The Towler Institute

Quantum foundations workshop

21st-Century directions in de Broglie-Bohm theory and beyond

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Vallico Sotto, Tuscany, Italy

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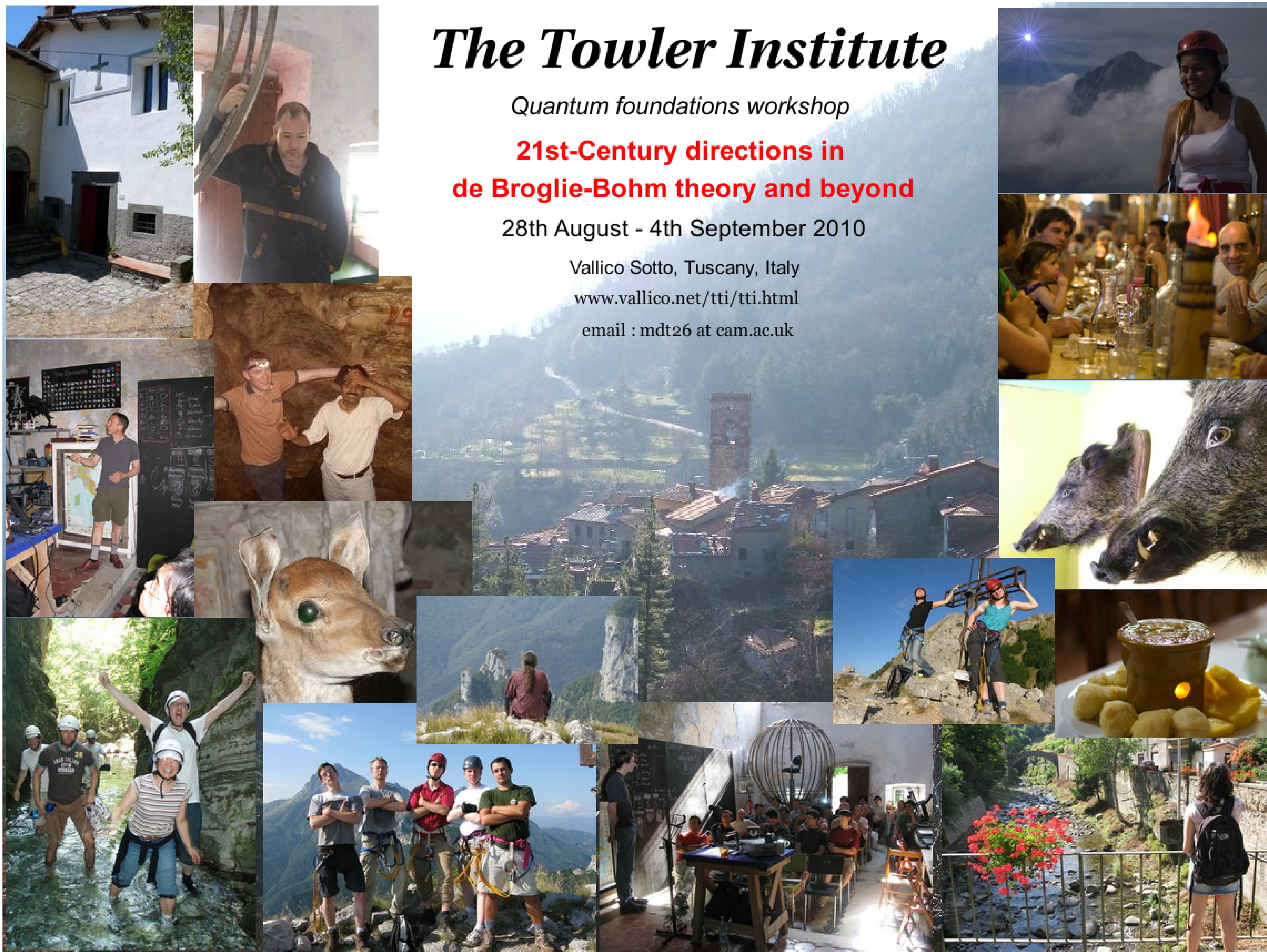
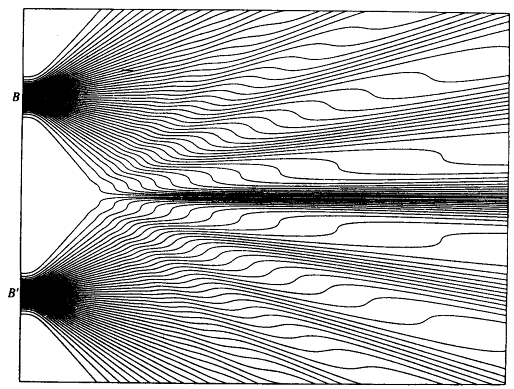
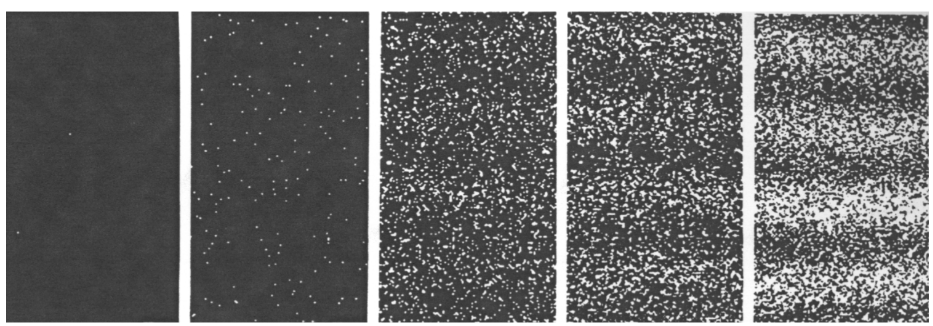


21st-century directions in de Broglie-Bohm theory and beyond

Louis-Victor-Pierre-Raymond, 7th duc de Broglie
(1892-1987)

David Joseph Bohm
(1917-1992)





21st-century directions in de Broglie-Bohm theory and beyond

DeBB theory has been around in some form since the mid-1920s and has been largely ignored by mainstream physicists ever since. If it was useful for anything surely more people would have heard of it by now? So one can ask, is it..

(a) ..a hopeless waste of time..

"*The theory is worthless nonsense.. If someone still believes this Bohmian nonsense, he should at least reduce his arrogant suggestions that he is ahead of the other physicists. In fact, he is still mentally living in the 17th century and is unable to grasp the most important revolution of the 20th century science.*"

[Lubos Motl, online]

..or (b) the key to a proper theory of quantum gravity?

"*..the results we reach show how easy it is to unify a classical (non-quantum) theory of space, time, gravity and cosmology with QM. What's the catch? The key move is to (a) reject Einstein's classical GTR and substitute for it a classical neo-Lorentz GTR; and to (b) select only Bohm's 1952 interpretation of QM..*"

[Quentin Smith, in *Einstein, Relativity, and Absolute Simultaneity*]

Discuss..

What is de Broglie-Bohm theory?

A causal account of quantum theory with an emphasis on a realist ontology.

