EPR-B Correlations Demystisized

A. F. Kracklauer

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Clauser-Aspect type EPR-B experiments.

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The source is assumed to emit a double signal for which individual signal components are anticorrelated and, because of the fixed orientation of the excitation source, confined to the vertical and horizontal polarization modes; i.e.

$$\begin{aligned} S_1 &= (cos(n\tfrac{\pi}{2}), sin(n\tfrac{\pi}{2})) \\ S_2 &= (sin(n\tfrac{\pi}{2}), -cos(n\tfrac{\pi}{2})) \end{aligned} \quad , \tag{1}$$

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The transition matrix for a polarizer is given by,

$$P(\theta) = \begin{bmatrix} \cos^2(\theta) & \cos(\theta)\sin(\theta) \\ \sin(\theta)\cos(\theta) & \sin^2(\theta) \end{bmatrix}, \tag{2}$$

so the fields entering the photodetectors are given by:

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Coincidence detections among N photodetectors (here $N = 2$) are proportional to the single time, multiple location second order cross correlation, i.e.:

$$P(r_1, r_2, ..r_N) = \frac{< \prod_{n=1}^{N} E^*(r_n,t) \prod_{n=N}^{1} E(r_n,t) >}{\prod_{n=1}^{N} < E_n^* E_n >}. \tag{4}$$

It is shown in Coherence theory that the numerator of Eq. (4) reduces to the trace of $\mathbf{J}$, the system coherence or “polarization” tensor. It is easy to show that for this model the denominator consists of constants equal to 1.

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The final result of the above is:

$$P(\theta_1, \theta_2) = \frac{1}{2}\sin^2(\theta_1 - \theta_2). \tag{5}$$

This is immediately recognized as the so-called ‘quantum’ result. (Of course, it is also Malus’ Law, thereby being in total accord with our premise.)

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GHZ type experiments:

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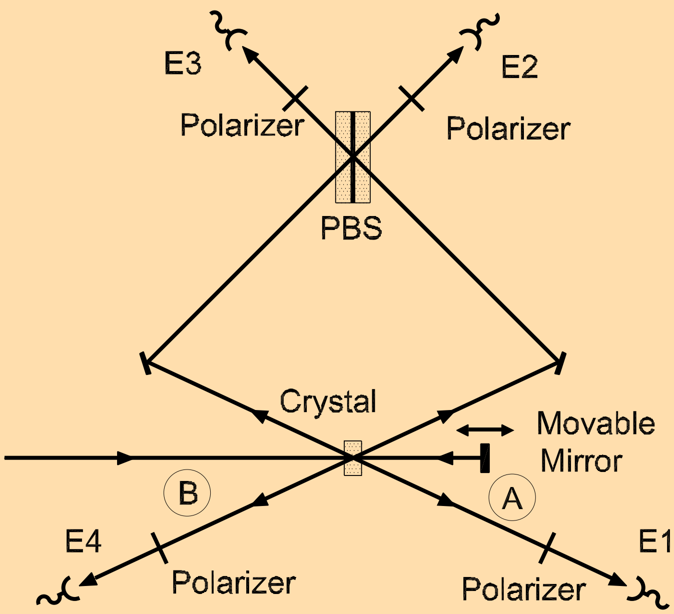
Consider recent four-fold GHZ experiment by PAN et al.:



Eq. (4) was implemented as follows: The crystal is assumed to emit a double signal for which individual signal components are anticorrelated and confined to the vertical and horizontal polarization modes; i.e.

$$\begin{aligned} A_1 = &\quad (cos(n\tfrac{\pi}{2}), sin(n\tfrac{\pi}{2})) \\ A_2 = &\quad (sin(n\tfrac{\pi}{2}), -cos(n\tfrac{\pi}{2}) \\ A_3 = &\quad (sin(m\tfrac{\pi}{2}), -cos(m\tfrac{\pi}{2})) \\ A_4 = &\quad (cos(m\tfrac{\pi}{2}), sin(m\tfrac{\pi}{2})) \end{aligned} \tag{6}$$

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The polarizing beam splitter (PBS) is modeled using the transition matrix for a polarizer, $P(\theta)$, Eq. (4) where $\theta = \pi/2$ accounts for a reflection and $\theta = 0$ a transmission. Thus the final field impinging on each of the four detectors is:

$$\begin{aligned} E_1 = &\quad P(\theta_1)A_1 \\ E_2 = &\quad P(\theta_2)(P(0)B_2 - P(\pi/2)A_3) \\ E_3 = &\quad P(\theta_3)(P(0)B_3 - P(\pi/2)A_2) \\ E_4 = &\quad P(\theta_4)B_4 \end{aligned} \tag{7}$$

which, using Eq. (4), does not result in a simple expression; but numerically:

