Title: Can â€˜sub-quantumâ€™ theories based on a background field escape Bellâ€™s no-go theorem ?

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Abstract: In systems described by Ising-like Hamiltonians, such as spin-lattices, the Bell Inequality can be strongly violated. Surprisingly, these systems are both local and non-superdeterministic. They are local, because 1) they include only local, near-neighbor interaction, 2) they satisfy, accordingly, the Clauser-Horne factorability condition, and 3) they can violate the Bell Inequality also in dynamic Bell experiments. Starting from this result we construct an elementary hidden-variable model, based on a generalized Ising Hamiltonian, describing the interaction of the Bell-particles with a stochastic â€˜backgroundâ€™ medium. We suggest that such a model is a simple version of a variety of recently developed â€˜sub-quantumâ€™ theories, by authors as Nelson, Adler, De la Pena, Cetto, Groessing, Khrennikov, all based on a background field. We investigate how the model might be turned into a realistic theory. Finally, it appears that background-based models can be tested and discriminated from quantum mechanics by a straightforward extension of existing experiments.

Overview

1. Intro: « Background fields » in experiments and theory
2. Bell's theorem: Surprises in Spin-Lattices
3. A HV toy model for real Bell experiments
4. Are realistic 'sub-quantum' theories possible ?
5. Conclusion
6. Appendix: link with non-local PR boxes and 'quantum Ising Hamiltonian'

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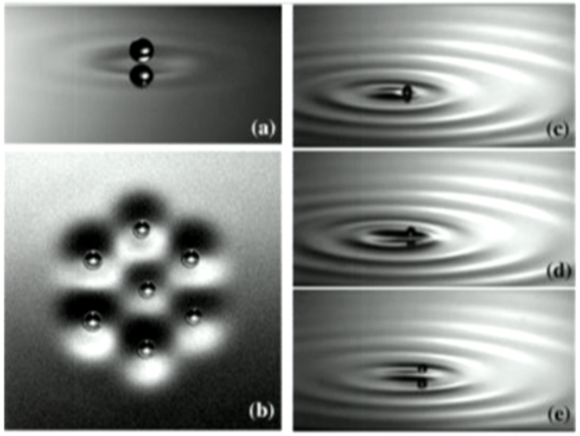
Introduction: background fields in experiments

- **Experiments** **Yves COUDER et al. (Paris)** **(Nature, PRL 2005 – 2013)**



- **Quantum-like behaviour through a 'pilot-wave' = external vibration + stochastic back-reaction of the droplet**
- https://www.youtube.com/watch?v=nmC0ygr08tE

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Introduction: background fields in experiments

PRL **97,** 154101 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

Single-Particle Diffraction and Interference at a Macroscopic Scale

Yves Couder[1,*] and Emmanuel Fort[2,†]

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(Received 13 July 2006; published 13 October 2006)

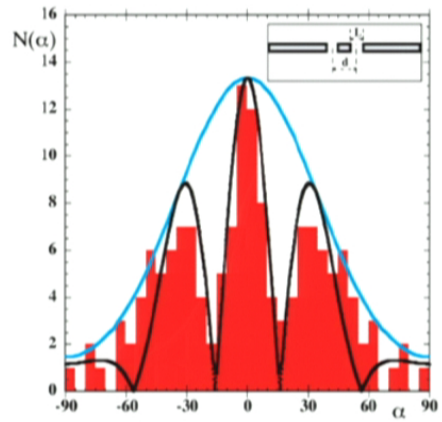

FIG. 3 (color online). Histogram for the deviation of 75 particles through two slits of width $L = 7.6$ mm, a distance $d =$

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Introduction: background fields in recent 'sub-quantum' theories

- **Theories of Nelson, Cetto, De la Pena, Adler, Groessing, Khrennikov, (Bohm).**

Grössing et al.,

Annals of Phys. 2012

arXiv:1106.5994v3 [quan

An explanation of interference effects in the double slit experiment: Classical trajectories plus ballistic diffusion caused by zero-point fluctuations

Gerhard Grössing,* Siegfried Fussy,* Johannes Mesa Pascasio,* and Herbert Schwabl*

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Abstract

A classical explanation of interference effects in the double slit experiment is proposed. We claim that for every single "particle" a thermal context can be defined, which reflects its embedding within boundary conditions as given by the totality of arrangements in an experimental apparatus. To account for this context, we introduce a "path excitation field", which derives from the thermodynamics of the zero-point vacuum and which represents all possible paths a "particle" can take via thermal path fluctuations. The intensity distribution on a screen behind a double slit is calculated, as well as the corresponding trajectories and the probability density current. The trajectories are shown to obey a "no crossing" rule with respect to the central line, i.e., between the two slits and orthogonal to their connecting line. This agrees with the Bohmian interpretation, but appears here without the necessity of invoking the quantum potential.

Keywords: quantum mechanics, ballistic diffusion, nonequilibrium thermodynamics, zero-point fluctuations

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Bell's theorem:

Surprises in Spin-Lattices

L. V., Found. Phys. 2013

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The stochastic version of Bell's theorem

Hypothesis of 'stochastic' hidden-variables:

$\underline{P(\sigma_i \mid \lambda)}$: λ determines the P of σ_i

(instead of $\sigma_i = \sigma_i(\lambda)$: deterministic HV)

$$M(a,b) = \langle \sigma_1 . \sigma_2 \rangle_{a,b} = \Sigma_{\sigma 1} \Sigma_{\sigma 2} \sigma_1 . \sigma_2 . P(\sigma_1, \sigma_2 | a,b).$$

$$X_{BI} = M(a,b) + M(a',b) + M(a,b') - M(a',b') \leq 2$$

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The stochastic version of Bell's theorem

1. **Hypothesis of 'stochastic' hidden-variables:**

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2. **Hypothesis of locality**

3. **Hypothesis of 'measure-ment independence'**

   ('free will' ?)

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

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The stochastic version of Bell's theorem

Jarrett 1984, Clauser-Horne, Bell, Shimony…

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

1. $P(\sigma_1|\sigma_2,a,b,\lambda) = P(\sigma_1|a,b,\lambda)$
   for all $(\lambda,\sigma_1,\sigma_2)$ **(OI)**
2. $P(\sigma_2|a,b,\lambda) = P(\sigma_2|b,\lambda)$
   for all λ and similarly for σ_1 **(PI)**
3. $\rho(\lambda|a,b) = \rho(\lambda|a',b') \equiv \rho(\lambda)$
   for all (λ,a,b) **(MI)**

OI = Outcome Independence
PI = Parameter Independence
MI = Measurement Independence

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The stochastic version of Bell's theorem

- **Note the generality of the theorem: <u>EVERY</u> local physical system (in which one can define HV λ) should satisfy OI, PI, MI and therefore the Bell inequality !**

The stochastic version of Bell's theorem

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- **OI, PI, MI are all conditions of *stochastic independence*.**

- **It is then tempting to investigate whether OI, PI, MI hold in known, *highly-correlated* systems.**

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Spin-lattices

- The Ising-lattice is a typical example of a highly correlated system in which long-range collective phenomena (such as phase transitions) occur (cf. Feynman [1988], Yeomans [1992]).
- It's physics is extraordinarily rich, notwithstanding its simplicity.

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Spin-lattices

- The Ising-lattice is a typical example of a highly correlated system in which long-range collective phenomena (such as phase transitions) occur (cf. Feynman [1988], Yeomans [1992]).
- It's physics is extraordinarily rich, notwithstanding its simplicity.

- Suppose Alice and Bob perform a Bell-type (thought) experiment on an ensemble of spin-lattices as schematized in Fig. 1.