Discussion may be subdivided into at least the following categories:

- DeBB as an 'interpretation' of non-relativistic quantum mechanics.
  ..a dynamical theory of particle trajectories, rather than a statistical theory of observation. Description of individual quantum events. No paradoxes.
- DeBB as a non-relativistic quantum theory in its own right.
  ..since it has a completely different set of basic axioms and because it makes different predictions. Possibility of new physics..
- DeBB as a relativistic quantum theory.
  DeBB formulations exist which reproduce all the predictions of ordinary quantum field theory, but best way to do do this much less clear. Possibility of new physics.
- Possible deeper meanings of the theory (both in physics and philosophy).
  Bohm's later concepts, such as the 'implicate order'. Basil Hiley's quantum algebra work.
- DeBB as a numerical technique for solving problems in e.g. physical chemistry.
- Stochastic models such as that of Nelson.
  Not strictly speaking deBB, but discussion very relevant.

How did I get involved in this?

- No background in quantum foundations - mainly *computational electronic structure theory*.
- 20 years experience in *solving the Schrödinger equation* (!). My group in Cambridge have been responsible for the practical development of continuum quantum Monte Carlo - the most accurate method known for solving the Schrödinger equation that also scales reasonably with system size.
- My group has created the well-known software package 'CASINO' to do QMC calculations; used (at least in principle) by over 300 people round the world.

QMC in the Apuan Alps VI, July 2010

QMC and the CASINO program V, August 2010

- Tens of thousands of people use the cheaper and less accurate density functional theory (DFT) method to do essentially the same thing. Vast numbers of applications in chemistry, biochemistry, drug design, condensed matter physics, materials science etc..

Question: *what interpretation of QM should a computational electronic structure theorist believe?*

Molecular dynamics: no measurement

Computational electronic structure theory in practice

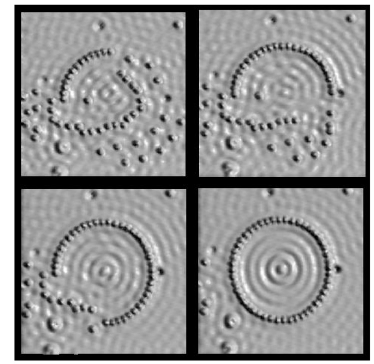
- Calculate total energy - analytic derivatives with respect to nuclear positions give *forces*.
- Create movies using *ab initio* molecular dynamics, where the nuclear positions are evolved using Newton's equations. Nuclei are taken to be *point particles* with classical trajectories.
- Sometimes, for light atoms like H, we think *quantum effects* such as zero-point motion or tunnelling are important. Then need *ab initio* path integral molecular dynamics to take account of the fact that the nuclei no longer follow Newtonian trajectories..
- In DFT the electrons have a sort of fuzzy charge density which is a 'solution to the Schrödinger equation' (in the Kohn-Sham sense) for a sequence of nuclear positions. So - because electrons are very light - either we don't believe they have trajectories at all, or we believe they move much faster than the nuclei and their (presumably non-classical) trajectories are 'smeared out'.
- In QMC the electrons are treated as point particles as well as the nuclei. These do not move along trajectories - principally because we essentially always treat the system as a 'stationary state'; we instead move the electrons along a stochastic random walk to sample the configuration space. The many-electron wave function is actually *represented* by the distribution of electrons in space and time, rather than through some expansion in analytic functions.

QM is a theory of **measurement**, *right? Yet I can calculate dynamical properties of real molecules and crystals - by averaging over atomic trajectories - and get results in very good agreement with experiment - using as input only the atomic numbers of the atoms. DFT/QMC people are thus not Copenhagenists (though most claim to be) but are in fact something like secret Bohmians. To a first approximation,* **none of them** *are aware of this, so I gave a graduate course on the subject!*

1927 was a long time ago: the case for realism

Orthodox Copenhagen QM is both an algorithm for obtaining statistical predictions for the results of experiments and a prescription for *avoiding fundamental questions*. Bohr *et al.* designed it that way because in 1927 quantum entities were unobservable and thus [non sequitur] not real: "*. . . the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them . . . is impossible.* " [Heisenberg, 1958]

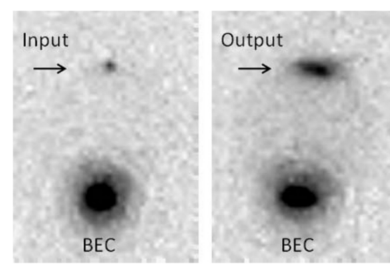
However, modern technological progress seems to show us that quantum entities exist whether we 'observe' or do experiments with them, or not.



Single atoms and even electrons can be isolated and trapped in containment vessels for long periods. Can repeat examination many times and get same data. Individual atoms can be 'pushed around' and arranged into patterns (which can also be imaged). These experiments all yield *consistent* results and information about quantum entities using a variety of techniques and under different conditions.

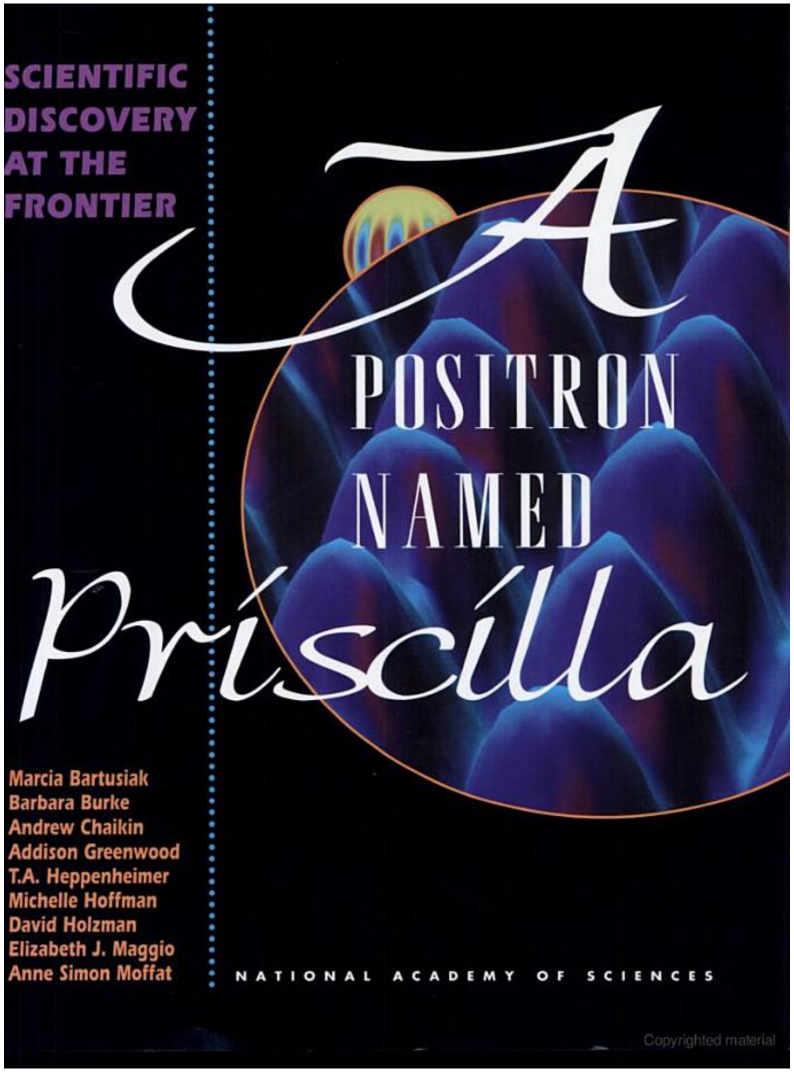
"*Perhaps the most convincing proof of the reality of the quantum world would be to capture some of its creatures and hold them in place for all to see. This has become feasible.*" [Ho-Kim *et al.*, 2004]

Evidence for existence of a '**wave field**' from *matter wave optics*. Ultracold atomic gases have dominant wave behaviour. Can manipulate by 'optical devices'. Significant quantities of matter diffracted, focussed, reflected etc. Also 'matter wave amplification' experiments: production of output of atoms with particular properties from BEC reservoir of atoms in a trap using process similar to stimulated emission of light in a laser. If matter wave can be subject to and utilized in such a process, it seems to follow that matter wave must *exist* in order to act and be acted upon.



