Solvay 1927

Quantum Theory at the Crossroads

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The 1927 Solvay Conference

Three theories extensively discussed.

No consensus reached.

Quantum Theory at the Crossroads

Reconsidering the 1927 Solvay Conference

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Basic Facts

* Fifth Solvay conference, Brussels, October 1927 (proceedings published in French in 1928)

* Attended by: Bohr, Born, de Broglie, Dirac, Ehrenfest, Einstein, Heisenberg, Kramers, Lorentz, Schrödinger, and others

* Five reports, each followed by extensive discussion:

1) Bragg: X-ray diffraction
2) Compton: experimental evidence for photons
3) De Broglie: "The New Dynamics of Quanta"
4) Born & Heisenberg: "Quantum Mechanics"
5) Schrödinger: "Wave Mechanics"

* "General Discussion of the New Ideas Presented"

- Causality, Determinism, Probability
- Photons
- Photons and Electrons

"The conference was surely the most interesting scientific conference I have taken part in so far."
(Werner Heisenberg, letter, 19 December 1927)

What actually happened, especially during the extensive discussions?

(not what you might think)

First, some widespread myths
and misunderstandings ...

Widespread “ Physicists’ ” Account

* Focussed on the “Bohr-Einstein debate”
  (esp. uncertainty relations)
  Victory for Bohr, defeat for Einstein

* Questions of interpretation were settled
  (esp. By Bohr and Heisenberg)

Examples:

Letter by Ehrenfest (often cited):

“Bohr towering completely over everybody ... defeating everybody ... Einstein all the time with new examples ... Bohr crushing one example after the other”

Heisenberg, 1929, writing in *Naturwissenschaften*:

the 1927 discussions “contributed extraordinarily to the clarification of the physical foundations of the quantum theory” and led to “the outward completion of the quantum theory, which now can be applied without worries as a theory closed in itself”

But in fact:

* The proceedings contain *no record* of the Bohr-Einstein debate. In the recorded discussions, both are relatively silent.

  •Informal discussions over breakfast and dinner, semi-private, overheard esp. by Heisenberg and Ehrenfest

  •What about the *42 pages* of the "General Discussion", and the other *published* discussions?

* Three versions of quantum theory were presented and extensively discussed. No clear victor. No consensus was reached.

* Born and Heisenberg's "quantum mechanics" was not today's QM (no collapse, no fundamental time evolution).

* Serious disagreements even among the "quantum mechanics" camp (e.g. between Dirac and Heisenberg).

Furthermore:

* There were *many* unresolved questions.
  Reminiscent of debates today: the "measurement problem", non-locality, existence of trajectories, etc.

* Langevin:
  at this conference "the confusion of ideas reached its peak".

* In the "General Discussion", Ehrenfest wrote on the blackboard:
"And they said one to another: Go to, let us build us a tower, whose top may reach unto heaven; and let us make us a name. And the Lord said: Go to, let us go down, and there confound their language, that they may not understand one another's speech".

(Genesis 11: 3-7)

* The confusion persists today. *No consensus even now!*

Myths about de Broglie's contribution

* Presented theory for one particle only.
  Could not reply to a criticism by Pauli.
  For example, Bohm and Hiley (1993):

"The idea of a "pilot wave" that guides the movement of the electron was first suggested by de Broglie in 1927, but only in connection with the one-body system. ... it was strongly criticised by Pauli. ... In consequence de Broglie abandoned his suggestion. The idea of a pilot wave was proposed again in 1952 by Bohm in which an interpretation for the many-body system was given. This latter made it possible to answer Pauli's criticism ... ".

* In fact:
  In 1927 de Broglie presented the *many-body theory*.
  De Broglie's reply to Pauli was essentially correct.

Historians' accounts are also flawed

* Jammer's classic book "*The Philosophy of Quantum Mechanics*" (1974) states that de Broglie's theory "was hardly discussed at all" and that "the only serious reaction came from Pauli".

In fact: *24* of the published pages of discussion are wholly or partly about de Broglie's theory!
With serious reactions and comments from: Pauli, Born, Brillouin, Einstein, Kramers, Lorentz, Schrödinger, and others.

•Mehra and Rechenberg, "*The Historical Development of Quantum Theory*" (6 volumes): focus on the "Bohr-Einstein debate" (later recollections by Heisenberg and Bohr).

Why not focus more on the actual content of the published conference proceedings?

