



a nonlocal quantum engineer

contemplate but don't forget to calculate !

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talk at symposium
“ *shut up and **contemplate** !* ”

University of Vienna, March 3rd, 2017



universität
wien

engineer's career at Harwell

John Stewart Bell graduated at Queen's University Belfast

in experimental physics 1948

in mathematical physics 1949

high interest in quantum mechanics

showing his dissatisfaction !

position at AERE Harwell from 1949 on
joined accelerator group of Walkinshaw (Malvern)

William Walkinshaw:

“ a young man of high caliber who showed his independence ... his mathematical talent was superb and elegant.”

papers on electron and proton linear accelerators

e.g. *“basic algebra on strong focussing systems”*

“linear accelerator phase oscillations”

“phase debunching by focussing foils in proton linear accelerator”



John on his new “Ariel”
at Harwell 1952

turn to particle physics & Bohm's qm

in mid 1950s Bell turned to nuclear and particle physics
“time reversal in field theory ...”, CPT theorem, PhD thesis **fundamental** !
“anomalous magnetic moments of nucleons”, collab. Tony Skyrme

at that time paper of David Bohm appeared 1952
“interpretation of quantum theory in terms of hidden variable”

Mary: for John a “revelation”

“everything has definite properties”

I remember John saying

Bell's talk about Bohm's theory
in TH division

fierce debates with audience
especially with Franz Mandl

1954 John married Mary Ross
“mathematical engineer”
accelerator physicist



engineer's job at cern

1960 John and Mary moved to CERN

John to TH Div Mary to Accelerator Research Group

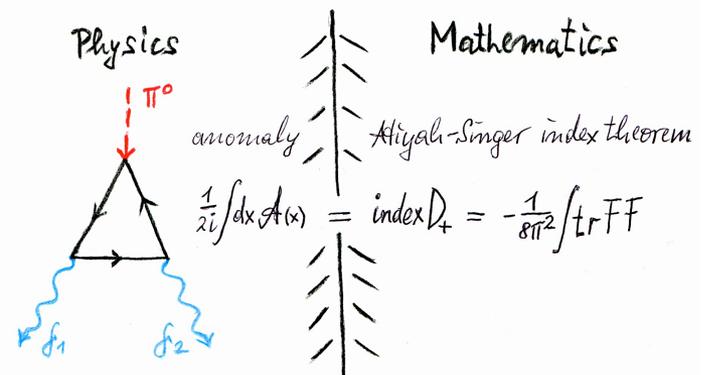
interest in weak interactions

collaborations with Tini Veltman W bosons

with Jack Steinberger K mesons

Anomaly in QFT breakdown of classical symmetry due to quantum effects
 $\pi^0 \rightarrow \gamma \gamma$ decay Bell-Jackiw, Adler 1969 axial current not conserved
ABJ anomaly, modified PCAC with anomaly term

ground breaking work !
key to deeper understanding of QFT
anomaly restricts theory
gauge theories, gravitation
physics — **mathematics** (topology)



“neutrino – nucleon interaction”, collab. Chris Llewellyn Smith
“anomalous magnetic moment of muon”, collab. Eduardo de Rafael
“QCD, gluon condensate, potential models”, collab. R.A.B.

magic moments

moment

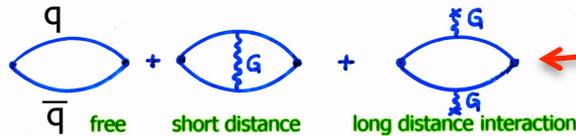
nonrelativistic

$$M(\tau) = \int dE \cdot e^{-E\tau} \text{Im}\Pi(E)$$

theoretical moment

calculation

$$M(\tau) = \frac{3}{8m^2} 4\pi \left(\frac{m}{4\pi\tau}\right)^{\frac{3}{2}} \left[1 + \frac{4}{3} \alpha_s \sqrt{\pi \cdot m} \cdot \tau^{\frac{1}{2}} - \frac{4\pi^2}{288m} \left\langle \frac{\alpha_s}{\pi} GG \right\rangle \cdot \tau^3 \right]$$



quark-antiquark bound states
“quarkonium”

vacuum polarization tensor

gluon condensate
responsible for confinement
Shifman, Vainshtein, Zakharov

binding energy

excellent results

$$M(\tau) \rightarrow E = -d/d\tau \log M(\tau) \quad \tau \text{ optimized}$$

equivalent potential of Bell-Bertlmann

$$V_{BB}(r) = -4 \alpha_s/3r + \pi^2/144 \langle \alpha_s/\pi GG \rangle m r^4$$

bridge ?