Many older physicists get really angry about this and clearly will never overcome the dominant thought patterns of the prevailing paradigm of orthodox quantum theory (such as the denial of an independently existing quantum realm). So be it.

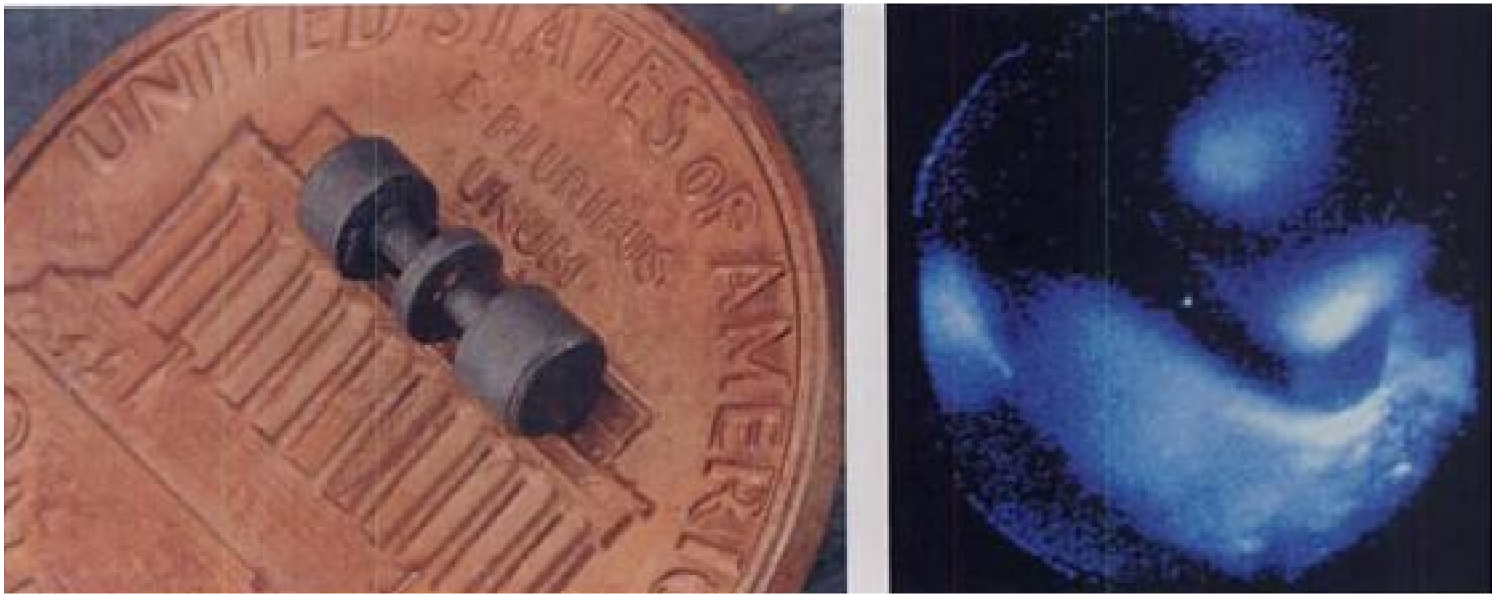
The impossible observed



Hans Dehmelt has carried out exquisitely precise studies of *individual electrons and positrons* - including measuring their magnetic moments to twelve decimal places - by capturing them in electromagnetic traps. Because positrons do not exist naturally on Earth, he showed that the particular positron under study had no opportunity to swap with a different one. He has held that particle in place for as long as three months. He writes "*The well-defined identity of this elementary particle is something fundamentally new, which deserves to be recognized by being given a name, just as pets are given names of persons.*" So he called her **Priscilla**, and won the Nobel prize for it in 1989.

Bohr, Pauli and other Copenhagenists had conclusively proved in 1928 that the magnetic moment of a free electron could never be observed (an argument still being defended up to 1985). '*From these arguments we must conclude that it is meaningless to assign to the free electron a magnetic moment*'. Today this quantity may be the best measured number in all of science.

Astrid the atom



Dehmelt also trapped a single barium atom that he named Astrid, and kept it floating like a pixie in a tiny ion-trap vacuum chamber for ten months. Under suitable conditions, she turned out to be visible to the naked eye..

It used to be claimed that no-one could ever see an atom with their naked eyes. The mistake here is assuming that *smallness* is the important issue; actually *brightness* and *isolation from other atoms* are what matters. A laser-stimulated barium atom produces 10^8 photons per second; your eyes can collect several thousand. The normal retina is sensitive to even a few photons, so you can see the atom, just as you would a distant star or any other bright, isolated object.

An alternative view: 'hidden variables'

Do experiment on ensemble of systems with 'identical state preparation' (i.e. each system prepared with same Ψ). Initially, nothing to distinguish any one system from any other. Nevertheless, results are (say) particle positions randomly distributed as Ψ^2 over the ensemble. Copenhagenists conclude Nature 'inherently probabilistic'. However there is another way: imagine QM '*incomplete*' (as Einstein repeatedly insisted): then there is some 'hidden variable' making each system different from the outset.

For example, say electrons are particles with definite position at all times (hardly revolutionary!). Then ψ^2 represents distribution of particles with imperfectly known positions (the 'hidden variables'). 'Identical state preparation' then means 'choosing starting positions from a fixed probability distribution' with consequent randomness on hitting the screen. If it were possible to derive such a theory, suggests much of apparent peculiarity of QM arose from *mistaking an incomplete description for a complete one*. This is what de Broglie and Bohm believed.

Recall that 100+ years ago, an important step took place (Boltzmann, Maxwell, Gibbs, Einstein) when classical thermodynamics was *derived* from microscopic physics, from the behaviour of the constituents of the macroscopic systems (very controversial at the time! Mach etc.). A hidden variable derivation of QM would be essentially equivalent to that. Is this possible?

Footnote: Even if they don't admit it, one would think that almost all quantum physicists believe in hidden variables. Framed in QM terms, there are only two other alternatives:

(1) Ψ and only Ψ exists (and thus doesn't just represent 'knowledge' or whatever) - Everett.
(2) solipsism (only your mental processes exist).

If you believe **neither** of these things, then you believe in hidden variables. Don't you? However..

Hidden variables impossible since lots of famous people say so..

"*The idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them… is impossible.*" [Heisenberg, 1958]

"*Every attempt, theoretical or observational, to defend such a hypothesis (the notion of hidden variables supplementing the wave function description) has been struck down.*" [J.A. Wheeler (1983)]

"*It is clear that* [the double slit experiment] *can in no way be reconciled with the idea that electrons move in paths. In quantum mechanics there is no such concept as the path of a particle.*" [Landau and Lifshitz, *Quantum Mechanics* textbook, 1977].

"[The quantum postulate] *implies a renunciation of the causal space-time coordinates.*" [Bohr, 1934]

"*No concealed parameters can be introduced with the help of which the indeterministic description could be transformed into a deterministic one. Hence if a future theory should be deterministic, it cannot be a modification of the present one but must be essentially different. How this could be possible without sacrificing a whole treasure of well-established results I leave to the determinists to worry about.*" [Born, 1949]

"*How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it.*" [Feynman, 1965]

There's more..