Three rival approaches to quantum theory

1. De Broglie's pilot-wave theory
   (particle trajectories guided by Ψ)

2. Born and Heisenberg's "quantum mechanics"
   (static, abstract formalism for closed systems, based on matrices)

3. Schrödinger's "wave mechanics"
   (particles as localised wave packets)

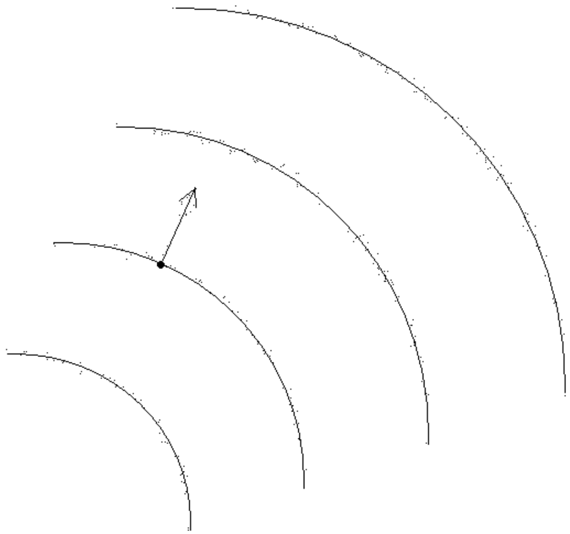
Here, focus on 1

De Broglie's pilot-wave theory

* New, non-Newtonian dynamics.
  Particle *velocities* are determined by the law of motion

$$m\frac{d\mathbf{x}}{dt} = \nabla S$$ (one body)

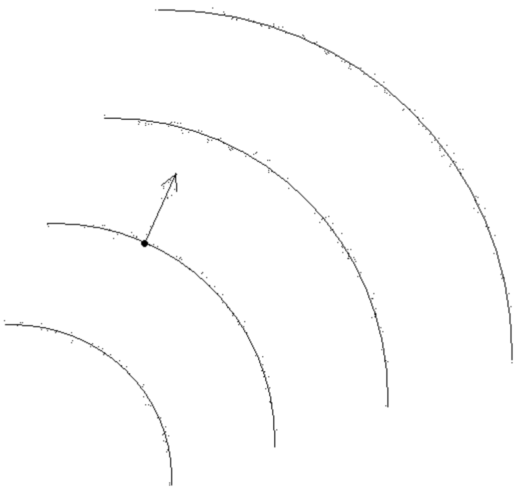
  where *S* is the phase of a wave Ψ



* Unifies principles of Maupertuis and Fermat:

$$\delta \int_a^b m\mathbf{v} \cdot d\mathbf{x} = 0 \quad \longleftrightarrow \quad \delta \int_a^b dS = 0$$

* For an N-body system (de Broglie 1927):



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

$$i\frac{\partial \Psi}{\partial t} = \sum_{i=1}^{N} -\frac{1}{2m_i}\nabla_i^2 \Psi + V\Psi$$

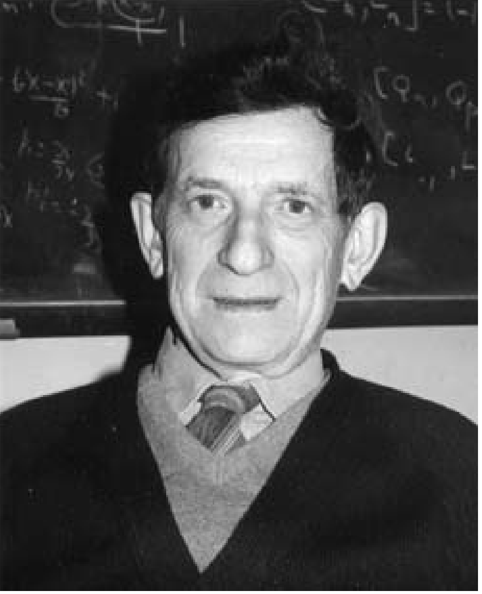
Deterministic dynamics in configuration space

(de Broglie called it “pilot-wave theory”)

* Distribution $P = |\Psi|^2$ is preserved in time (“equilibrium”)

[Get QM (Bohm 1952). But can drop $P = |\Psi|^2$ (AV 1991)]