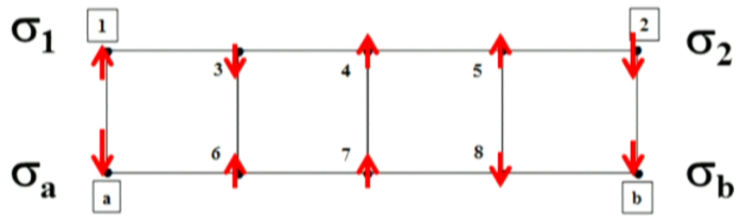

Fig. 1. 10 spins on a lattice

- 10 spins (± 1) $\sigma_1, \sigma_2, \ldots, \sigma_8, \sigma_a, \sigma_b$
- The role of (a,b) is taken by (σ_a, σ_b)
- The role of the HVs λ is taken by $\lambda \equiv (\sigma_3, \sigma_4, \ldots \sigma_8)$ (or any subset of this set)
- This is a 'HV' system in the sense that $P(\sigma_i|\lambda)$, $P(\sigma_1, \sigma_2|\lambda, a, b)$ etc. are defined.

Spin-lattices

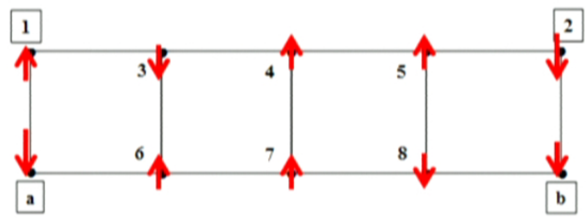

Fig. 1. 10 spins on a lattice

- The system Hamiltonian is the usual Ising Hamiltionian:

$$H(\theta) = -\Sigma_{i,j} J_{ij}.\sigma_i.\sigma_j - \Sigma_i h_i.\sigma_i. \qquad (\text{all } \sigma_i = \pm 1) \qquad (4)$$

- Here θ is a 10-spin configuration ($\sigma_a, \sigma_b, \sigma_1, \ldots \sigma_8$), the h_i are local magnetic fields, and the J_{ij} are the interaction constants, as usual assumed to be zero between non-nearest neighbors. [So: local interaction.]
- Interaction (J_{ij}) is mediated via a Coulomb potential (cf. Feynman [1988]).
- Note that if J_{ij} are positive, then the total energy H in (4) decreases if spin-i and spin-j are aligned, i.e. have the same value. Spins seem to 'feel' whether their neighbors are aligned or not; this leads to collective modes.

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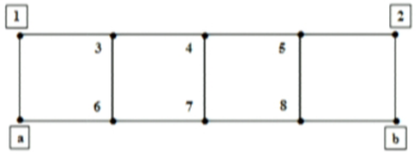
Spin-lattices

- The probability of a given 10-spin configuration (at fixed temperature $1/\beta$) is the usual Boltzmann probability:

$$P(\theta) = e^{-\beta H(\theta)} / Z, \quad \text{with } Z = \Sigma_\theta e^{-\beta H(\theta)}, \text{ the partition function.} \qquad (5)$$



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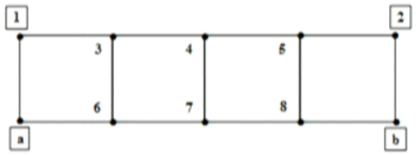

- Suppose Alice and Bob perform a Bell-type experiment on an ensemble of spin-lattices as in Fig. 1. **Suppose Alice can measure the spin (± 1) on nodes 1 and a, and Bob on 2 and b, for each element of the ensemble. They can then empirically determine the 16 joint probabilities** $P(\sigma_1,\sigma_2|\sigma_a,\sigma_b) \equiv P(\sigma_1=\varepsilon_1, \sigma_2=\varepsilon_2 |\sigma_a=\varepsilon_a, \sigma_b=\varepsilon_b)$ (all $\varepsilon_i = \pm 1$) **simply by counting relative frequencies over the ensemble.**

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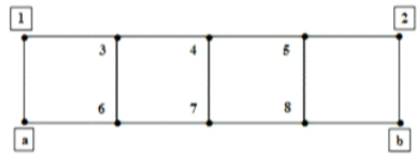

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- These are the only probabilities needed to verify the BI.
- The BI is:

$$X_{BI} = M(a,b) + M(a',b) + M(a,b') - M(a',b') \leq 2, \qquad (6)$$

where

$$M(a,b) = <\sigma_1.\sigma_2>_{a,b} = \Sigma_{\sigma 1}\Sigma_{\sigma 2}\, \sigma_1.\sigma_2.P(\sigma_1,\sigma_2|\sigma_a,\sigma_b). \qquad (\sigma_a = +1 = \sigma_b \quad \sigma_{a'} = -1 = \sigma_{b'}) \qquad (7)$$

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$$P(\sigma_1, \sigma_2 \,|\sigma_a, \sigma_b) = \frac{P(\sigma_1, \sigma_2, \sigma_a, \sigma_b)}{P(\sigma_a, \sigma_b)} \equiv \frac{P(\eta_1)}{P(\eta_2)}, \quad (13)$$

where η_1 is a 4-spin configuration and η_2 a 2-spin configuration. Any probability $P(\eta)$ with η an m-spin configuration ($m \leq 10$) is given by:

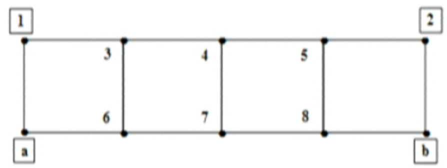
$$P(\eta) = \sum_{\theta(\eta)}^{2^{10-m}} P(\theta), \quad (14)$$

where the sum runs over the 2^{10-m} 10-spin configurations $\theta(\eta)$ that contain η. $P(\theta)$ is the Boltzmann factor in (5), involving the Hamiltonian (4). Thus we find:

$$P(\sigma_1, \sigma_2 \,|\sigma_a, \sigma_b) = \frac{\sum_{\theta(\eta_1)}^{2^6} e^{-\beta H(\theta)}}{\sum_{\theta(\eta_2)}^{2^8} e^{-\beta H(\theta)}} \quad . \quad (15)$$

Spin-lattices

- Using Eq. (4) – (7) one finds that the BI in our thought experiment can be strongly violated, for a wide range of parameter values for β, h_i, J_{ij}.
- For instance for $\beta = 1$, $h_i \,\varepsilon \{-1, 1, 3\}$, $J_{ij} \,\varepsilon \{1, 2, 3, 4\}$ we find that $X_{BI} = 2.87 > 2$ (2.87 is at least a local maximum), to be compared to $2\sqrt{2} \approx 2.83$, the value for the singlet state.



Cf. L.V., Found. Phys. 2013

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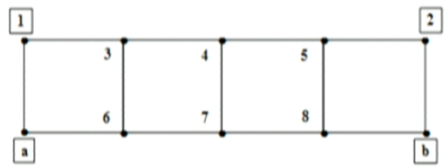

Cf. L.V., Found. Phys. 2013

- The locality of the system is confirmed by the fact that the Clauser-Horne factorability condition (the conjunction of OI and PI) is always satisfied:

$$P(\sigma_1,\sigma_2|a,b,\lambda) = P(\sigma_1|a,\lambda).\,P(\sigma_2|b,\lambda)$$ for all $(\lambda,\sigma_1,\sigma_2,a,b)$ and for any parameter set (β, h_i, J_{ij})

- Same conclusion for a variety of 1-D and 2-D SLs small enough for num. sim.