"*It should be emphasized, however, that the probability function does not in itself represent a course of events in the course of time. It represents a tendency for events and our knowledge of events. The probability function can be connected with reality only if one essential condition is fulfilled: if a new measurement is made to determine a certain property of the system.*" [Heisenberg 1958]

"*In contrast to ordinary mechanics, the new quantum mechanics does not deal with a space-time description of the motion of atomic particles... The difficulties* $\cdots$ *seem to require just that renunciation of mechanical models in space and time which is so characteristic a feature in the new quantum mechanics.*" [Bohr 1934]

"*..We consider it juvenile deviationism .. we don't waste our time ...* [by] *actually read*[ing] *the paper. If we cannot disprove Bohm, then we must agree to ignore him.*" [Oppenheimer, 1953. Abraham Pais also referred to 'juvenile deviationism'.]

"..[Bohm] *is a public nuisance.. a Trotskyite and a traitor*" [Princeton Institute, 1953]

"..[Bohm's work is] *a short-lived decay product of the mechanistic philosophy of the 19th century*" [Rosenfeld]

"*To hope for hidden variables is as ridiculous as hoping that* $2 \times 2 = 5$." [Heisenberg]

To cap it all, much to everyone's delight, von Neumann gave a *mathematical proof* that hidden variables are *impossible*.

Laying the boot in

Bohrian rhetoric of finality and inevitability: '*We see that it cannot be otherwise*', '*This is something there is no way round*', '*The situation is an unavoidable one*', [complementarity] is '*most direct expression of a fact..as the only rational interpretation of quantum mechanics*', '*obvious*', '*evident*', '*clear from the outset*', '*a simple logical demand*', '*we must recognize*', '*it is imperative to realize*'. **(Circular) demonstrations of consistency disguised as compelling arguments of inevitability**. [Those who do not agree are] '*unable to face the facts*' and disagreeing with the orthodox view thus becomes bad for your career..

The resistance: last men standing

"*Bohr's approach to atomic problems is really remarkable. He is completely convinced that any understanding in the usual sense of the word is impossible. Therefore the conversation is almost immediately driven into philosophical questions, and soon you no longer know whether you really take the position he is attacking, or whether you really must attack the position he is defending.*" [Schrödinger, letter to Wien]

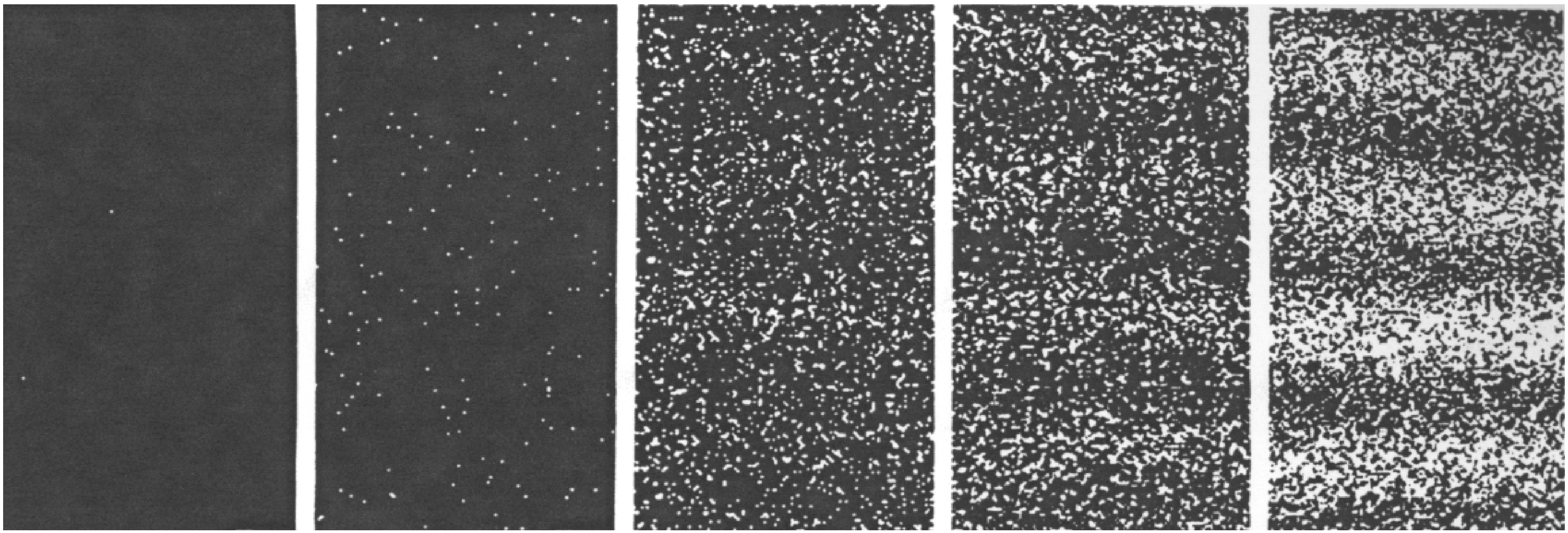
"[Complementarity] *is a thoughtless slogan. ... If I were not thoroughly convinced that the man* [Bohr] *is honest and really believes in the relevance of his - I do not say theory but - sounding word, I would call it intellectually wicked.*" [Schrödinger]

"*I am, in fact, rather firmly convinced that the essentially statistical character of contemporary quantum theory is solely to be ascribed to the fact that this theory operates with an incomplete description of physical systems.*" [Einstein]

The return of pilot waves

Or, why Bohr, Heisenberg, Pauli, Born, Schrödinger, Oppenheimer, Feynman, Wheeler, von Neumann and Einstein were all wrong about quantum mechanics.

Cambridge University Physical Society, 21st October 2009



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So why can't electrons have trajectories?

Because von Neumann proved hidden variables were impossible. However, '*such was the momentum of the Copenhagen interpretation and von Neumann's reputation that when Grete Hermann pointed out in 1935 that the supposed proof contained a blatant and devastating fallacy, she was simply ignored, and the Copenhagen interpretation remained the almost unquestioned accepted interpretation for decades.*' It was left to Bell to rediscover the flaw in 1966.

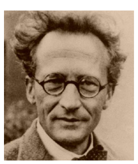
The eigenvalue-eigenstate link: position and momentum represented by operators that do not commute (and therefore cannot have complete set of common eigenstates). If accept quantity has definite value only if system is in eigenstate of corresponding observable, then particle cannot have both a well-defined position and well-defined momentum ever $\Longrightarrow$ no trajectory. Completely ambiguous! The numbers refer only to the *measured* values. Dirac said, '*measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured*', but jumped from where? Any serious analysis of a hidden variable theory shows us - sadly - that '*most of what can be measured is not real and most of what is real cannot be measured*'.

The Uncertainty Principle $\Delta x \Delta p \geq \frac{\hbar}{2}$ implies that particles cannot have simultaneously well-defined x and p $\Longrightarrow$ no trajectory. Not so. Now understood that Heisenberg's principle doesn't relate to measurements on individual systems. Uncertainty in the value of a dynamical variable refers to the statistical spread over the measured values for the various identical members of an ensemble of systems.

Atoms with *Newtonian* trajectories: a surprising observation

Classical atoms are small and we cannot know their position with certainty, so we deal with a statistical ensemble in which only the *probability density* $\rho(\mathbf{x}, t)$ is known.

