What in the world is quantum mechanics about exactly?

QM is about:

- wavefunctions $\Psi$
- operators $\hat{H}$
- Schrödinger eq.:
  \[ i\hbar \frac{\partial \Psi}{\partial t} = \hat{H} \Psi \]
- and how to solve it.
- but what in the world?

The wavefunction is not like the world:

$\Psi = \Psi_1 + \Psi_2$

would be unrecognizable.

So:

[Statistical Interpretation]

Statistics of what?

'Measurement' results
But what, when, and where, is a measurement, measured.

Measurable... measured... the dynamical variable that is being
the system to jump into an eigenstate of

\[ |\psi(1)\rangle \]

\[ |\psi(2)\rangle \]

... a measurement always causes

with the average of all the results obtained
the average of a large number of times
for the system in the state corresponding
if the measurement of the observable

eigenvalues...

Real dynamical variable is one of its

\[ B^3e \]

Any result of a measurement of a

Director: Principles of O.M. (4th ed.)
measurements, make jumps,

... measured ... the dynamical variable that is being
the system to jump into an eigenstate of

$|\beta\rangle$ ... a measurement always causes

with $x_{0} < 1.5 \times 1^{-}$ the average of all the results obtained

the average of the measurement of the observable

eigenvalues ... if the system is in the state corresponding to

Real dynamical variable is one of its

$|\beta\rangle$ ... any result of a measurement of a

Direct Principles of Q.M. (4th ed.)
but:

who is qualified to make a 'measurement'? were there 'measurements' before life? are there 'good' and 'bad' measurements? are the 'jumps' instantaneous? if these are idealized measurements what about real ones?

no serious person takes these axioms seriously.

example of taking them seriously and not liking the results:

the Zeno paradox.
`measure` some `observable` repeatedly over period $T$ at intervals $T/N$

If $\alpha$ is first result the probability that all subsequent results are also $\alpha$ is

$$|\langle \alpha | e^{-iHT/N} | \alpha \rangle |^{2N}$$

$$\sim |\langle \alpha | 1 - iHT/N - \frac{1}{2} H^2 T^2/N^2 \ldots | \omega \rangle |^{2N}$$

$$\sim 1 - |\langle \alpha | H^2 | \omega \rangle T^2/N$$

$$\sim 1 \quad \text{for} \quad N \to \infty$$

i.e. continuous observation.

e.g. a watched kettle never boils

a watched clock never moves

a watched unstable particle does not decay.

G.C. Ghirardi

C. Omera

T. Weber

A. Rimini

Nuovo Cimento

$52A$ (1979) 421

P. Pearle

preprint, June 1980
impossible! but with what axioms?
old axioms for 'macroscopic' observables
like instrument pointer readings —
'observed' once.

all practical purpose
$\psi_1 + \psi_2$, $\psi_1\psi_2$ or $\psi_2$
'measurement' problem

M. Cini
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G. Mattioli
F. Nicolo

M. Cini
M. DeMaria
G. Mattioli
F. Nicolo

Foundations of Physics
9 (1979) 479

Nuovo Cimento
47B (1978) 201

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1FUM 228 /FT
March 1979

important, but approximate. and for
vaguely defined 'macroscopic' observables
In conclusion the possibility seems to exist of going out of the paradoxes connected with the occurrence of interference terms among macroscopically distinguishable states, assuming that physical observables incompatible with the macroscopic quantities or at least with some privileged set of such quantities do not exist. Since however the idea that every self-adjoint operator... corresponds to an observable... is quite naturally built in the mathematical structure of quantum mechanics, a consistent and logically satisfactory introduction of such a principle should require some kind of reformulation of the theory and perhaps some deep change in it.

approximate
'macroscopic'
continuous observation?
Let's try to leave mind out of it.

Mind as agent external fields where? Points? But fields of points are not observable. Lorentz invariance? Space-time averages? Dispersion?

What does it observe? System eye brain mind.

Apparatus
The most serious attempt known to me to make an exact formulation of quantum mechanics is that of de Broglie (1927) and Bohm (1952).

It considers only the position of things, e.g. instrument pointers.

In a relativistic theory a c-number distribution

\[ T_{\mu \nu}(t, \vec{r}) \]

In nonrelativistic theory

\[ T_{\mu \nu}(t, \vec{r}) = \sum_n m_n c^2 \delta(\vec{r} - \vec{r}_n) \]

The \( \vec{r}_n \) are not 'observables' but beagles — where the buck stops they are what, in the world, the theory is about, exactly.


The deBB theory uses also the Schrödinger wavefunction \( \Psi(t, \vec{r}_1, \vec{r}_2, \ldots) \).

The dynamical history of the world is given by functions

\[ \Psi(t, \vec{r}), \dot{X}_1(t), \dot{X}_2(t), \ldots \]
The equations of motion are

\[ i \hbar \frac{\partial \psi}{\partial t} = H \psi \]

\[ H = \sum_i \frac{p_i^2}{2m_i} + V(t, \vec{r}) \]

\[ m \frac{\partial^2 \psi}{\partial x_i^2} = \frac{\partial}{\partial x_i} \left( m \frac{\partial \psi}{\partial x_i} \right) \]

\[ \text{Im} \log \psi(t, \vec{x}) \]

where

\[ u_i \equiv \frac{1}{\sqrt{2}} \Gamma_i \]

\[ x \equiv \frac{x_1}{\sqrt{2}}, \frac{x_2}{\sqrt{2}}, \ldots \]

In the beginning God chose some initial wavefunction

\[ \psi(0, \vec{x}) \]

and then chose the initial configuration

\[ x_1(0), \frac{x_2}{\sqrt{2}}, \ldots \]

at random from an ensemble with distribution

\[ \prod d^3x \left| \psi(0, \vec{x}) \right|^2 \]