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Spin-lattices

- **Measures introduced by Michael Hall (Phys. Rev. A; Phys. Rev. Lett. 2010, 2011) to quantify violation of OI, PI, MI:**

Outcome Dependence (OD), Parameter Dependence (PD) and Measurement Dependence (MD):

$$OD = \sup_{(a,b,\lambda)} \sum_{\sigma_1,\sigma_2} | P(\sigma_1,\sigma_2 | a,b,\lambda) - P(\sigma_1 | a,b,\lambda).P(\sigma_2 | a,b,\lambda) | \quad (7)$$

$$PD = \sup_{(a,a',b,\sigma_2,\lambda)} | P(\sigma_2 | a,b,\lambda) - P(\sigma_2 | a',b,\lambda) | \quad (8)$$

$$MD = \sup_{(a,a',b,b')} \int d\lambda. | \rho(\lambda | a,b) - \rho(\lambda | a',b') | . \quad (9)$$

Here $\sup_{(X)}(Y)$ indicates the maximum value of Y when varying the parameters X over all their values.

- **OD = PD =! 0, always**

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Spin-lattices

- If the BI is violated, at least one of the conditions MI, OI, PI does not hold.
- It appears that in all these lattices the 'resource' for violation of the BI is violation of MI, as can again be calculated taking $\lambda \equiv (\sigma_3, \sigma_4, \ldots \sigma_8)$.
- So $\rho(\lambda | \sigma_a, \sigma_b) \neq \rho(\lambda | \sigma_{a'}, \sigma_{b'})$ for ANY value of $(\lambda, \sigma_a, \sigma_b)$
- For the above parameter set MD = 1.99 (its maximum possible value is 2)

$$MD = \sup_{(a,a',b,b')} \int d\lambda . \, | \rho(\lambda | a,b) - \rho(\lambda | a',b') | .$$

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Spin-lattices

- **In this experiment, MI is violated WITHOUT SUPERDETERMINISM OR CONSPIRACY.**

- **MI [$\rho(\lambda|a,b) = \rho(\lambda|a',b')$] is always deemed 'obvious' because of a 'free will' argument:** violating MI means that the HVs λ depend on (a,b), which means by standard rules of probability calculus that the analyzer angles (a,b) depend on the HVs λ. But (a,b) can be freely or randomly chosen in experiments – so how could these angles depend on the HVs λ ? -- variables which moreover determine the probabilities for the left and right outcomes.
- **Ergo, MI must hold, unless one accepts a conspiratorial world.**

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- **Ergo, MI must hold, unless one accepts a conspiratorial world.**

- **But our model shows that is false: the same results obtain in an experiment in which Alice and Bob freely set σ_a and σ_b !**

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- Alice and Bob can do two equivalent experiments (Ex1 and Ex2) to determine the needed probabilities $\underline{P(\sigma_1,\sigma_2|\sigma_a,\sigma_b)}$, exactly as in real Bell experiments.
- Either (Ex1) they 'postselect' 4 sub-ensembles out of one long run, each sub-ensemble corresponding to one of the 4 possible couples of (σ_a, σ_b)-values.
- (Ex2) If they have sufficiently sophisticated technological means to *control* σ_a and σ_b, i.e. set σ_a and σ_b to either +1 or -1 *at their free choice*, they can do 4 consecutive experiments, each corresponding to a fixed value of σ_a and σ_b. The dynamics of the system (Eq. (3) and (4)) remains unchanged in this second experiment. Therefore all probabilities $P(\sigma_1,\sigma_2|\sigma_a,\sigma_b)$ are identical in both experiments.

Spin-lattices

$$P(\sigma_1,\sigma_2 \,|\sigma_a,\sigma_b) = \frac{P(\sigma_1,\sigma_2,\sigma_a,\sigma_b)}{P(\sigma_a,\sigma_b)} \equiv \frac{P(\eta_1)}{P(\eta_2)}, \tag{13}$$

where η_1 is a 4-spin configuration and η_2 a 2-spin configuration. Any probability $P(\eta)$ with η an m-spin configuration ($m \leq 10$) is given by:

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$$P(\sigma_1,\sigma_2 \,|\sigma_a,\sigma_b) = \frac{\sum_{\theta(\eta_1)}^{2^6} e^{-\beta H(\theta)}}{\sum_{\theta(\eta_2)}^{2^8} e^{-\beta H(\theta)}} \,. \tag{15}$$

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Spin-lattices

$$P(\sigma_1,\sigma_2\ |\sigma_a,\sigma_b) = \frac{\sum_{\theta(\eta_1)}^{2^6} e^{-\beta H(\theta)}}{\sum_{\theta(\eta_2)}^{2^8} e^{-\beta H(\theta)}} \quad . \qquad (15)$$

Probabilities (15) can easily be computed by numerical simulation – but we do not even need to do so for our present purpose.

Ex2) A second way to determine the $P(\sigma_1,\sigma_2|\sigma_a,\sigma_b)$ is available to Bob and Alice if they can intervene on σ_a and σ_b. If they have sufficient technological means to control σ_a and σ_b they can do 4 consecutive experiments each corresponding to a given value of σ_a and σ_b. In that case they will find:

$$P^*(\sigma_1,\sigma_2\ |\sigma_a,\sigma_b) = \frac{P^*(\sigma_1,\sigma_2,\sigma_a,\sigma_b)}{P^*(\sigma_a,\sigma_b)} = \frac{P^*(\eta_1)}{1}, \qquad (16)$$

where the asterisk simply reminds us that the probability is determined in an experiment in which σ_a and σ_b have a given value. Now with (5) we have:

$$P^*(\eta_1) = \sum_{\theta(\eta_1)}^{2^6} P^*(\theta) = \sum_{\theta(\eta_1)}^{2^6} \frac{e^{-\beta H(\theta)}}{Z^*}. \qquad (17)$$

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- **So we have here a local physical system, in which MI and the BI are violated, without superdeterminism** (as is actually obvious since the system / experiment is 'physical').

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Spin-lattices

- The most advanced dynamic Bell experiments are Weihs et al. (PRL 1998) or Scheidl et al. PNAS 2010 (Zeilinger group).
- It is well-known that the Ising model can be interpreted as a statistical model for the motion of atoms. "Lattice gas Hamiltonian" + Boltzmann config. probability
- As recalled below, Hamiltonian (3) is the low-order approximation of a Hamiltonian that describes a quite general system of interacting particles – also rapidly moving molecules as in a lattice-gas.

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Spin-lattices

- In short, let us see if we can construct an explicit HV model for the most advanced experiment, namely Scheidl et al, PNAS 2010

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A HV toy model

for dynamic Bell experiments

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The experiment by Scheidl et al., PNAS 2010

- <u>Simultaneously</u> **close various loopholes, essentially the locality and freedom-of-choice loopholes.**
- The authors explain: "The locality loophole arises when Alice's measurement result can in principle be causally influenced by a physical (subluminal or luminal) signal from Bob's measurement event or Bob's choice event, and vice versa. The best available way to close this loophole is to space-like separate every measurement event on one side from both the measurement [outcome independence, OI] and setting choice [setting independence, PI] on the other side."
- **In other words, in this manner OI and PI would be imposed in the experiment.**
- "Experimentally, the freedom-of-choice loophole can only be closed if Alice's and Bob's setting values are chosen by random number generators and also if the transmission of any physical signal between their choice events and the particle pair emission event is excluded, i.e., these events must be space-like separated […]".
- MI: $\rho(\lambda|a,b) = \rho(\lambda|a',b')$

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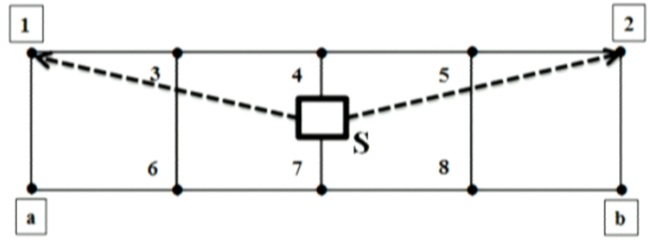
The experiment by Scheidl et al., PNAS 2010