- Probability must be conserved, i.e. $\int \rho d^3x = 1$ for each t. Therefore must satisfy continuity equation $\partial\rho/\partial t = -\nabla \cdot (\rho\mathbf{v})$ where $\mathbf{v}(\mathbf{x}, t)$ is the velocity of the particle.
- Classical mechanics has various equivalent formulations. Choose the less well-known *Hamilton-Jacobi* version, where velocity $\mathbf{v}(\mathbf{x}, t) = \frac{\nabla S(\mathbf{x},t)}{m}$ and $S(\mathbf{x}, t)$ - related to the 'action' - is a solution of the Hamilton-Jacobi equation, $-\frac{\partial S}{\partial t} = \frac{(\nabla S)^2}{2m} + V$.
- Can write the two green *real* equations more elegantly as a single *complex* equation. To do this, introduce a complex function $\Psi = \sqrt{\rho}e^{\frac{iS}{\hbar}}$ where $\hbar$ is arbitrary constant giving dimensionless exponent. The two equations may then be rewritten as:



$$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V - Q\right)\Psi \qquad \text{with} \qquad Q = -\frac{\hbar^2}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}.$$

This is the time-dependent Schrödinger equation (!) with an extra term Q. Note $|\psi(\mathbf{x}, t)|^2$ has same interpretation as in QM: a probability density of particle positions. *So to recover classical mechanics from quantum mechanics we simply have to subtract out something that behaves exactly like a potential, thus implying that* **QM is just like classical statistical mechanics with a non-classical dynamics** *(due to an 'extra force' $-\nabla Q$ over and above the classical $-\nabla V$).* (?!?)

How to find a valid hidden variables theory?

We wish to change QM from a *statistical theory of observation* into a *dynamical theory of particle trajectories* (that looks like classical statistical mechanics with an extra force?), without altering the predictions that the theory makes. What changes are required?

We simply drop the usual positivistic philosophical baggage and look at the equations: in particular we stop saying that particles don't exist when no-one is looking at them. To do this, change the meaning of one word: **probability**. $|\Psi^2(\mathbf{x}, t)|^2$ is now the probability of the particle (or configuration) *being* at $\mathbf{x}$ at time t, rather than the probability of *being found there in a suitable measurement*. Has implication that particles exist continuously and have *trajectories*, independently of being observed.

In doing this we are making a *metaphysical commitment* (defining an 'ontology'). Most physicists wrongly think that 'metaphysics' is a term of abuse - but it isn't.

Because we are being honest, we must also say what we think the wave function Ψ means. It is often claimed to represent '*information*' or 'knowledge', but it seems clear from the fact that it can be directly manipulated by essentially optical instruments that it represents something real. 'Something' wave-like passes along the different paths in an interference experiment; to refuse to call it 'real' is merely to play with words. We therefore say a *wave field* exists and this is represented mathematically by the usual QM wave function evolving according to Schrödinger's equation.

Wave-particle duality : both particles **and** wave exist!

These are the **only** *changes required to orthodox QM to get an apparently completely valid hidden variables theory - the 'pilot-wave theory' of de Broglie and Bohm. All equations and results follow directly from the established formalism of orthodox QM.*

Particle trajectories regained: de Broglie-Bohm theory

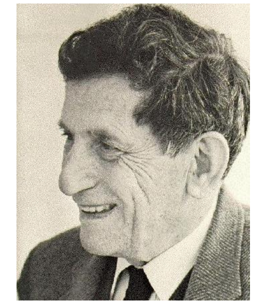
Wave field evolution from Schrödinger equation $i\hbar\frac{\partial\Psi}{\partial t} = \sum_{i=1}^{N} -\frac{\hbar^2}{2m_i}\nabla_i^2\Psi + V\Psi$. Evolving quantum system behaves like 'probability fluid' of $|\Psi|^2 = \Psi\Psi^*$ with an associated time-dependent quantum probability current $\mathbf{j} = \frac{\hbar}{m}\mathrm{Im}(\Psi^*\nabla\Psi)$. Suspect particle trajectories follow streamlines of current, thus velocity $\mathbf{v} =$ current/density $= \frac{\hbar}{m}\mathrm{Im}\nabla\ln\Psi$. Using complex polar form of $\Psi = |\Psi|\exp[iS/\hbar]$, we see the *phase* $S(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_N, t)$ of the wave function is defined by $S = \hbar\mathrm{Im}\ln\Psi$. Thus deduce trajectories $\mathbf{x}_i(t)$ given by the *de Broglie guidance equation* for the velocity:

$$\mathbf{v}_i = \frac{d\mathbf{x}_i}{dt} = \frac{\nabla_i S}{m_i}$$

- Can write in 2nd-order '$F = ma$' form by taking time derivative, i.e. $m_i\ddot{\mathbf{x}}_i = -\nabla_i(V + Q)$, where $Q = -\sum_i \frac{\hbar^2}{2m_i}\frac{\nabla_i^2|\Psi|}{|\Psi|}$ (*quantum potential*). Extra 'quantum' force is $-\nabla_i Q$ (big where large curvature in wave field). *Non-classical* dynamics since particles 'pushed along' by wave along trajectories perpendicular to surfaces of constant phase, as well as by 'classical force' from other particles. Particles evolving in this way naturally become distributed as $|\Psi|^2$ (dust in a hurricane).
- Guidance equation *identical* to trajectory equation in Hamilton-Jacobi theory (a standard form of classical mechanics like Hamiltonian or Lagrangian dynamics). There S is indefinite integral of classical Lagrangian with respect to t (note the 'action' is the *definite* integral with fixed endpoints). Suggests immediately how to obtain the classical limit (impossible in orthodox QM!).
- Can also guess guidance equation from de Broglie relation $\mathbf{p} = \hbar\mathbf{k}$ (connects particle and wave properties). Wave vector $\mathbf{k}$ defined only for plane wave. For general wave, obvious generalization of $\mathbf{k}$ is local wave vector $\nabla S(\mathbf{x})/\hbar$. Hence $\mathbf{v} = \nabla S/m$.

De Broglie-Bohm theory

(a.k.a. Bohmian mechanics, pilot-wave theory, Bohm interpretation, causal interpretation, etc..)



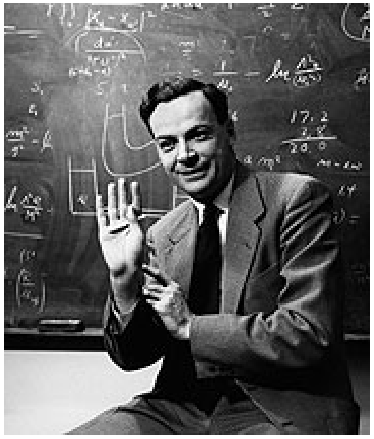
What is de Broglie-Bohm theory (at least in its basic form)?

- One might say it is the *original* interpretation of QM developed by de Broglie from 1923-1927, and rediscovered and improved by David Bohm in 1952.
- It is also a new theory (different axioms, new predictions) and a mathematical reformulation of QM equivalent in status to, say, Feynman's path-integral theory.

Why are people interested in it?

- It shows that QM can simply be interpreted as the statistical mechanics of particles with a non-classical dynamics. QM does not have to be 'weird'.
- It directly resolves all paradoxes of orthodox QM, in particular the measurement problem/wave collapse, all without the usual massively expanded ontology of parallel worlds, shadow universes, multiple intersecting realities etc..
- The *quality of its explanation* is greatly superior to the orthodox theory (which anyway rejects the need for explanations on principle).
- If adopted widely, it would greatly reduce the amount of time spent trying to explain the unexplainable to novices.
- It can be used to do interesting calculations based on 'quantum trajectories' (there is a community of physical chemists who do this).