* *Exactly the theory advertised by Bell (1987)*



Contrast with Bohm (1952)
(Newtonian dynamics)

$$m_i \frac{d^2 \mathbf{x}_i}{dt^2} = -\nabla_i (V + Q)$$

$$Q \equiv -\sum_{i=1}^{N} \frac{1}{2m_i} \frac{\nabla_i^2 |\Psi|}{|\Psi|}$$

Get QM if assume initial $P = |\Psi|^2$ *and* $\mathbf{p}_i = \nabla_i S$

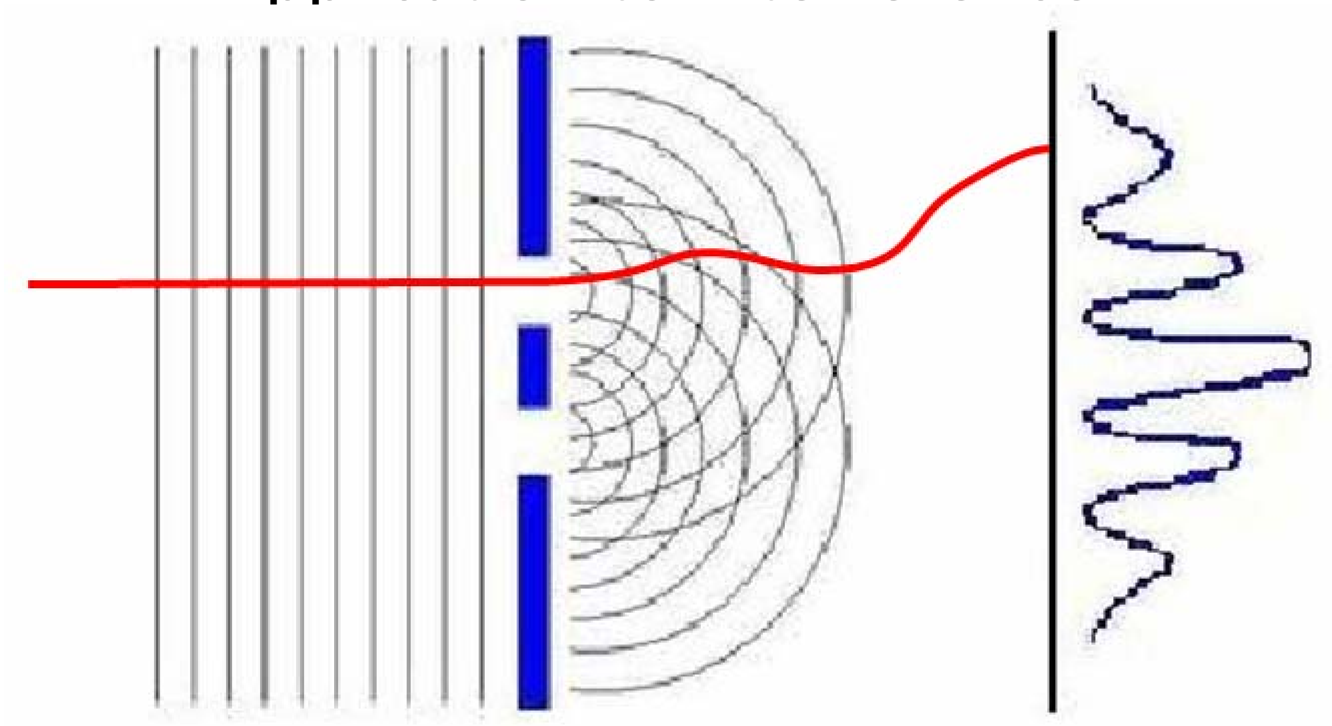
For Bohm, $\mathbf{p}_i = \nabla_i S$ is an initial condition; can drop it.

For de Broglie, $\mathbf{p}_i = \nabla_i S$ is the law of motion.

De Broglie's dynamics and Bohm's dynamics are different.

"Bohmian mechanics" is a misnomer for de Broglie's dynamics.