Back-up

- Summarizing, the essential experimental conditions of the experiment in [Scheidl et al. 2010] were the following:
  - E1) The measurement events were spacelike separated (SLS);
  - E2) The left (right) measurement event was SLS from the choice of b (a);
  - E3) The setting choice events were SLS;
  - E4) The emission event and the setting choice events were SLS. ⟵ MI
- **Spacelike separation between relevant events was obtained by fast and random switching of the settings at 1 MHz, and/or by the fact that in some reference frame the events happened simultaneously (SLS is invariant under Lorentz transformation).**

The model in a nut-shell

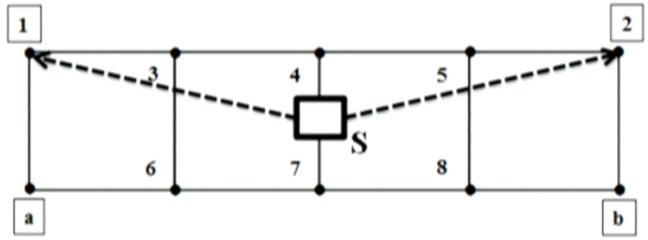


- Bell particles move through a "background gas / medium", spread-out over a lattice
- Bell particles, analyzers AND the "background particles" are ALL described by a
  <u>hidden stochastic property λ</u> $(\lambda_1,\lambda_2,\ldots,\lambda_a,\lambda_b)$ $(\lambda_i=\pm 1)$
- In the model we consider only 10 nodes – it is a toy model !
- All λ interact via a Hamiltonian:

$$H(\lambda_1,\lambda_2,\ldots\lambda_n) = c_0 + \sum_{i=1}^{n} c_{1i}.\lambda_i + \sum_{i,j=1}^{n} c_{2ij}.\lambda_i.\lambda_j + \sum_{i,j,k=1}^{n} c_{3ijk}.\lambda_i.\lambda_j.\lambda_k + \ldots \qquad (10)$$

- The probability for a given configuration $\theta = (\lambda_1,\lambda_2,\ldots\lambda_a,\lambda_b)$: $P(\theta) = e^{-\beta H(\theta)} / Z$.
- I submit this is as a simple description of a "stochastic background medium"

The model in a nut-shell



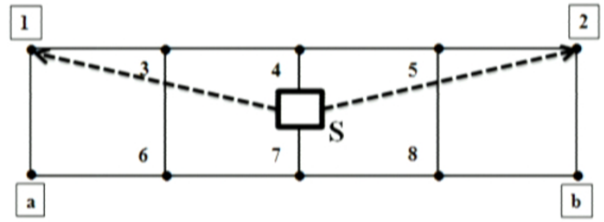
- Bell particles move through a "background gas / medium", spread-out over a lattice
- Bell particles, analyzers AND the "background particles" are ALL described by a <u>hidden stochastic property λ</u> $(\lambda_1,\lambda_2,\ldots,\lambda_a,\lambda_b)$ $(\lambda_i = \pm 1)$
- In the model we consider only 10 nodes – it is a toy model !
- All λ interact via a Hamiltonian:

$$H(\lambda_1,\lambda_2,\ldots\lambda_n) = c_0 + \sum_{i=1}^{n} c_{1i}.\lambda_i + \sum_{i,j=1}^{n} c_{2ij}.\lambda_i.\lambda_j + \sum_{i,j,k=1}^{n} c_{3ijk}.\lambda_i.\lambda_j.\lambda_k + \ldots \qquad (10)$$

- The probability for a given configuration $\theta = (\lambda_1,\lambda_2,\ldots\lambda_a,\lambda_b)$: $P(\theta) = e^{-\beta H(\theta)} / Z$.
- I submit this is as a simple description of a "stochastic background medium"

The experiment by Scheidl et al., PNAS 2010

Slightly idealized scheme (symmetric)**:**



$t = 0$: emission
$t = t_0$: measurement

Fig. 2. Idealized scheme of the Bell experiment.

Particles 1 and 2 leave a source S and are measured (at time t_0) when arriving at points 1 and 2.

- **The two particles leave a source S at a speed close enough to the speed of light, following the dashed trajectories in Fig. 2.**
- **A&B measure the spins σ_1 and σ_2 at time t_0, the moment the particles arrive at nodes 1 and 2, which are close to nodes a resp. b.**
- **Alice's and Bob's number generators randomly chose between (a,a') and (b,b') with a frequency of 1 MHz.**
- **Then we have the 4 conditions of SLS E1)-E4) of Ref. [PNAS], as one easily verifies.**

A hidden-variable model for the PNAS experiment.

- **H1)** **The essential hypothesis is that the Bell particles and analyzers interact with a '<u>background λ-field' or 'background medium'</u> (particles) characterized by HVs λ. For definiteness, we will suppose that the particles are lead-out on a 2D lattice.**

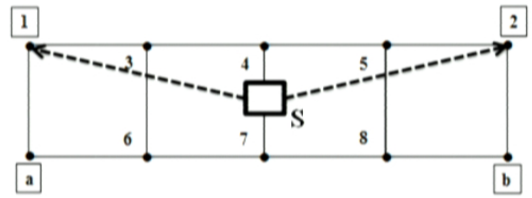


Fig. 2. Idealized scheme of the Bell experiment.

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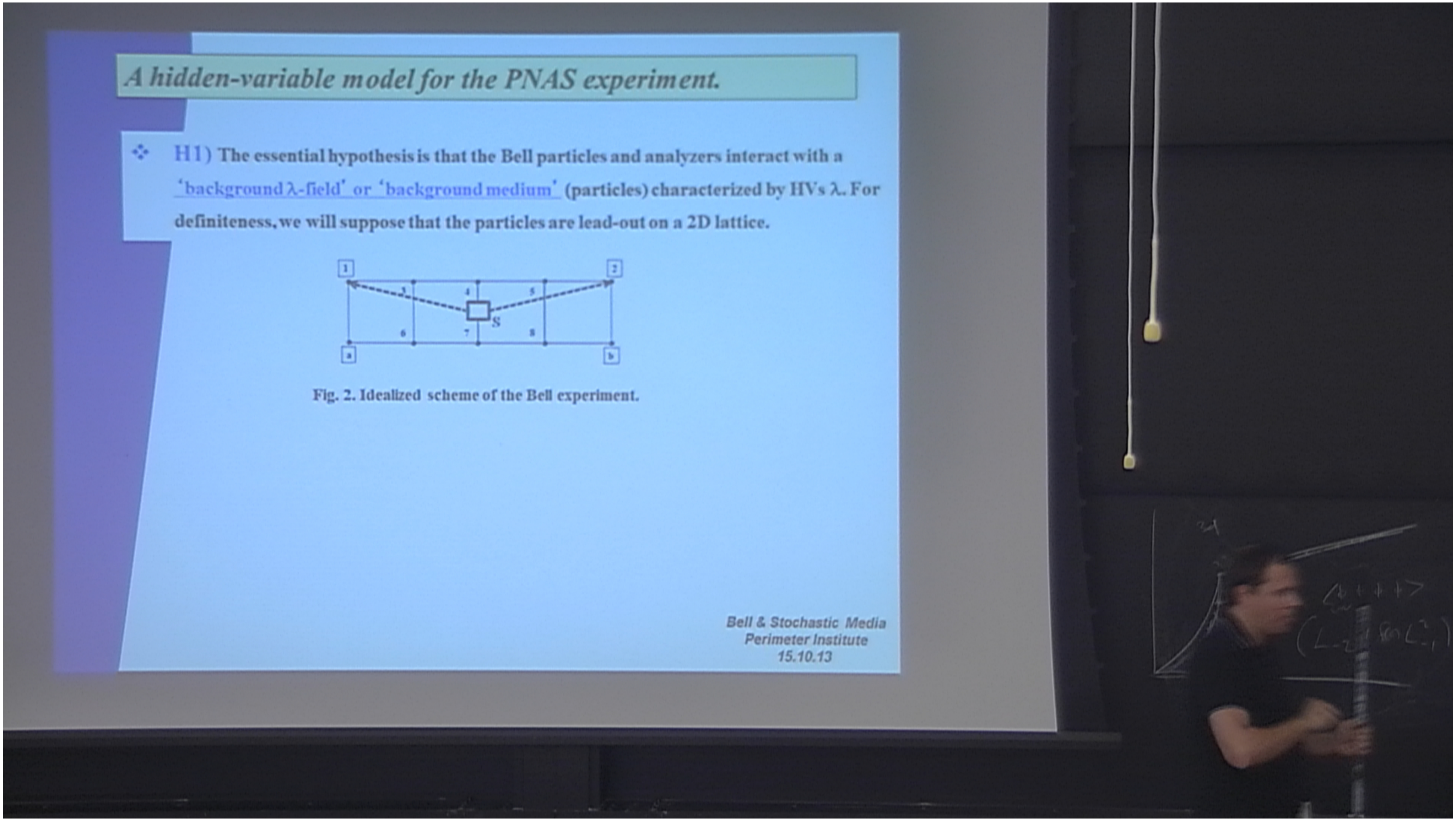
A hidden-variable model for the PNAS experiment.
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1
2
3
4
5
S
6
7
8
a
b
Fig. 2. Idealized scheme of the Bell experiment.
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A hidden-variable model for the PNAS experiment.