Two-slit experiment with electrons



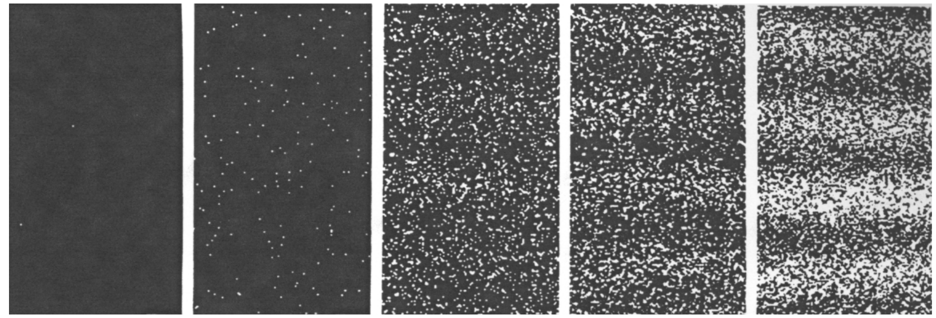
- *"A phenomenon which is impossible, absolutely impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the only mystery."*

- *"Do not keep saying to yourself, if you can possibly avoid it, 'But how can it be like that?' because you will get 'down the drain,' into a blind alley from which nobody has yet escaped. Nobody knows how it can be like that."*

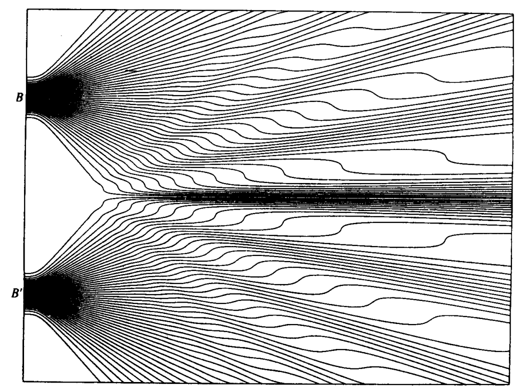
- *"Many ideas have been concocted to try to explain the curve for* P_{12} [that is, the interference pattern] *in terms of individual electrons going around in complicated ways through the holes. None of them has succeeded."*

- This experiment *"has been designed to contain all of the mystery of quantum mechanics, to put you up against the paradoxes and mysteries and peculiarities of nature one hundred per cent."*

- *"How does it really work? What machinery is actually producing this thing? Nobody knows any machinery. Nobody can give you a deeper explanation of this phenomenon than I have given; that is, a description of it."*



Pilot-wave theory: while each particle track passes through just one slit, the wave passes through both; the interference profile that consequently develops in the wave generates similar pattern in the trajectories guided by the wave.



Compare Feynman commentary with that of John Bell:

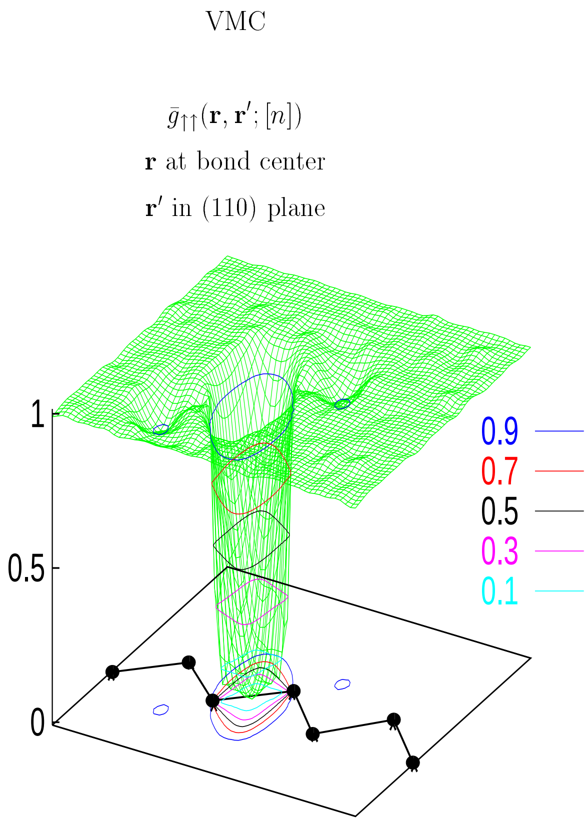
"Is it not clear from the smallness of the scintillation on the screen that we have to do with a particle? And is it not clear, from the diffraction and interference patterns, that the motion of the particle is directed by a wave? De Broglie showed in detail how the motion of a particle, passing through just one of two holes in the screen, could be influenced by waves propagating through both holes. And so influenced that the particle does not go where the waves cancel out, but is attracted to where they cooperate. This idea seems to me so natural and simple, to resolve the wave-particle dilemma in such a clear and ordinary way, that it is a great mystery to me that it was so generally ignored."

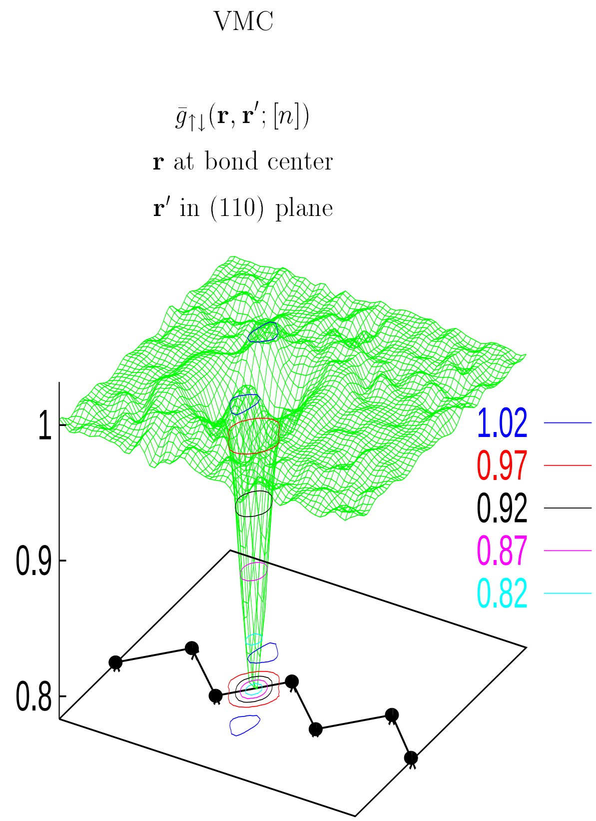
Things which are different in this model

- Nature isn't intrinsically random or probabilistic.
- There is no 'wave function collapse' (i.e. Schrödinger equation is always valid for time-development of wave field, not just when nobody is looking).
- Uncertainty principle has no ontological consequences (it refers to ensembles).
- Particles are not indistinguishable.
- Better approach to classical limit (i.e. where wave component is passive).
- Angular momentum really is due to things rotating about an 'orbit'.
- 'Spin' appears to be best defined as the polarization-dependent part of the wave field's angular momentum - *not* as a property of the particle.
- Well-defined mechanism for quantum tunnelling.
- There seems to be a preferred frame (but that's OK).
- Operators on Hilbert space and all that play no fundamental role, but are exactly right mathematical objects to provide compact representation of the statistics in a deBB universe.
- Hermitian operators are important because their eigenvalues are space-time constants.
- There are no quantum jumps. Existence of discrete energy levels due to restriction of basically continuous theory to motion associated with subclass of eigenfunctions.
- Momentum from quantizing '$m\mathbf{v}$' does not give the momentum of the deBB particle (except in the classical limit). Heisenberg's $\mathbf{p}_x$ refers to one component of the stress tensor of the wave field.

