BELL'S THEOREM:

Conflict between quantum mechanics
and principle "nothing faster than light"

Several steps - Surprises:

do not dwell on one
trust me and come back to it later

HISTORICAL APPROACH

End of 19th century: physics fitted conventional thinking {"quiet waters"}

Then came splashes

Bell's theorem = #4

Before #1: Michelson Morley experiment:

frames in motion

but same value measured for speed of light

–> Lorentz relativity:

aether, measuring sticks contracted, clocks slowing down

–> invariance –> restframe of aether unknown, but it exists

no problem with faster than light influences,

Two events A and B: A before B in aether frame

A can influence B even faster than light

in some restframes: A before B in some frame,

in others: A after B

But only the aether restframe counts

Splash #1 Einstein's relativity:

aether restframe cannot be determined –> it does not exist

–> all restframes are equal

–> no backward in time influence in any restframe

–> no influence faster than light

Then came QUANTUM MECHANICS:

Principle: measurement changes an observed object:

–> Uncertainty principle:

cannot know both x et p of an object exactly.

One of them remains hidden

Splash #2: Bohr et al: both x ond p cannot exist simultaneously

with infinite precision

particle described by wave function Ψ

Ψ = property of particle + knowledge about it

no reality associated with Ψ, till something is measured

x only exists when x is observed

p ---------- p ----------

Already A conflict with relativity:

After measurement of x: Ψ collapses everywhere instantaneously

OK because Ψ not "real"

Yet Einstein is not convinced:

"I believe the moon exists even when I do not look at it"

Measurement = discovery + transformation of reality

–> "Hidden variables"

Splash ≠ 3. Einstein Podolsky & Rosen (EPR) paradox (1935)

Two particles a et b:

x_a and x_b, associated to X_a et X_b, p_a et p_b, associés à P_a et P_b:

$X_a - X_b$ commute with $P_a + P_b$,

–> ∃ eigenvector of $X_a - X_b$ and of $P_a + P_b$ at the same time

= fonction d'onde $\Psi = \delta(x_a - x_b - k) = \delta(p_a + p_b) \exp\{i\, k\, p_a\}$

if I measure x_a and x_b, then $x_a - x_b = k$ = known value

---------- p_a and p_b ---- $p_a + p_b = 0$

–> if I measure x_a, I know I will find $x_b = x_a - k$ before measurement of x_b,

∃ something attached to particle b with property: –> $x_b = x_a - k$

no excuse not to have it in the theory (EPR: element of reality corresponding to x_b)

Was it created by measurement of x_a? No it would require a faster than light influence

–> element of reality corresponding to given x_b before any measurement

that value of x_b not described by Ψ: "quantum mechanics is incomplete"

There is more: same argument for p_b :

if i measure p_a then p_b , I know I will find $p_b = -p_a$

∃ something attached to particle b: –> $p_b = -p_a$ (element of reality corresponding to p_b)

element of reality created by measurement of p_a? No it would require a faster than light influence

–> before any measurement,

∃ one element of reality determining a value for p_b and one determining x_b

Argument OK if there is no influence faster than light

Anyway Ψ before any measurement cannot describe these elements of reality

EPR: "Quantum mechanics is incomplete"

Bohr: difficult answer to understand –> my interpretation:

sentences he used: concept of reality should be changed

no quantity can be defined without specifying the measurement apparatus –> old belief there is an "influence" not a not a "mechanical disturbance",

–> Speeds > c, are they OK for influences?