Application to Interference

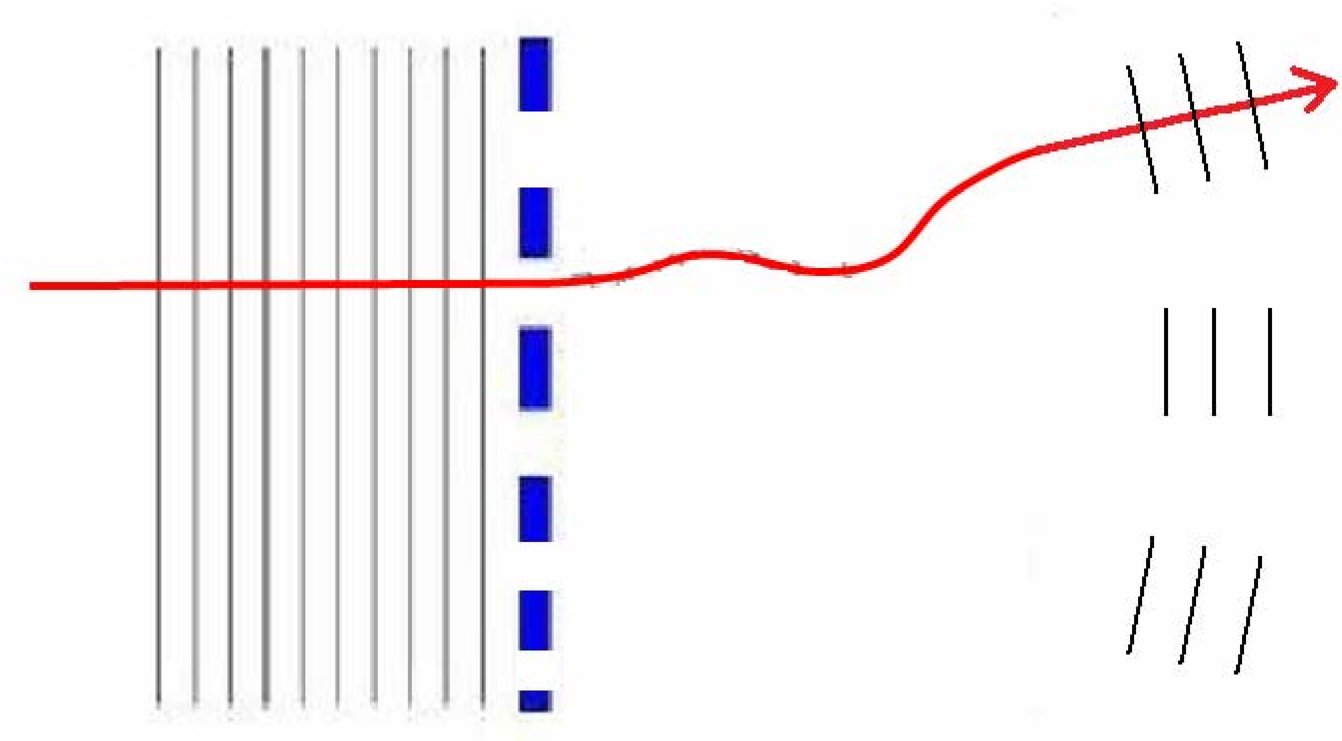


Agrees with experiment, if assume initial $P = |\Psi|^2$

(But *not* for initial $P \neq |\Psi|^2$. QM is a special case (AV 1991))

"... the bright and dark fringes predicted by the new theory will coincide with those predicted by the old. ... one can do an experiment of short duration with intense irradiation, or an experiment of long duration with feeble irradiation ... " (de Broglie 1927)

Electron diffraction by a crystal



"... the scattered amplitude will show maxima ... . Because of the role of pilot wave played by the wave Ψ , one must then observe a selective scattering of the electrons in these directions" (de Broglie 1927)

Discussion of de Broglie’s theory (Brussels 1927)

Extensive, wide-ranging. Some examples:

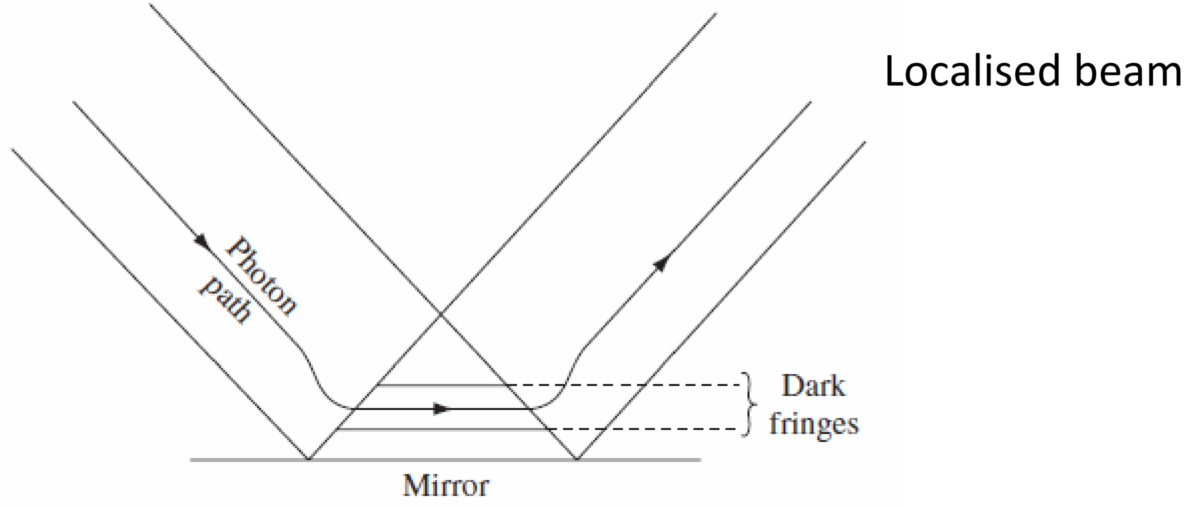
* Alternative velocity fields? (Schrödinger)