Theorem: The probability at time t of configuration

\[ x_1(t), x_2(t), \ldots \]

is

\[ \prod d^3x(t) \left| \psi(t, \vec{x}(t), \frac{x_2(t)}{\sqrt{2}}, \ldots) \right|^2 \]

for all practical purposes
'macroscopic' variables (e.g. instrument pointer positions) are functions of the 'microscopic' x. The deBB probability for such variables, and correlations between them, is identical with that of ordinary QM, i.e. for us that is unambiguous (wavefunction reduction!). — i.e. for all practical purposes.

deBB is sharp where other versions are fuzzy. It shows that the vagueness, subjectivity, and even indeterminism, of contemporary theory, are not dictated by experiment — but by lack of imagination. It puts in disturbingly clear focus questions which are blurred in what Einstein called 'the tranquilizing philosophy' from Copenhagen.

Indeterminism; why was it embraced so readily by the founding fathers? Only the initial conditions are undetermined in deBB — as in classical mechanics.
M. Jammer

P. Forman: Weimar culture, causality, and quantum theory, 1918-1927
in Historical studies in the physical sciences
(R. McCormach, ed., Philadelphia 1971)

".... overwhelming evidence that in the years after the end of the first world war, but before the development of an acausal quantum mechanics, under the influence of 'currents of thought,' large numbers of German physicists, for reasons only incidentally related to developments in their own discipline, distanced themselves from, or explicitly repudiated, causality in physics."

E. Amaldi: Radioactivity, a pragmatic pillar of probabilistic conceptions.
in Problems in the Foundations of Physics
Varenna 1977
(G. Toraldo di Francia, ed.
North Holland 1979)

Statistical mechanics
radioactive decay
— exponential law
\[ m \dot{\vec{x}_1} = \frac{2}{\delta \vec{x}_1} \Im \log \psi(\vec{x}_1, \vec{x}_2) \]

**Non Locality**

**Special case**

\[ \psi(\vec{x}_1, \vec{x}_2) = \phi(\vec{x}_1) \chi(\vec{x}_2) \]

\[ \log \psi = \log \phi(\vec{x}_1) + \log \chi(\vec{x}_2) \]

\[ m \dot{\vec{x}_1} = \frac{2}{\delta \vec{x}_1} \Im \log \phi(\vec{x}_1) \]

— independent of \( \chi \).

But with superposition

\[ \psi(\vec{x}_1, \vec{x}_2) = \sum \phi_n(\vec{x}_1) \chi_n(\vec{x}_2) \]

\( \chi \) depends on \( \chi \)'s as well as \( \phi \)
even if the \( \chi \)'s are all far away.

So \( \dot{\vec{x}_1} \) depends on distant external fields
because such fields change the \( \chi \).

Could this non-locality be avoided by a more clever construction of beable orbits?

The investigation, triggered by this question, is not confined either to the non-relativistic context or to that of determinist, or beable, variables.
certain results of relativistic QM imply nonlocality.

E.g. \( e^+ e^- (\text{positronium}^+ \to \gamma \gamma) \) final state \( \frac{1}{2} (\ket{1x} \ket{1x} - \ket{1\bar{x}} \ket{1\bar{x}}) \) polarization correlation.

Analyser
\[ C \quad \square \quad \square \quad \square \quad C \]
Counter

Analyser at angles \( \alpha \) and \( \beta \)

\[
P(\text{yes, yes}) = P(\text{no, no}) = \frac{1}{2} \left( \sin (\alpha - \beta) \right)^2
\]

\[
P(\text{yes, no}) = P(\text{no, yes}) = \frac{1}{2} \left( \cos (\alpha - \beta) \right)^2
\]

\[
E(\alpha, \beta) = P(\text{yes, yes}) + P(\text{no, no}) - P(\text{yes, no}) - P(\text{no, yes})
\]

\[
= -\cos \phi, \quad \phi = 2(\alpha - \beta)
\]

Which in 'locally inexplicable' (the straight line would not be
Example: on randomly chosen day

A = no of auto accidents in Milan
B = " " " " " " Rome
\[ P(A, B) = \text{joint probability distribution} \]

Correlation:
\[ P(A, B) \neq P_1(A) P_2(B) \]

Explicitability:
\[ P(A, B) = \int \ldots \int \phi(\lambda, a, b, \ldots) \]
\[ P_1(A|a, b, \lambda) P_2(B|a, b, \lambda) \]

correlations due to common causes

Local Explicitability:
\[ P(A, B) = \int \ldots \int \phi(\lambda, a, b, \ldots) \]
\[ P_1(A|a, \lambda) P_2(B|b, \lambda) \]

e.g., if \( a \) is temperature in Milan
\( b \) is temperature in Rome

for given \( a, b \)
\[ P(A, B|a, b) = \int \lambda \phi(\lambda|a, b) \]
\[ P_1(A|a, \lambda) P_2(B|b, \lambda) \]
\[
P(A, B | a, b) = \int dx \, \varphi(a, x, b) \\
P_1(A | a, x) \cdot P_2(B | b, x)
\]

\[
\varphi(a, x, b) = \varphi(x)
\]

\[
\Rightarrow \text{Clauser-Holt-Horne-Shimony inequality}
\]

\[
|E(a, b) - E(a', b)| + |E(a', b) + E(a, b')| \leq 2
\]

Where
\[
\bar{E} = \sum_{A, B = \pm 1} A B \cdot P(A, B | a, b)
\]

With
\[
\pm 1 = \text{yes / no}
\]

Which is not satisfied by QM:

\[
E = - \cos 2(a-b)
\]

by factor up to \(\sqrt{2}\)