That was 1935*: Unresolved controversy*

1952: Bohm: invents a hidden variables theory that reproduces predictions of quantum mechanics

his theory involves faster than light effects,

–> motivated by EPR, but does not resolve the conflict demonstrated by EPR

invents same system later used to demonstrate Bell's theorem

Splash #4: 1964, Bell theorem:

Quantum mechanics implies faster than light influences

even if there is an underlying reality

–> EPR wrong because premise in conflict with quantum mechanics

Demonstration has evolved and became easy

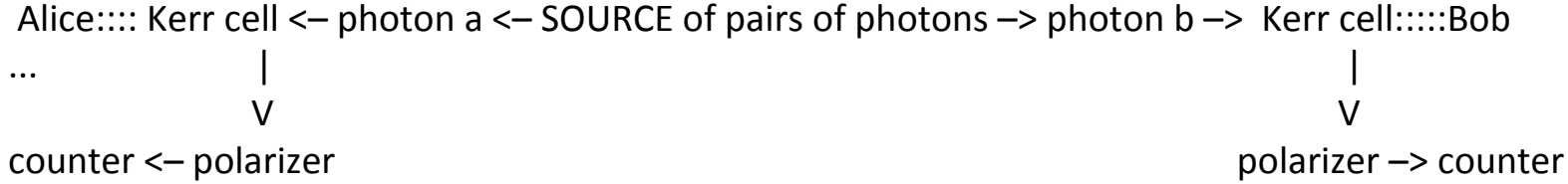
It uses Bohm's: two photon system, emitted in opposite directions

i.e.

a pair of two photons both with vertical polarizations V V and

---------- slanted ---------- both at angle γ

in quantum superposition: $\Psi = \Psi_{V\,V} + \Psi_{\gamma\,\gamma}$ (entanglement)



First setup: both Kerr cells off: 9% pairs with clicks in Alice's and in Bob's counters
these are pairs of photons of interest

2nd setup: Alice's Kerr cell off; Bob's Kerr cell on: 37.5% such double clicks
If click in Alice's, always click in Bob's
–> in pair of interest: Bob's photon: not fewer clicks

3d setup: Alice's Kerr cell on; Bob's Kerr cell off: 37.5% such double clicks
If click in Bob's, always click in Alice's
–> in pair of interest: Alice's photon: not fewer click

4th setup: both Kerr cell on: expect: pairs of interest: not fewer double clicks,
i.e > 9% double clicks
Quantum theory predicts: ???

Conclusion:

For pairs of interest:

when Alice's Kerr cell is off: probability of Bob's photon not reduced by turning Bob's cell on

and ---------- on: ---------- becomes zero ----------

or

when Bob's Kerr cell is off: probability for Alice's photon not reduced by turning Alice's cell on

and ---------- on: ---------- becomes zero ----------

Either

Alice's Kerr cell influences Bob's photon probability

or

Bob's Kerr cell influences Alice's photon probability

Either way: ∃ influence of a Kerr cell somewhere over photon somewhere else

if experimental setup:

both Kerr cell decisions and both photon arrivals in short time interval:

then Influence faster than light

1. Are these quantum mechanics predictions correct? - Do it yourself:

source of two photons with a pair of photons with both polarizations lined up vertically

\+ a pair of photons with both polarizations slanted at an angle γ

Both polarizers are horizontal

Kerr cells turn the polarizations by an angle equal to 90^o - γ

Set up amplitudes and phases of the two kinds of pairs of photons to interfere 100% destructively for double clicks in the on-on setup.

2. What has been checked experimentally? - Everything but with some loopholes

What are Bell's inequalities? - Fundamental one is:

"The number of pairs producing double clicks in off-off setup but not in the on-on setup are part of the sample of pairs that produce a click in Alice's counter but not in Bob's in the off-on setup or a click in Bob's counter but in not in Alice's in the on-off setup"

It can be derived from the same argument as our demonstration:

3. Can one use this effect to communicate faster than light? - NO.

No other quantum system either

SIGNIFICANCE

Different people have different conclusions.

1) A special different from others
in which time coincides with causal order
e.g. Lorentz relativity

2) "Reality" depends of the observer

3) Quantum mechanics does not apply to "counterfactuals"

4) All invariances are broken. - Look for violations
Geneva's experiment

Is it necessary that everyone agrees?