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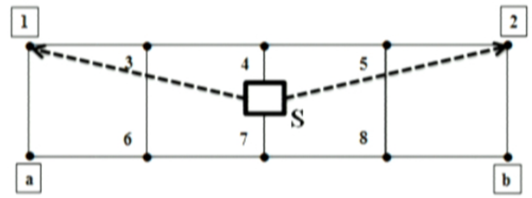

Fig. 2. Idealized scheme of the Bell experiment.

- **More specifically, suppose that at nodes 3, 4,…8 of the lattice sit particles that are characterized by $\lambda_3, \lambda_4, \ldots \lambda_8$. The λ_i are stochastic parameters; assume, again to simplify the calculation, that all λ_i can only take two values (± 1) (one could call the λ_i 'generalized spins').**

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A HV Toy Model.

- **H2)**

  Particles 1 and 2 $\leftrightarrow$ σ_1 and σ_2 *and* HVs λ_1 and λ_2; $\sigma_{1(2)} = \lambda_{1(2)}$

  Analyzers $\leftrightarrow$ a and b *and* HVs λ_a and λ_b; $\lambda_{a(b)} = a(b)$

  So $\underline{P(\sigma_1,\sigma_2|a,b) = P(\lambda_1,\lambda_2|\lambda_a,\lambda_b)}$.

- We also assume the convention that a and b only take the values ±1, which is enough for verifying the BI. All λ_i only take values ±1.

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- We also assume the convention that a and b only take the values ± 1, which is enough for verifying the BI. All λ_i only take values ± 1.

- **H3) DET All λ_i (i = a,b,1,…,8) interact, via a Hamiltonian to be specified, with close (say 1st and 2nd) neighbors only. When the Bell-particles move through the lattice, they interact with the background medium and the analyzers. The Hamiltonian of this potentially highly complex system will in general not only depend on the generalized 'spin' degrees of freedom (DOFs) $\lambda_1, \lambda_2, \ldots \lambda_a, \lambda_b$, but also on other DOFs, e.g. the velocities of particles 1 and 2. <u>All the latter DOFs are supposed to be *deterministic*</u>; only the 'spin' DOF are stochastic (much as in Ising systems). This implies…**

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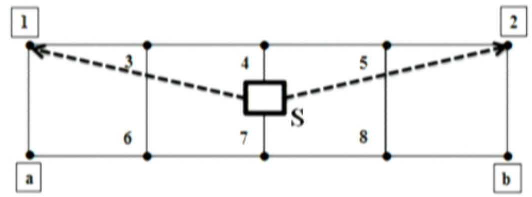
A Hidden-Variable Model.

- **H4)** **The ensemble probability for a configuration $\theta \equiv (\lambda_1, \lambda_2, \ldots, \lambda_a, \lambda_b)$ is the Boltzmann probability, ubiquitous in statistical physics:**

$$P(\theta) = e^{-\beta H(\theta)} / Z. \qquad (9)$$



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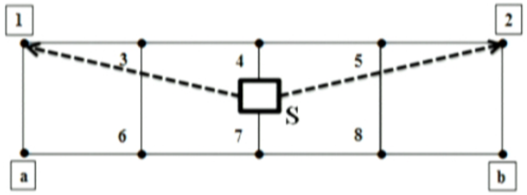

- **We have chosen the assumptions so as to drastically simplify the description of the potentially complex interactions that may occur in the system.**
- ***Even without making hyp. H1)-H4)*, a general Hamiltonian of n 'spin' DOFs $H(\lambda_1, \lambda_2, \ldots \lambda_n)$ can be written as a Taylor expansion as follows:**

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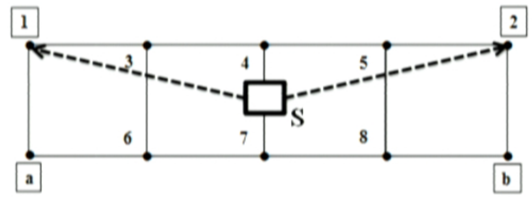

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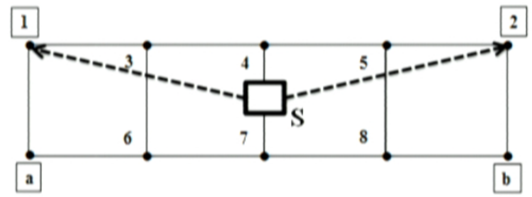

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The factors $c_{p.}$ (p > 1) are the <u>interaction parameters (cf. Ising or lattice-gas Hamiltonian)</u>. We take $c_{p.} = 0$ for interaction beyond say 2nd neighbours, as one always does (cf. H3)).

A Hidden-Variable Model.

- **We do not need a more detailed form of the H. To calculate $P(\sigma_1,\sigma_2|a,b)$ at t_0 via (9), we need the energy $H_{t0}(\lambda_1,\lambda_2,\ldots\lambda_n)$ for each element of the ensemble. As said, the Hamiltonian will in general depend on other-than-spin DOFs, but these are absorbed in the spin-independent factors ($c_{p.}$) of (10). But by assumption H3) DET, in particular at t_0 these factors have identical values for the whole ensemble. We thus end up with a standard Ising-type problem, except that the Hamiltonian includes higher-order terms; the $c_{p.}$ are parameters of the model.**
- **Put differently: I need H3) DET, in order to be able to calculate $P(\theta) = P(H(\theta)) = e^{-\beta H(\theta)} / Z$.**

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- **Put differently: I need H3) DET, in order to be able to calculate $P(\theta) = P(H(\theta)) = e^{-\beta H(\theta)} / Z$.**
- **Z is the sum of terms $e^{-\beta H(\theta)}$ over all energy states in the ensemble (taken at t_0). This sum is "Ising-like" if all the parameters in $H(\theta)$ are constant over the ensemble (at t_0). Only then Z is a sum of terms that only differ in their θ. That the parameters in $H(\theta)$ are constant over the ensemble is guaranteed by H3) DET.**

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A Hidden-Variable Model.