$\langle GG \rangle m r^4$
mass dependent !
steep !

$$V_{\text{model}}(r) = -4 \alpha_s/3r + a r$$

potential models

mass independent
flat



John & Reinhold

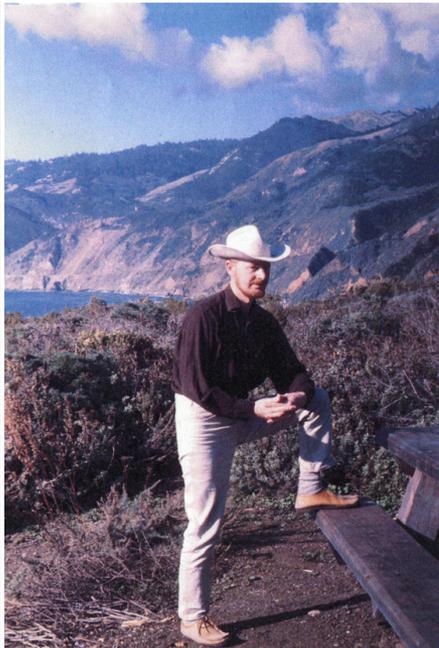
engineer's hobby

J&M sabbatical 1963-1964 at SLAC, University of Wisconsin, Brandeis University

John's leisure time devoted to foundations of quantum mechanics – “*hobby*”!
whereas his professional job at cern: particle physics – “*quantum engineer*”!

time for contemplation 2 seminal works

1. contextuality **2. Bell's theorem** via Bell inequalities
HVT hidden variable theory: observables $A, B, C \rightarrow v(A), v(B), v(C)$ values



John in California 1964

- I. “*On the problem of hidden variables in quantum mechanics*”
criticizing John von Neumann: “*HV are incompatible with QM*”
operators A, B, C : $C=A+B \rightarrow v(C)=v(A)+v(C)$ values HV
Bell: “*this is wrong!*” for noncommuting operators
ok for QM expectation values

Bell's corollary: 1966

Additivity for expectation values of commuting operators cannot hold for dispersion-free states if $\dim > 2$.



it's impossible to assign definite values for each observable in each individual system

\rightarrow contextuality HVT – QM

Kochen–Specker Theorem 1967

Bohm's theory of QM

1. $\psi(x,t)$ **wavefunction**, pilot wave

$$i\hbar d/dt \psi(x,t) = H \psi(x,t) \quad \text{Schrödinger equation}$$

$$H = p^2/2m + V \quad \text{Hamiltonian} \quad \psi(x,t) = R(x,t) e^{i\hbar S(x,t)}$$

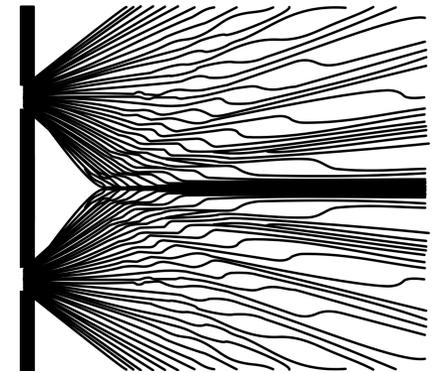
2. $x(t)$ **coordinate**, configuration, hidden variable, real !

trajectory, guiding equation of particle

$$m v = m dx/dt = d/dx S(x,t) = \frac{1}{\rho} \text{Im} \psi^* d/dx \psi(x,t)$$

distribution of particles in configuration space

$$\rho = |\psi|^2 \quad \text{Born rule}$$



Bohmian trajectories
particle through double slit
Bohm equivalent to QM

N – particles, \mathbb{R}^{3N} configuration space

$$m_i v_i = m_i dx_i/dt = d/dx_i S(x_1, x_2, \dots, x_N, t)$$

i th trajectory depends on actual positions of all particles !

2-particle system time evolution

$$m dx_1/dt = 1/\rho(x_1, x_2, t) \text{Im} \psi^* d/dx_1 \psi(x_1, x_2, t)$$

$$m dx_2/dt = 1/\rho(x_1, x_2, t) \text{Im} \psi^* d/dx_2 \psi(x_1, x_2, t)$$

highly nonlocal !

trajectory 1 depends on trajectory 2 and on common wavefunction

factorizable wavefunction

$$\psi(x_1, x_2, t) = \eta(x_1, t) \cdot \chi(x_2, t)$$

$$m dx_1/dt = 1/|\eta(x_1, t)|^2 \text{Im} \eta^* d/dx_1 \eta(x_1, t)$$

$$m dx_2/dt = 1/|\chi(x_2, t)|^2 \text{Im} \chi^* d/dx_2 \chi(x_2, t)$$

local

specific feature of Bohm's theory ?

