S. M. Roy

What in the world is quantum mechanics about exactly?

QM is about:

wavefunctions Ψ

A_μ operators H

$F_{\mu\nu}$ schrodinger eq:

$$i\hbar \frac{\partial \Psi}{\partial t} = H \Psi$$

and how to solve it.

Bari 1980 Oct 18

but what <u>in the world</u>?

the wavefunction is not like the world:

$$\Psi = \Psi_1 + \Psi_2$$

would be unrecognizable.

so: $\boxed{\text{Statistical Interpretation}}$

statistics of what?

'measurement' results

Dirac: Principles of Q.M. (4th ed)

p36 .... any result of a measurement of a real dynamical variable is one of its eigenvalues ....

p46 .... if the measurement of the observable ξ for the system in the state corresponding to $|x\rangle$ is made a large number of times the average of all the results obtained will be $\langle x|\xi|x\rangle$ ....

p36 .... a measurement always causes the system to jump into an eigenstate of the dynamical variable that is being measured ....

'measurements' make 'jumps'

but what, when, and where, is a 'measurement'

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but what, when, and where, is a 'measurement' 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.

<u>example</u> of taking them seriously
and not liking the results:

The Zeno paradox.

Zeno paradox

'measure' some 'observable' repeatedly over period T at intervals T/N

If α is first result the probability that all subsequent results are also α is

$$\left|(\alpha| e^{-iHT/N} |\alpha)\right|^{2N}$$

$$\sim \left|(\alpha| 1 - iHT/N - \tfrac{1}{2}H^2T^2/N^2 \ldots |\alpha)\right|^{2N}$$

$\boxed{\langle\alpha|H|\alpha\rangle = 0}$

or look at higher order terms $|(\alpha|H|\alpha)|^2$

$$\sim 1 - (\alpha|H^2|\alpha)T^2/N$$

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

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 <u>52A</u> (1979) 421

4. P. Pearle } preprint, june 1980

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

all practical purposes

$\psi_1 + \psi_2$ ψ_1 or ψ_2

'measurement' problem

M. Cini M. De Maria G. Mattioli F. Nicolo	Foundations of Physics 9 (1979) 479
L. Lanz G. Lupieri	Nuovo Cimento 47B (1978) 201
" + A. Barchielli	IFUM 228/FT March 1979

Ludwig

important. but approximate. and for
vaguely defined 'macroscopic' observables

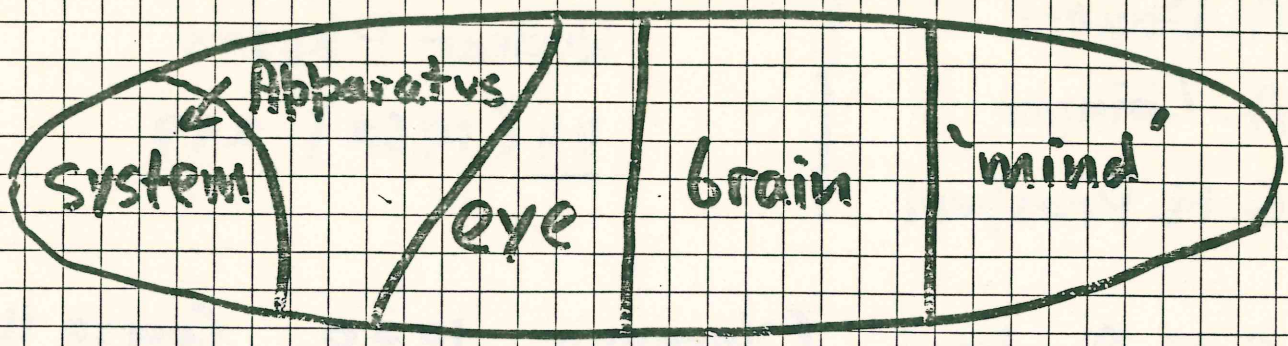
A. Daneri
A. Loinger
G. M. Prosperi

Nuclear Physics
<u>44</u> (1962) 297

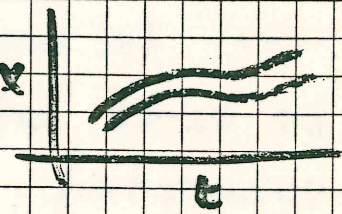
G. M. Prosperi (Varenna 1970 Course IL):

.... 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 priveleged 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?

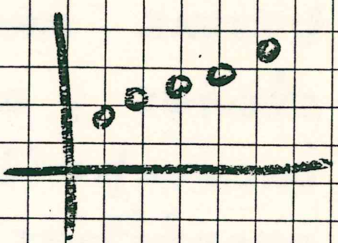


'mind' as 'observer':



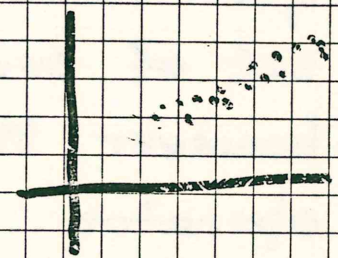
what does it observe ?

continuously ?



spae time averages ?