- The 16 probabilities needed to test the BI, i.e. $P(\sigma_1,\sigma_2|a,b)$ taken at t_0, can be calculated in the same manner as for Ising systems. Recall that by assumption H2) $P(\sigma_1,\sigma_2|a,b)$ is equal to $P(\lambda_1,\lambda_2|\lambda_a,\lambda_b) \equiv P(\lambda_1,\lambda_2|\lambda_a,\lambda_b)$, which follows in a straightforward manner from (9) and (10). Indeed, any probability $P(\eta)$ with η an m- 'spin' configuration ($m \leq 10$), so a subset of $(\lambda_a,\lambda_b,\ldots\lambda_8)$ is calculated by:

$$P(\eta) = \sum_{\theta(\eta)}^{2^{10-m}} P(\theta)$$

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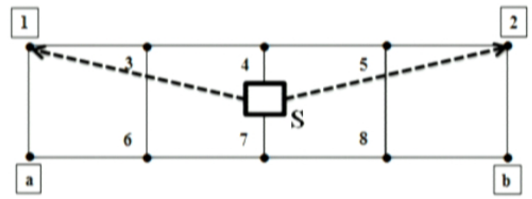
A Hidden-Variable Model.

Result of numerical simulations:

- By taking terms until 4th order in (10) into account we find that the BI is again violated for wide ranges of all the constants in (10).
- Importantly, the resource is again measurement dependence (MD), i.e. violation of MI. For instance, taking the $c_{p.}$-constants ($p \leq 2$) equal to those before and all $c_{3.} = 0.1$ and all $c_{4.} = 0.3$, we find BI = 2.82 and MD = 1.99.



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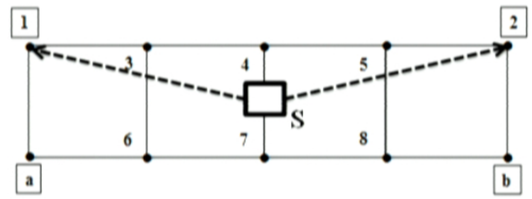

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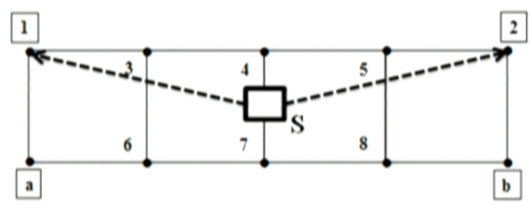

- At the same time we find that OI and PI are always valid: the system is local in the sense of Clauser-Horne (as expected).

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A Hidden-Variable Model.

- It is essential to note that MI is violated in this type of models without relying on superdeterminism or conspiracy.
- In above model Alice and Bob freely choose (a,b). Measurement dependence can arise through ordinary (Coulomb) interaction, even if a and b are perfectly freely chosen.
- It is almost always assumed that violation of MI contradicts 'free will' in a reasonable, non-superdeterministic world. MD would mean that the 'freely or randomly chosen' parameters (a,b) are *causally determined* by the HV λ. However, the above calculations prove that this is a false conclusion: *there can be stochastic dependence without causal determination*.

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- Think e.g. of $P(x|T)$ with x = half-life of a nucleus, T = temperature. $P(T|x) \neq P(T)$.

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A Hidden-Variable Model.

- So we have here a toy model for real Bell experiments, that violates the BI and is local and non-conspiratorial.
- The resource is violation of MI.

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A Hidden-Variable Model.

- So we have here a toy model for real Bell experiments, that violates the BI and is local and non-conspiratorial.
- The resource is violation of MI.
- The model seems not to violate principles of physics, but it is still a toy model:
  - It does not predict the cosine of the quantum correlation
  - The more physical model would have n (# lattice nodes) → ∞
- I submit the present results as a first step of a wider program.
- Intermediate conclusion: MI is not a generally valid condition in all local systems, at least not in all "background-based" systems.

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A realistic 'sub-quantum' theory ?

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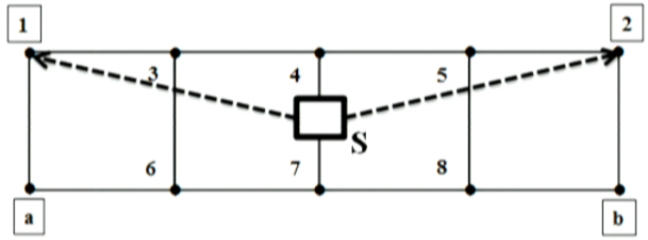
The model in a nut-shell



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- The probability for a given configuration $\theta = (\lambda_1,\lambda_2,...\lambda_a,\lambda_b)$: $P(\theta) = e^{-\beta H(\theta)} / Z$.

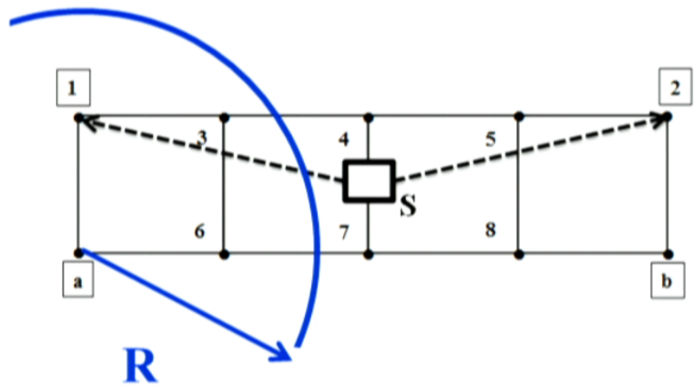
That supposes:

- **All SLs in the ensemble are in thermal equilibrium with a heat bath at 1/β.** [relax]
- **<u>There is causal contact between nearest neighbours</u>** **(cf. lattice-gas Hamiltonian)**

Generalisation

- **In order to have causal contact between NN, it is essential for the model that the switching frequency of the analyzers is not much higher than the 1 MHz used in [Scheidl et al. 2010]….** Else ‘a’ (b) has no contact with NN.

f_s =1 MHz, τ = 1 μs, R = 300 m



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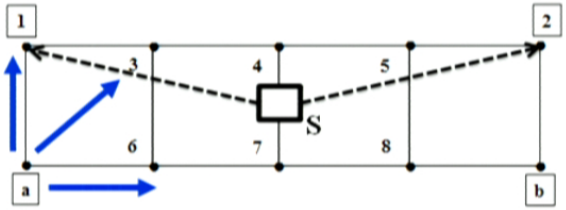
Generalisation



- In the model the interactions between the analyzers and their environment, e.g. between λ_a and λ_6, are mediated by a (possibly hidden) force potential. The switching should therefore be slow enough so that causal contact *with neighbors* can be established.
- In [Scheidl et al. 2010] the settings remained constant for **a duration of the order of 1μs**, which corresponds to a causal range **R = 300 m.** Therefore, if the 1st neighbors of nodes a and b, i.e. nodes 6 and 8, are positioned closer than **R**, $\lambda_a(\lambda_b)$ and $\lambda_6(\lambda_8)$ are time-like separated. Also between all other near-neighbor nodes there is some causal contact at t_0; (8) can then be applied, just as in a lattice gas.
- **This point is crucial, since it shows that MI can be violated in 'background-based' models *independently of the form of the Hamiltonian*.**

Generalisation.

- **Indeed, if the HVs (λ_6, λ_8) can have interacted at t_0 with λ_a and λ_b, then in general we have that**

$$P(\lambda_6, \lambda_8|\lambda_a,\lambda_b) \neq P(\lambda_6, \lambda_8|\lambda_{a'},\lambda_{b'}),$$

$$\text{so} \quad P(\lambda_3, \lambda_4,\ldots, \lambda_8|\lambda_a,\lambda_b) \neq P(\lambda_3, \lambda_4,\ldots, \lambda_8|\lambda_{a'},\lambda_{b'}),$$

$$\text{so} \quad P(\lambda_3, \lambda_4,\ldots, \lambda_8|a,b) \neq P(\lambda_3, \lambda_4,\ldots, \lambda_8|a',b'),$$ because of assumption H2).