Bell: **NO !**

Bell inequalities

2. “On the Einstein-Podolsky-Rosen paradox”

Bohm-EPR setup, where spin $1/2$ particles

are produced in a spin singlet state

measurement results of Alice and Bob

$$A(a,\lambda) = \pm 1, 0 \quad B(b,\lambda) = \pm 1, 0$$

expectation value of
joint measurements in HVT:

$$E(a,b) = \int d\rho(\lambda) A(a,\lambda) \cdot B(b,\lambda)$$

A does not depend on Bob's settings

B does not depend on Alice's setting

Bell's Locality Hypothesis



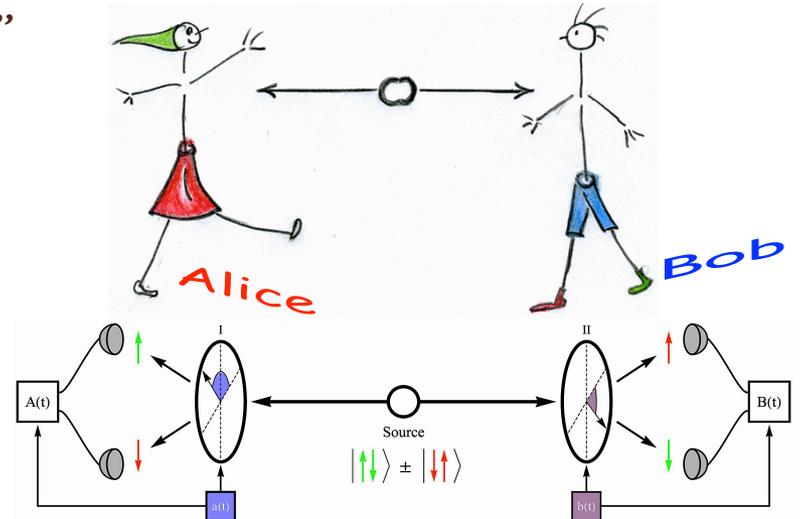
Bell inequality of Clauser-Horne-Shimony-Holt type

$$S_{\text{CHSH}} = |E(a,b) - E(a,b')| + |E(a',b) + E(a',b')| \leq 2$$

QM on the other hand

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

$$S_{\text{CHSH}} = 2\sqrt{2} \approx 2.8! \\ \text{at Bell angles}$$



Bohm-EPR setup with pair of spin $1/2$ particles

locality + realism = local realism

Bell's Theorem 1964

Local realistic theories are incompatible with quantum mechanics !

Bell-type experiments

1. generation experiments in the 1970s
Clauser, Freedman, Fry, Thompson, ...

2. generation experiments in the 1980s
Aspect, Dalibard, Grangier, Roger, ...

3. generation experiments in the 1990s
Weihs, Jennewein, Weinfurter, Zeilinger
Tittel, Brendel, Zbinden, Gisin
Bouwmeester, Pan, ..., Weinfurter, Zeilinger, ...

4. generation experiments after 2000
Ma, Scheidl, Ursin, Jennewein, Zeilinger, ...
Giustina, Resch, Ursin, Walther, Zeilinger, ...
Rauch, Hasegawa, ... ,
Rowe, Kielpinsky, Wineland, ...

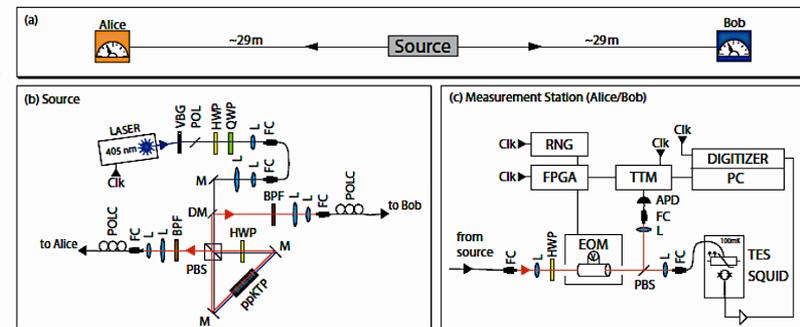
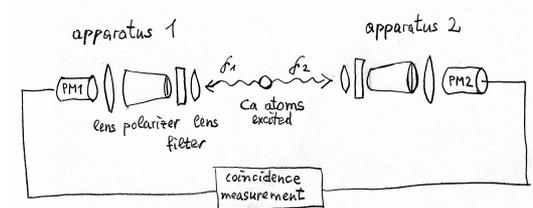
main loopholes

1. locality loophole
2. freedom-of-choice loophole
3. detection loophole

all 3 loopholes closed simultaneously in single experiment 2015

Zeilinger group (Vienna), Shalm group (Boulder), Hanson group (Delft)

all experiments in favour of QM with impressive accuracy, Bell inequalities violated



Local realistic theories are incompatible with Nature !

Oh, I'm a realist ...