Lorentz invariance ?



points ?

but fields at points

are not 'observable'

'mind' as agent

Ludwig ?

external fields ?

where ?

Lets try to leave mind

out of it. ?

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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 <u>position</u> of things e.g instrument pointers

In a relativistic theory a c-number distributio[n]

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

In nonrelativistic theory

$$T_{00}(t,\vec{r}) = \sum_n m_n c^2 \, \delta(\vec{r} - \vec{x}_n)$$

The $\vec{x}_n$ are not 'observables' but <u>beables</u>

— where the buck stops

they are what, in the world, the theory is about, <u>exact</u>ly.

<u>macro</u>scopic - microscopic ?

The deBB theory uses also the Schrodinger wavefunction $\psi(t, \vec{r}_1, \vec{r}_2 \ldots)$

The dynamical history of the world is given by functions

$$\underline{\psi(t,\vec{r})}, \ \underline{\vec{x}_1(t)}, \ \underline{\vec{x}_2(t)}, \ \ldots\ldots$$

The equations of motion are

$$i\hbar \frac{\partial \psi}{\partial t} = H \psi$$

$$H = \sum \frac{1}{2m}\left(\frac{\partial^2}{\partial \vec{r}^2}\right) + V(t, \vec{r})$$

$$m_n \dot{x}_n(t) = \partial/\partial x_n \ \mathrm{Im} \log \psi(t, \vec{x})$$

where $\vec{r} \equiv \vec{r}_1, \vec{r}_2 \ldots\ldots$

$\vec{x} \equiv \vec{x}_1, \vec{x}_2 \ldots\ldots$

nt to practical school

In the beginning God chose some initial wavefunction

regard w ph reduction.

$$\psi(0, \vec{r})$$

and then chose the initial configuration

$$\vec{X}_1(0), \vec{X}_2(0), \ldots\ldots$$

<u>at</u> <u>random</u> from an ensemble with distribution

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

<u>Theorem</u> The probability at time t of configuration

$$X_1(t), X_2(t), \ldots\ldots$$

is

$$\prod d^3x(t) \left|\psi(t, \vec{x}_1(t), \vec{x}_2(t), \ldots\ldots)\right|^2$$

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 <u>in so far as that is unambiguous</u> (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 197

"..... 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

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$$m_1 \dot{\vec{x}}_1 = \frac{\partial}{\partial \vec{x}_1} \mathrm{Im} \log \psi(\vec{x}_1, \vec{x}_2)$$

Non Locality

special case

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

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

$$m_1 \dot{\vec{x}}_1 = \frac{\partial}{\partial \vec{x}_1} \mathrm{Im} \log \phi(\vec{x}_1)$$

— independent of χ.

But with superposition

$$\psi(\vec{x}_1, \vec{x}_2) = \sum_n \phi_n(\vec{x}_1)\, \chi_n(\vec{x}_2)$$

$\dot{\vec{x}}_1$ depends on χ's as well as ϕ's even if the χ's are all far away.

So $\dot{\vec{x}}_1$ depends on distant external fields because such fields change the χ's

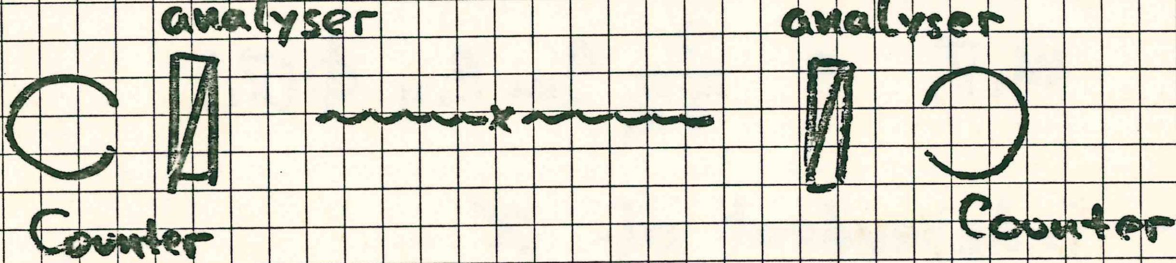
Could this non locality be avoided by a more clever construction of beable orbits?

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

e.g. $e\bar{e}$ (positronium, $^1S_0$) $\to \gamma\gamma$

final state $\frac{1}{\sqrt{2}}\left(|x\rangle|y\rangle - |y\rangle|x\rangle\right)$

polarization correlation



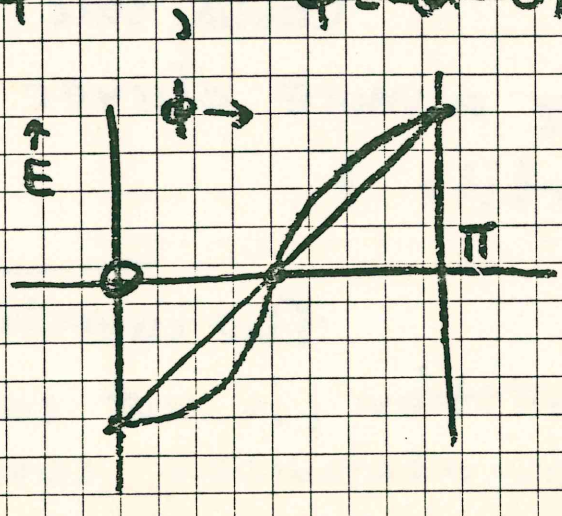
analysers at angles a and b

$$P(\text{yes},\text{yes}) = P(\text{no},\text{no}) = \tfrac{1}{2}\left(\sin(a-b)\right)^2$$
$$P(\text{yes},\text{no}) = P(\text{no},\text{yes}) = \tfrac{1}{2}\left(\cos(a-b)\right)^2$$