- **But that means that MI can be violated for a general 'background-based' HVT that includes these variables (λ_6, λ_8) [in general HVs 'near the analyzers']** ***independently of the form of the Hamiltonian.***

- In a field vocabulary, it's even more evident. The analyzers may first interact with 'something' in their neighborhood (say a λ-field, or λ-medium) which then interacts in turn with the Bell particles. The first interaction can create a correlation between the analyzer settings and the field-values in their vicinity, from which our conclusion follows.

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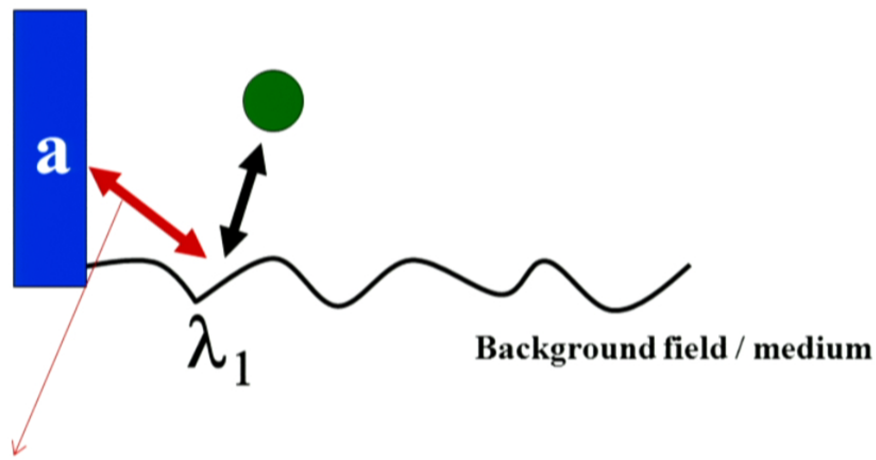
A Hidden-Variable Model.

❖ **It appears that MI can be violated in a background-based HVT largely independently of the form of the Hamiltonian.**



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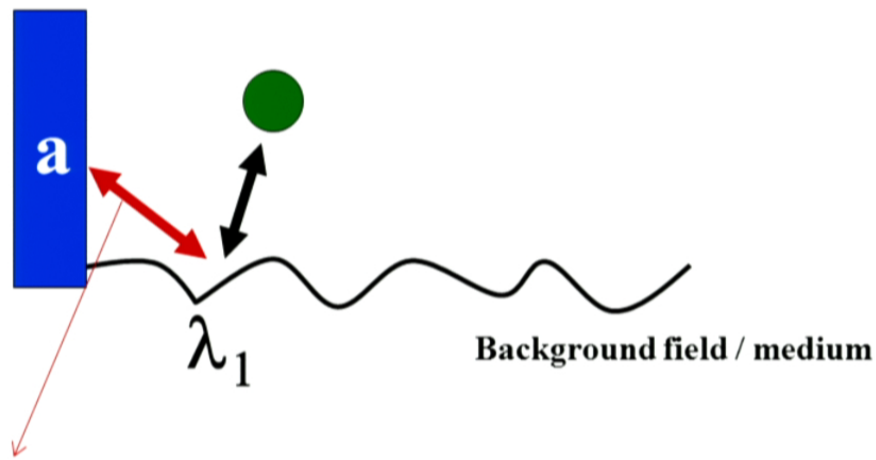

$$\rho(\lambda_1,\lambda_2|\mathbf{a},\mathbf{b}) \neq \rho(\lambda_1,\lambda_2|\mathbf{a'},\mathbf{b'})$$ **(quite independently of Hamiltonian)**

Such a mechanism has been conjectured by J. Butterfield [1992]

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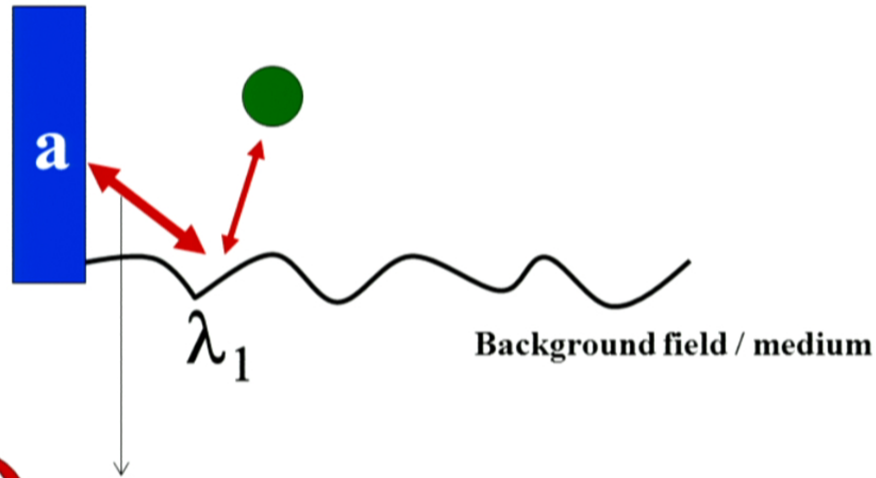

$$\rho(\lambda_1,\lambda_2|\mathbf{a},\mathbf{b}) \neq \rho(\lambda_1,\lambda_2|\mathbf{a}',\mathbf{b}')$$ **(independently of Hamiltonian)**

❖ **In sum:** ***an experiment as [Scheidl et al.] may separate left and right wings, but not the analyzers from their nearby environment.***

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Generalisation.

- Link with recently developed 'sub-quantum' theories that aim at explaining certain aspects of quantum mechanics ?
- These theories are all based on a <u>stochastic 'zero-point field' or 'vacuum field'</u> (see e.g. De la Peña and Cetto [1996], Khrennikov [2011], Grössing [2012] and refs. therein).
- In these models quantum particles as electrons etc. interact with a background field, adopting as a consequence a Brownian motion from which the quantum statistics is assumed to arise.

- Conjecture: the model based on H1)-H4) is a simple version of such stochastic background-based models.

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Upgrading the model (research outline).

- For the model to predict the correct quantum correlations for the singlet state (cosine), I conjecture that it will also have to violate OI, not only MI.
- The left and right spins (σ_1 and σ_2) are *connected through the conservation of total spin in the singlet state*.
- Such a symmetry may, it seems, very well correlate the two spins even at the time of measurement, and even if the spins weakly interact with a background medium.
- OI: $P(\sigma_1|\sigma_2,a,b,\lambda) = P(\sigma_1|a,b,\lambda)$ for all $(\lambda,\sigma_1,\sigma_2)$

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Upgrading the model (research outline).

- For the model to predict the correct quantum correlations for the singlet state (cosine), I conjecture that it will also have to violate OI, not only MI.
- The left and right spins (σ_1 and σ_2) are *connected through the conservation of total spin in the singlet state*.
- Such a symmetry may, it seems, very well correlate the two spins even at the time of measurement, and even if the spins weakly interact with a background medium.
- OI: $P(\sigma_1|\sigma_2,a,b,\lambda) = P(\sigma_1|a,b,\lambda)$ for all $(\lambda,\sigma_1,\sigma_2)$
- It has already explicitly been argued that in such a system with a conservation law OI is a very questionable condition (cf. van Fraassen [1982], p. 26) – it is actually counterintuitive.

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Upgrading the model (research outline).

- Including this symmetry into the model is next step.
- Once this is shown to be possible, the next step is to investigate the limit of the number of lattice sites n → ∞, which is physically the most convincing configuration.
- Let us note that simultaneous violation of MI and OI results in a cumulative resource for violating the BI, as proven in (Hall [2011]).

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Testing the model & background-based theories.