Einstein in 1926: '*Your theory will one day get you into hot water*', because '*when it comes to observation, you behave as if everything can be left as it was, that is, as if you could use the old descriptive language.*'

Fermionic repulsion in a trajectory theory





Why is the parallel spin hole wider and deeper than the antiparallel one? Nobody knows, other than to say ‘because of the Pauli exclusion principle’, or ‘due to statistical repulsion’, or ‘because fermions cannot be in the same state’, or whatever.

Fermionic repulsion in a trajectory theory

A total antisymmetrical wave function for a many-electron system can occur in a number of ways. For 2 electrons there are 3 states of interest where the electrons 'avoid each other'. Collectively called the 'triplet state' with total z-components of spin $\hbar$, $-\hbar$, 0. Their wave functions (which are products of space and spin) all have antisymmetrical spatial components so $\Psi = 0$ if $\mathbf{x}_1 = \mathbf{x}_2$ and are given by:

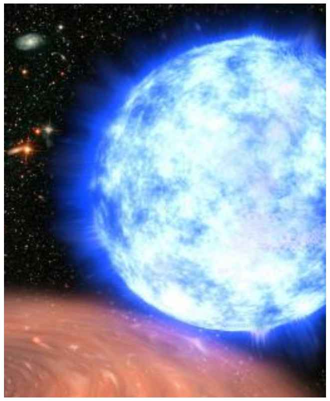
$$
\begin{aligned}
\Psi &= \{\psi_A(\mathbf{x}_1)\psi_B(\mathbf{x}_2) - \psi_A(\mathbf{x}_2)\psi_B(\mathbf{x}_1)\}\,\alpha(1)\alpha(2) \\
\Psi &= \{\psi_A(\mathbf{x}_1)\psi_B(\mathbf{x}_2) - \psi_A(\mathbf{x}_2)\psi_B(\mathbf{x}_1)\}\,\beta(1)\beta(2) \\
\Psi &= \{\psi_A(\mathbf{x}_1)\psi_B(\mathbf{x}_2) - \psi_A(\mathbf{x}_2)\psi_B(\mathbf{x}_1)\}\,\{\alpha(1)\beta(2) + \alpha(2)\beta(1)\}
\end{aligned}
$$

Now let the spatial part be written in complex polar form: $\psi_A(\mathbf{x}_1)\psi_B(\mathbf{x}_2) - \psi_A(\mathbf{x}_2)\psi_B(\mathbf{x}_1) = R\mathrm{e}^{i\frac{S}{\hbar}}$. When this is zero the amplitude R must be zero (since $\mathrm{e}^{i\frac{S}{\hbar}}$ cannot be zero by definition). Thus, as a nodal region of the wave field is approached, the value of R will tend to zero. The (repulsive) quantum force on each particle is $\mathbf{F}_i = (\mathrm{d}\mathbf{p}_i/\mathrm{d}t) = -\nabla_i Q$ where $Q = -\hbar^2/2mR(\nabla_1^2 R + \nabla_2^2 R) +$ spin-dependent terms. Finding the negative gradient of Q (ignoring the spin-dependent terms since the spatial terms will dominate as R tends to zero) gives:

$$
\mathbf{F}_i = \frac{\hbar^2}{2mR^2} \sum_{j=1}^{2} \left[R\nabla_i(\nabla_j^2 R) - (\nabla_i^2 R)(\nabla_j R) \right]
$$

It can be seen that as $R \longrightarrow 0$ then $\mathbf{F}_i \longrightarrow \infty$. The 'Pauli repulsion' force $\mathbf{F_i}$ exerted by the wave field on the two fermions prevents them coming into close proximity of each other when their 'spins are the same' (i.e. in cases where the spatial part of Ψ is antisymmetric). More generally, the dynamics as shown by this trajectory theory prevent fermions occupying the same quantum state.

An example: electron degeneracy pressure



When a typical star runs out of fuel it collapses in on itself and eventually becomes a *white dwarf*. The material no longer undergoes fusion reactions, so the star has no source of energy, nor is it supported against gravitational collapse by the heat generated by fusion. It is supported only by *electron degeneracy pressure*. This is a force so large that it can stop a star from collapsing into a black hole, yet no-one seems to know what it is.. Which of the four fundamental forces is responsible for it? None of them seems to have the right characteristics..

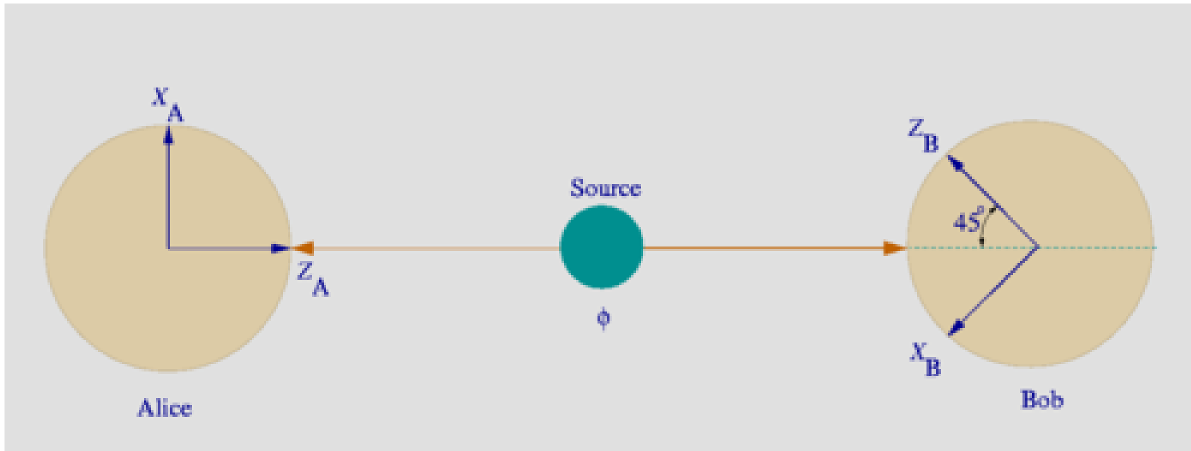
Degenerate matter: At very high densities *all* electrons become free as opposed to just conduction electrons like in a metal. When this happens, degeneracy pressure (which is essentially independent of temperature) becomes bigger than the usual thermal pressure.

Usual explanation: *Electron degeneracy pressure is a quantum-mechanical effect arising from the Pauli exclusion principle. Since electrons are fermions, no two electrons can be in the same state, so not all electrons can be in the minimum-energy level. Rather, electrons must occupy a band of energy levels. Compression of the electron gas increases the number of electrons in a given volume and raises the maximum energy level in the occupied band. Therefore, the energy of the electrons will increase upon compression, so pressure must be exerted on the electron gas to compress it. This is the origin of electron degeneracy pressure.* [Wikipedia]

All explanations apparently boil down to "because of the Pauli Exclusion Principle" or "because fermions can't be in the same state". The origin of the Pauli repulsion preventing particles being in the same state (i.e. having identical probability distributions) is *not understood*. When analyzed from the deBB perspective, the pressure is due to the 'quantum force' of the wave field acting on the electrons.