* Recoil of a single photon on a mirror? (Kramers)

* Electron orbits in hydrogen (Lorentz, Ehrenfest, Schrödinger)

* Same speed, beginning and end of an elastic collision? (Born)

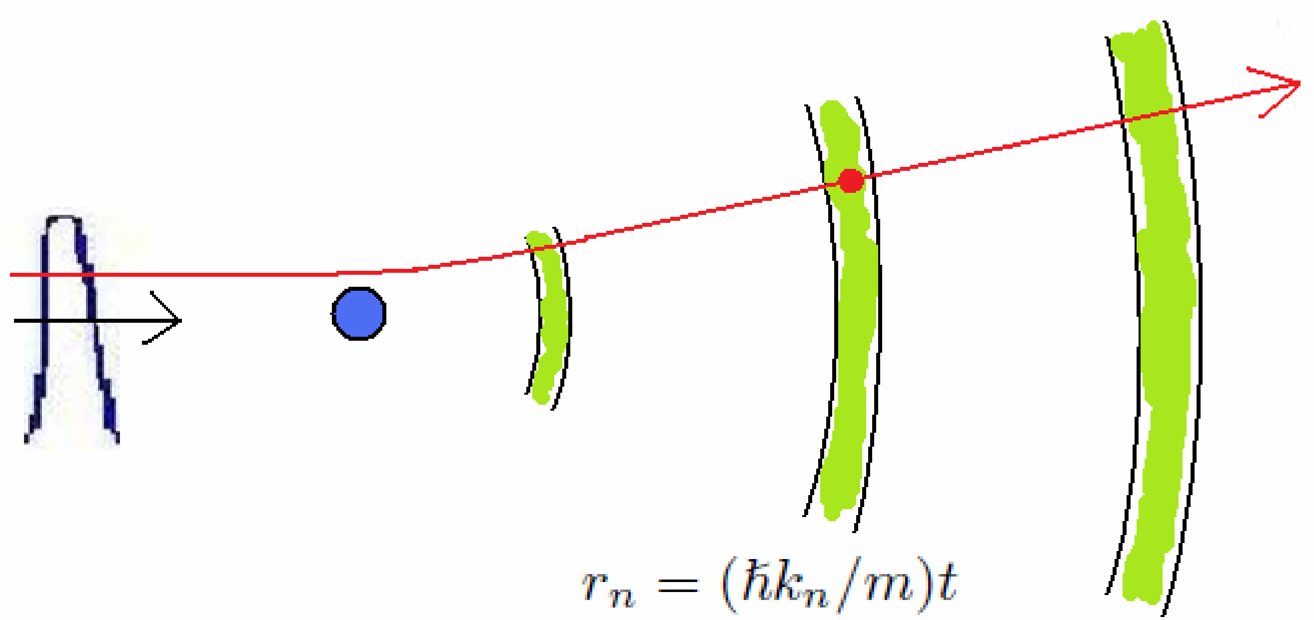
Illustration by Brillouin:



* Uniform velocity at the end of an *in*elastic collision? (Pauli)

Confusing example (rotator, misleading optical analogy)

De Broglie gave the essential point: separation of packets



$$\Psi(\mathbf{x}_s, \mathbf{x}_a, t) = \phi_0(\mathbf{x}_a) e^{-iE_0 t/\hbar} \psi_{\text{inc}}(\mathbf{x}_s, t) + \sum_n \phi_n(\mathbf{x}_a) e^{-iE_n t/\hbar} \psi_n(\mathbf{x}_s, t)$$

Summary for de Broglie at Solvay 1927

De Broglie presented the pilot-wave dynamics of a many-body system.

He discussed some elementary applications (interference, scattering).

The theory was discussed extensively.

De Broglie defended the theory fairly well.

Foundations of quantum mechanics: an old and new problem

--- determinism (de Broglie) versus indeterminism (many others)

--- objective process (Dirac) versus subjective (Heisenberg)

--- state vector collapse (Dirac) versus phase randomisation (Born & Heisenberg)

--- time-evolving wave function is fundamental (de Broglie, Schroedinger) or phenomenological (Born and Heisenberg)

--- locality versus completeness (Einstein)

The foundational debate is still very much alive, as it was in October 1927