- **Suppose there is a "background". If the polarization direction in a Bell experiment is switched rapidly enough in the time interval (0, t_0), one expects that a λ-field or medium *will at most experience a smeared-out or averaged influence from the analyzer settings*.**

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- In other words $\rho(\lambda)$ may depend on (a,a',b,b') but not just on (a,b). ***But that is equivalent to MI***: the same distribution for λ applies to the 4 subensembles for (a,b); **the BI can again be derived**. Cf. Bell.

- Such a decoupling of the analyzers from their environment can be simulated in our model by letting the interaction constants $c_{p.}$ $(p \geq 2)$ between $\lambda_a(\lambda_b)$ and its neighbors tend to zero (which indeed corresponds to giving an averaged value $(1\text{-}1)/2 = 0$ to λ_a and λ_b).

$$c_{pa.} \rightarrow \varepsilon.\, c_{pa.} \quad ; \quad c_{pb.} \rightarrow \varepsilon.\, c_{pb.}$$

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Testing the model.

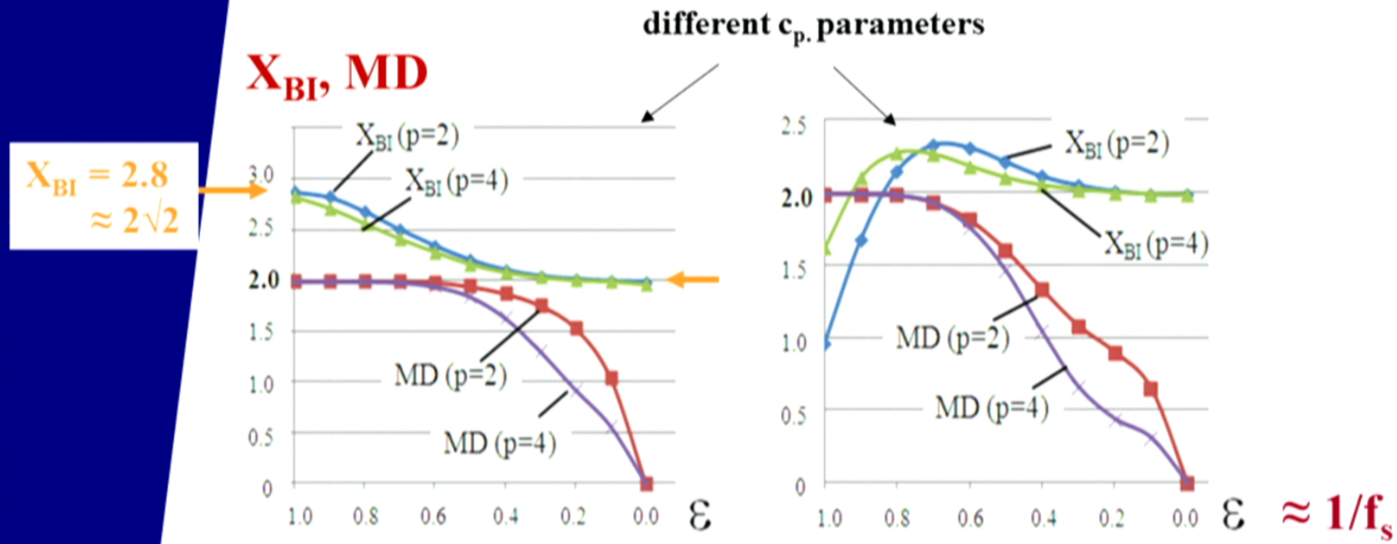

Fig. 3a (left). X_{BI} and MD as a function of the coupling constant ε, for 2nd (p=2) and 4th (p=4) order approximation. For p = 2, the $c_{p,}$-constants are those of footnote 1, except that $J_{a1} = 2.\varepsilon$ ($=J_{b2}$) and $J_{a6} = 3.\varepsilon$ ($=J_{b8}$). For p = 4, idem plus all $c_{3,} = 0.1$, $c_{4,} = 0.3$, again multiplied by ε if involving a or b.

Fig. 3b. Idem as Fig. 3a, except that the J_{ij} ($\equiv c_{2,}$) constants are now $J_{a1}=3$, $J_{a6}=J_{36}=J_{67}=2$, $J_{13}=J_{34}=1$, $J_{47}=0.5$.

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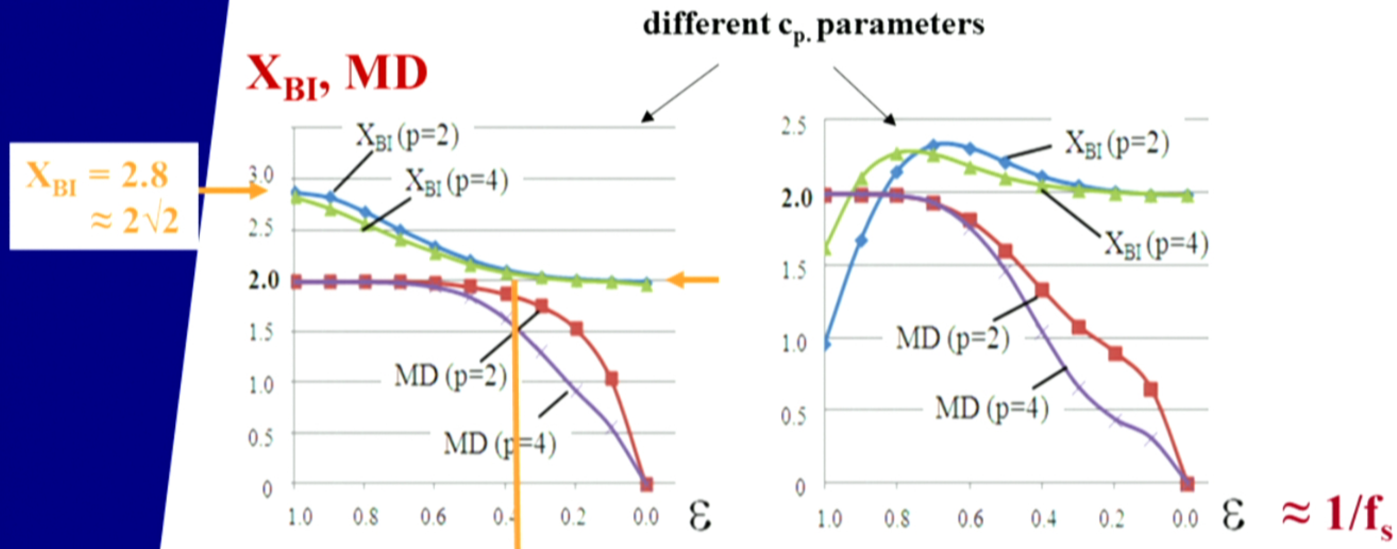

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Fig. 3b. Idem as Fig. 3a, except that the J_{ij} (≡ c_2) constants are now $J_{a1}=3$, $J_{a6}=J_{36}=J_{67}=2$, $J_{13}=J_{34}=1$, $J_{47}=0.5$.

- If one assumes that the coupling breaks down when the causal range R becomes of the order of L(polarizer), say 10 cm, one finds a decoupling frequency of the order of a few GHz, to be compared to 1 MHz.
- This is close to being realisable (G. Weihs).

Conclusion

- We presented a toy model that is local, non-superdeterministic and that violates the BI.
- The resource is violation of MI.
- The model seems not to contradict physical principles; it allows an interpretation in terms of a background medium.
- Assuming a background medium / field, MI can be violated beyond the specific assumptions of the toy model.

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- Under this semantic shift, MI appears an unreasonable premise of the BI…
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- There is thus an incentive to construct realistic background-based models (reproducing the cosine).
- These could be tested by experiments that are a straightforward extrapolation of existing experiments.

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