, effectively stripping him of his American citizenship.

After teaching in Brazil, Bohm went to the Technion in Israel and to Bristol University in England. Although he was later cleared of the contempt charges and was eventually allowed to travel back to the U.S., Bohm settled permanently at Birkbeck College, London, in 1961.

In addition to his interpretation of quantum mechanics, he contributed to mainstream physics, working on plasmas, metals and liquid helium. In 1959 he and his student Yakir Aharonov discovered what is now known as the Aharonov-Bohm effect. They showed that quantum mechanics predicts that the motions of charged particles can be influenced by the presence of magnetic fields even if those particles never enter the regions to which those fields are confined. Subsequent experiments have amply confirmed the effect [see “Quantum Interference and the Aharonov-Bohm Effect,” by Joseph Imry and Richard A. Webb; *Scientific American*, April 1989].

Later in life Bohm became interested in broader philosophical questions. He developed a picture of the universe as an interconnectedness of all things, a notion he called “implicate order.” He wrote several books on physics, philosophy and the nature of consciousness. He was in the middle of a collaborative effort on another quantum mechanics book when he died of a heart attack in October 1992. Friends and colleagues remember Bohm not only as brilliant and daring but also as extraordinarily honest, gentle and generous.
The Exact Mathematical Formulation of Bohm's Theory

Bohm's theory in its entirety consists of three elements. The first is a deterministic law (namely, Schrödinger's equation) that describes how the wave functions of physical systems evolve over time. It is:

\[ i \frac{\hbar}{2\pi} \frac{\partial}{\partial t} \psi(x_1, x_3N, t) = H\psi(x_1, x_3N, t) \]

where \( i \) is the imaginary number \( \sqrt{-1} \), \( \hbar \) is Planck's constant, \( \psi \) is the wave function, \( H \) is a mathematical object called the Hamiltonian operator, \( N \) is the number of particles in the system, \( x_1, x_3N \) represent the spatial coordinates of those particles, and \( t \) is the time. Loosely speaking, the Hamiltonian operator describes the energy in the system.

The second element is a deterministic law of the motions of the particles:

\[ \frac{dX_i(t)}{dt} = \frac{j_i(X_1, \ldots, X_3N, t)}{|\psi(X_1, \ldots, X_3N, t)|^2} \]

where \( X_1, \ldots, X_3N \) represent the actual coordinate values of the particles, \( dX_i(t)/dt \) is the rate of change of \( X_i \) at time \( t \), and \( j_i \) represents the components of the standard quantum-mechanical probability current. The subscript \( i \) ranges from 1 to \( 3N \).

The third element is a statistical rule analogous to one used in classical statistical mechanics. It stipulates precisely how one goes about “averaging over” one’s inevitable ignorance of the exact states of physical systems. It runs as follows. Assume one is given the wave function of a certain system but no information about the positions of its particles. To calculate the motions of those particles in the future, what one ought to suppose is that the probability that those particles are currently located at some position \( (X_1, \ldots, X_3N) \) is equal to \( |\psi(X_1, \ldots, X_3N)|^2 \). If information about the positions of the particles becomes available (as during a measurement), the rule indicates that that information ought to be used to “update” the probabilities through a mathematical procedure called straightforward conditionalization.

That is literally all there is to Bohm’s theory. Whatever else we know about it—everything presented in this article, for example—derives strictly from these three elements.
Quantum Dynamics with Bohmian Trajectories

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detailed study. Furthermore, we have discussed that the Bohmian grid is best-adapted to the problem of numerical integration of eqs 5–7, because the grid points naturally avoid regions where R becomes very small.
Optical discrimination between spatial decoherence and thermalization of a massive object

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