$$E(a,b) = P(\text{yes},\text{yes}) + P(\text{no},\text{no}) - P(\text{yes},\text{no}) - P(\text{no},\text{yes})$$
$$= -\cos\phi\ , \quad \phi = 2(a-b)$$

which is 'locally inexplicable'

(the straight line would not be)



Example: on randomly chosen day

A = no of auto accidents in Milan

B = " " " " " Rome

$P(A,B)$ = joint probability distribution

Correlation:

$$P(A,B) \neq P_1(A)\, P_2(B)$$

Explicability:

$$P(A,B) = \int d\lambda\, da\, db \ldots \rho(\lambda, a, b, \ldots)\, P_1(A \mid a, b, \lambda)\, P_2(B \mid a, b, \lambda)$$

correlations due to common causes

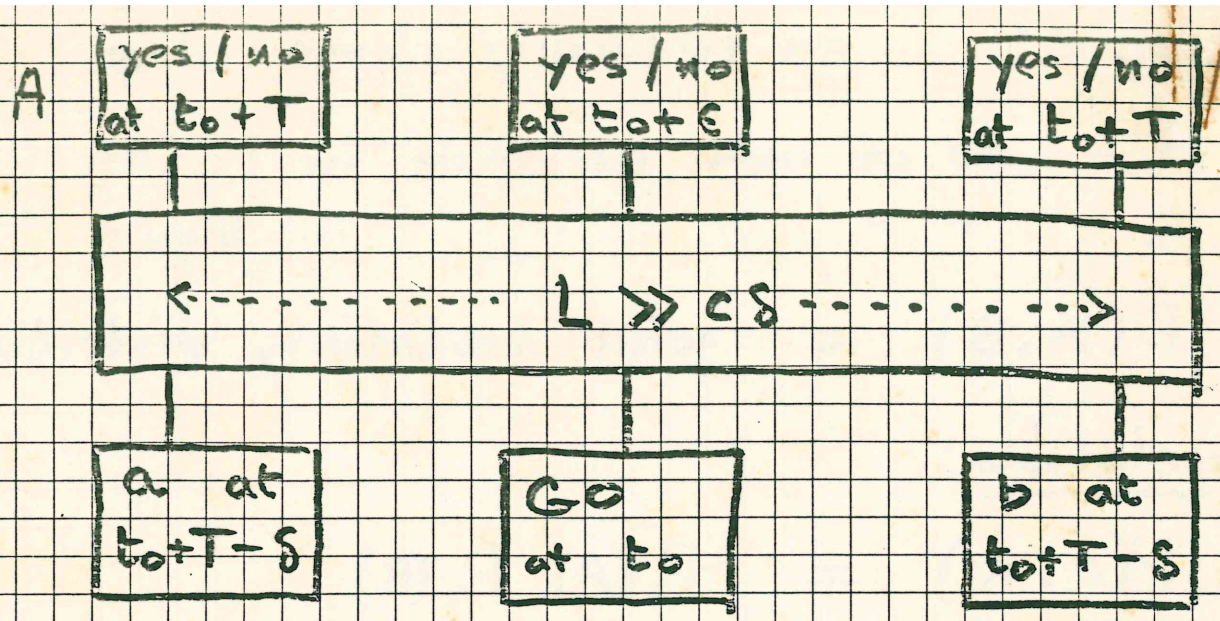
Local Explicability:

$$P(A,B) = \int d\lambda\, da\, db \ldots \rho(\lambda, a, b, \ldots)\, P_1(A \mid a, \lambda)\, P_2(B \mid b, \lambda)$$

e.g. if a is temperature in Milan
b is temperature in Rome

for given a, b

$$P(A,B \mid a,b) = \int d\lambda\, \rho(\lambda \mid a, b)\, P_1(A \mid a, \lambda)\, P_2(B \mid b, \lambda)$$



$$P(A,B|a,b) = \int d\lambda\, \rho(\lambda|a,b)\, P_1(A|a,\lambda)\, P_2(B|b,\lambda)$$

$$\rho(\lambda|a,b) = \rho(\lambda)$$

$\Rightarrow$ Clauser-Holt-Horne-Shimony inequality

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

where $\quad E = \sum_{A,B=\pm 1} AB\, P(A,B|a,b)$

with $\quad \pm 1 \equiv$ yes / no

which is not satisfied by QM:

$$E = -\cos 2(a-b)$$

by factor up to $\sqrt{2}$