Bell's view about the realism of Nature

"Oh, I'm a realist and I think that idealism is a kind of ... I think it's an artificial position which scientists fall into when they discuss the meaning of their subject and they don't know what it means. I think that in actual daily practice all scientists are realists, they believe that the world is really there, that it is not a creation of their mind. They feel that there are things there to be discovered, not a world to be invented ... "

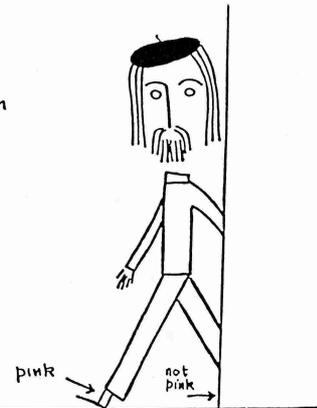
experimental results are predetermined !
otherwise (without realism):

"It's a mystery if looking at one sock makes the sock pink and the other one not-pink at the same time."

John did hold on the hidden variable program, he was not discouraged by outcome of the EPR-Bell experiments but rather puzzled. For him *"The situation was very intriguing that at the foundation of all that impressive success [of quantum mechanics] there are these great doubts"*.

Les chaussettes
de M. Bertlmann
et la nature
de la réalité

Fondation Hvgot
juin 17 1980



words to be forbidden ...

“against ‘measurement’” Bell the moralizer

words forbidden in serious discussion:

“system, apparatus, environment, microscopic, macroscopic, reversible, irreversible, observable, information, measurement”

system, apparatus, environment

- artificial division of world

microscopic, macroscopic, reversible, irreversible

- defy precise definition

observable

- complicated, theory-laden business

information

- whose information ?
information about what ?

measurement

- worst word of all ! measurement causes system to jump into eigenstate, ...

measurement replaced by experiment

- experimental science aims to **understand** the world !

“ordinary QM is just fine FAPP”

J.S. Bell

Schrödinger Symposium

Friday 18. 9. 87

Theme of contribution to
panel. discussion 14.00 - 15.30

Words that should be forbidden in
serious discussion: system,
apparatus, microscopic, macroscopic,
reversible, irreversible, observable,
measurement, for all practical
purposes.

“QM is not just about piddling
laboratory operations !”

nonlocal quantum engineer

John not so much concerned about **contextuality** – in contrast to me
John disturbed by **nonlocal feature** of QM – equivalent to breaking of Lorentz invariance

at the end of his ‘Bertlmann’s socks’ paper:

“It may be that we have to admit that causal influences do go faster than light. The role of Lorentz invariance in a completed theory would then be very problematic.”

1981

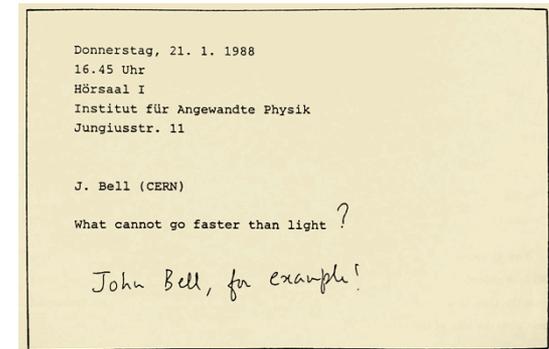
“la nouvelle cuisine” paper (1990) based on talk at University of Hamburg

“What cannot go faster than light ?”

John thinking, what exactly that means, his whole body or just his legs, his cells or molecules, atoms, electrons ...
is it meant that none of his electrons go faster than light ?

in modern view of Nature sharp location of objects has dissolved

- fuzziness of wave function
- fluctuations in QFT



John: *“The concept ‘velocity of an electron’ is now unproblematic only when not thought about it”*

an engineer enjoys technology

giant wheel Prater Vienna



John & Reinhold

John: *“British engineering of the 19th century”* 1980

Prater Liliputbahn



John in Liliputbahn

engineer meets metaphysics

Transcendental Meditation Centre, Seelisberg, CH

Maharishi Mahesh Yogi interested in physics

Conference “Physics and Consciousness” 1978

M: *“meditating coherently amplifies squared the effect”*

– QM: amplitude squared = probability

M: *“mind in meditation [without thoughts] is not void but rich and fertile”*

– QFT: vacuum not void but full of field fluctuations

Bell was invited among others as participant
John’s opinion ?



Maharishi



biographie

Schrödinger

Mary Bell:

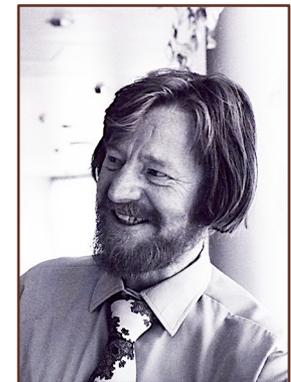
Schrödinger’s text marked by John:

“Whence come I and whither go I ?

That is the great unfathomable question.

The same for every one for us.

Science has no answer to it.”



Bell