Non-locality

Definition: *a direct influence of one object on another, distant object, contrary to our expectation that an object is influenced directly only by its immediate surroundings*.



What Einstein-Podolsky-Rosen (EPR) experiment implies:

- Measurement on one side instantly predicts result on other (parallel analyzers).
- If do not believe one side can have causal influence on other, require results on both sides to be determined in advance. But this has implications for non-parallel settings which conflict with quantum mechanics (*Bell*).

Bell's analysis showed that *any account* of quantum phenomena needs to be non-local, not just any 'hidden variables' account i.e. nonlocality is implied by the predictions of standard quantum theory itself. Thus, if nature is governed by these predictions (which it is, according to real experiments) then nature is non-local.

Tim Maudlin's book *Quantum non-locality and relativity* (available at the back of the church) is very good for this and many other things

Nonlocality and configuration space and relativity

QM and experiment show violation of Bell's inequality (VBE) for events at space-like separations (implying non-locality). **How does this square with relativity?** No problem - remember, light speed is not a speed *limit*; it is the speed which remains *invariant* under certain (Lorentz) transformations of the reference frame. What constraints do VBE+QM imply? According to Maudlin, results unequivocal:

- VBE does *not* require superluminal matter or energy transport.
- VBE does *not* entail the possibility of superluminal signalling.
- VBE does require superluminal *causal connections*.
- VBE can be accomplished only if there is superluminal *information transmission*.

If you don't want to believe non-locality, what options do you have? (tongue in cheek..)

(1) Deny reality (*then there is nothing be non-local*); (2) Believe many worlds interpretation (*then* **everything** *happens, so you can't say there are non-local correlations*); (3) Allow things to move backwards in time (*Maudlin claims Cramer's transactional interpretation not a solution.*). Of all the apparent bizarrerie, believing that influences - in the above sense - travel very fast seems more appealing (at least to me), but the 'means' by which this is accomplished is not understood.

Both pilot-wave theory and experiment seem to imply existence of preferred reference frame (the one in which non-local correlations are absolutely simultaneous). Suggests *neo-Lorentzian interpretation* of relativity more appropriate than standard Einstein-Minkowski one. (See my course, Lecture 5). Note also that deBB theory can be made relativistic; predictions agree with experiment but disagree with dogma of relativistic metaphysics (preferred frame, Lorentz invariant on average). Highly interesting!

NB: Valentini showed superluminal signalling becomes possible under conditions of *quantum non-equilibrium*, and that deBB theory makes *testable predictions* (potentially measurable in CMB?)

An interesting observation about Feynman's path integral QM

Want to calculate *propagator* K (carries wave function Ψ from past into future).

- In *Feynman's path integral theory* the propagator is

$$K^F(\mathbf{x}_1, t_1; \mathbf{x}_0, t_0) = N \sum_{\text{all paths}} \exp\left[\frac{i}{\hbar}\int_{t_0}^{t_1} L_c(t)\,\mathrm{d}t\right].$$

Here propagator linking two spacetime points calculated by linearly superposing amplitudes $e^{iS/\hbar}$ (obtained by integrating **classical** Lagrangian $L_c(t) = \frac{1}{2}mv^2 - V$) associated with infinite number of **all possible paths** connecting the points. Get future wave function at $\mathbf{x}_1$ from $\Psi(\mathbf{x}_1, t_1) = \int K^F(\mathbf{x}_1, t_1; \mathbf{x}_0, t_0)\Psi(\mathbf{x}_0, t_0)\,\mathrm{d}x_0$.

- In the equivalent pilot-wave theory expression the propagator is

$$K^{PW}(\mathbf{x}_1, t_1; \mathbf{x}_0, t_0) = \frac{1}{J(t)^{\frac{1}{2}}} \exp\left[\frac{i}{\hbar}\int_{t_0}^{t_1} L_q(t)\,\mathrm{d}t\right].$$

i.e. get same result as Feynman by integrating **quantum** Lagrangian $L_q(t) = \frac{1}{2}mv^2 - (V + Q)$ along precisely **one** path - the one the particle actually follows. Integral over K with different starting points not required since trajectories don't cross, i.e. $\Psi(\mathbf{x}_1, t_1) = K^{PW}(\mathbf{x}_1, t_1; \mathbf{x}_0, t_0)\Psi(\mathbf{x}_0, t_0)$

Not many people know this..

Aims of the conference

From the programme document:

This is the official programme document for the 2010 international workshop *21st-century directions in de Broglie-Bohm theory and beyond* - the first workshop of a series in the field of quantum foundations to be held at the Apuan Alps Centre for Physics. The general purpose of workshops at this venue is to gather together a limited number of expert physicists to discuss subjects where the need for new insights is felt with particular intensity, as is most certainly the case with the de Broglie-Bohm formulation of quantum mechanics. Largely neglected for most of its eighty-five year history, it has been the subject of increasing interest in the last few decades. If the theory is to remain relevant and vigorous, it is essential to decide where it is to go next within the wider context of the foundations of quantum mechanics, and to understand how it may contribute to the sum of human knowledge. With this workshop we hope to begin to answer these questions.

Interesting questions

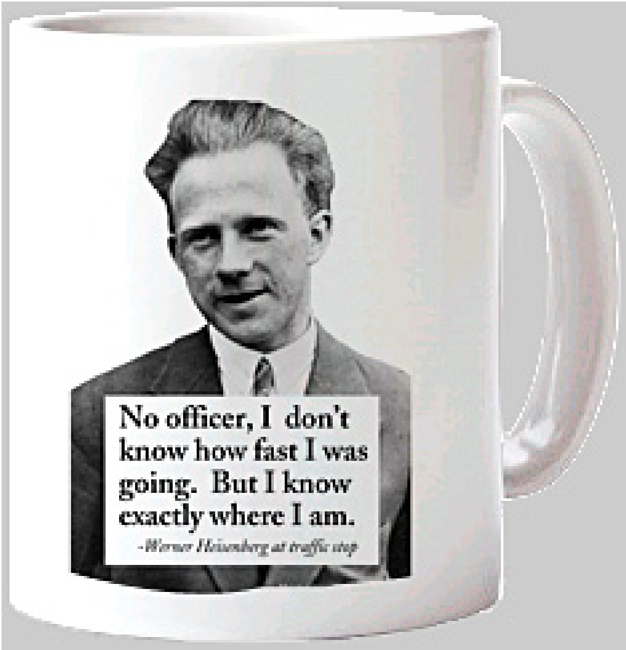
- How can deBB be experimentally tested? Are there any theoretical flaws?
- Can deBB give ideas for possible theoretical work in e.g. quantum gravity etc.?
- What, if anything, does the existence of the deBB model suggest about the universe?
- What is the best way to present deBB in a relativistic context? (MDT advanced course)
- Is there a deeper way to understand deBB? (Basil?)
- What are the practical uses of deBB (say, in computational simulation techniques)?

Not interesting questions

- Which is the best interpretation of quantum mechanics?

Antony Valentini will expand on this in a minute...

Final thought from Heisenberg



"*In classical physics the aim of research was to investigate objective processes occurring in space and time. In the quantum theory, however, the situation is completely different. The very fact that the formalism of quantum mechanics cannot be interpreted as visual description of a phenomenon occurring in space and time shows that quantum mechanics is in no way concerned with the objective determination of space-time phenomena*" [Heisenberg, 1965].

Hmmm...