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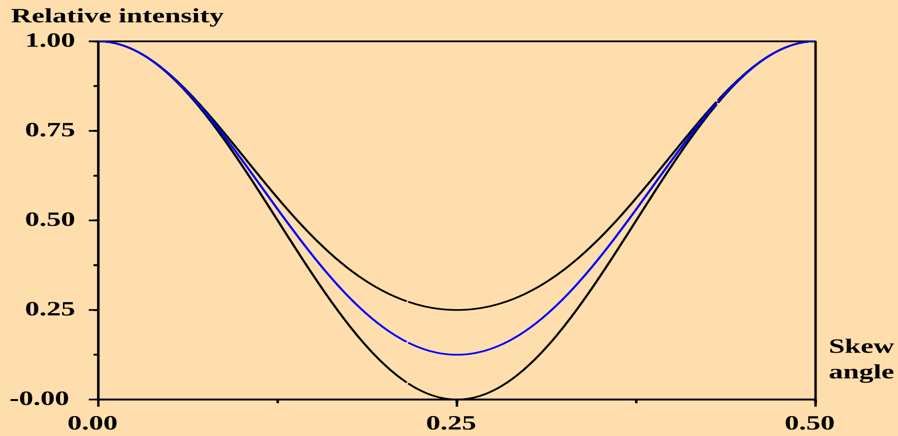
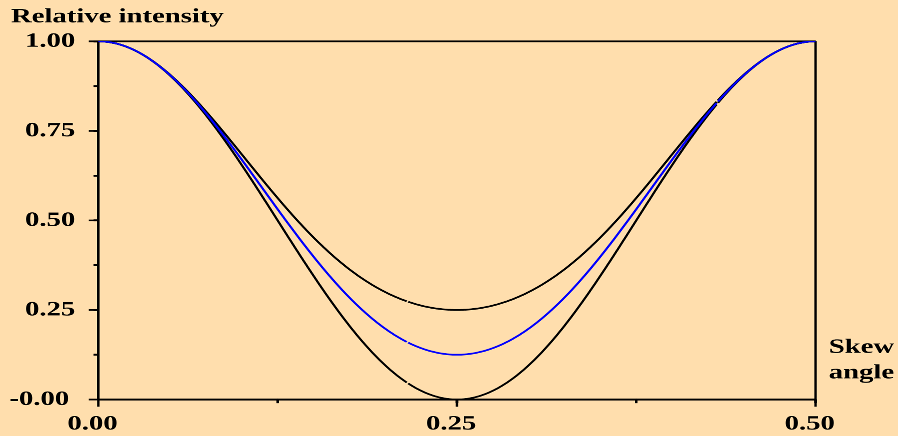


The principle results reported by PAN et al.: Of the 16 possible regimes setting: $\theta_i = \{0, \pi/2\}$ only $\{0, \pi/2, \pi/2, 0\}$ and $\{\pi/2, 0, 0, \pi/2\}$yield a four-fold coincidence count, C; the regime $\{\pi/4, \pi/4, \pi/4, \pi/4\}$ occurs with an intensity $C/4$ and the regime $\{\pi/4, \pi/4, \pi/4, -\pi/4\}$with zero intensity. Further, both of the later regimes yield an intensity of $C/8$ when the time between pair creation is so large that that there is no "cross-talk" between channels 2 and 3. Our model mimics everything.



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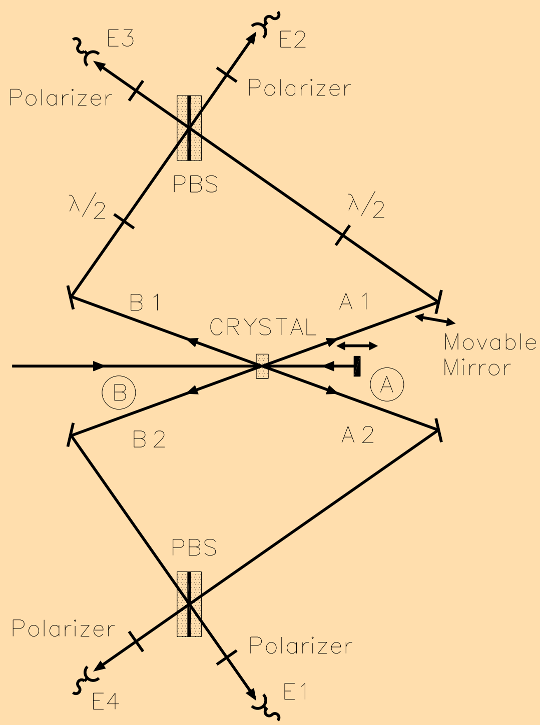
A more recent experiment to demonstrate "entanglement purification"



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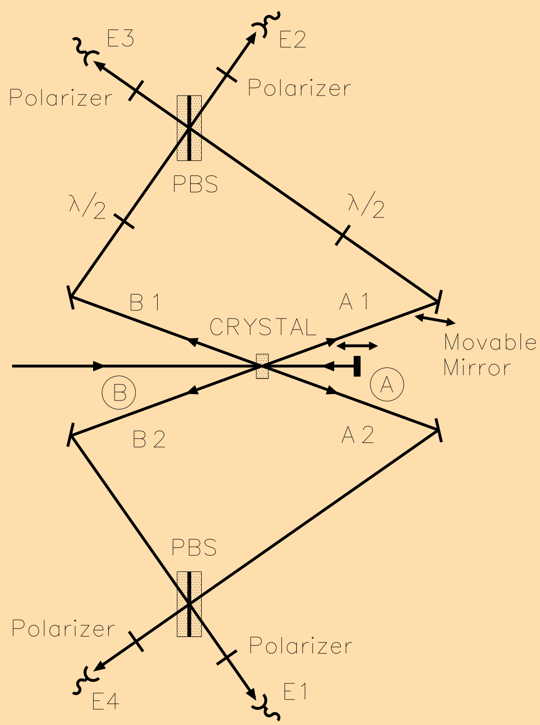
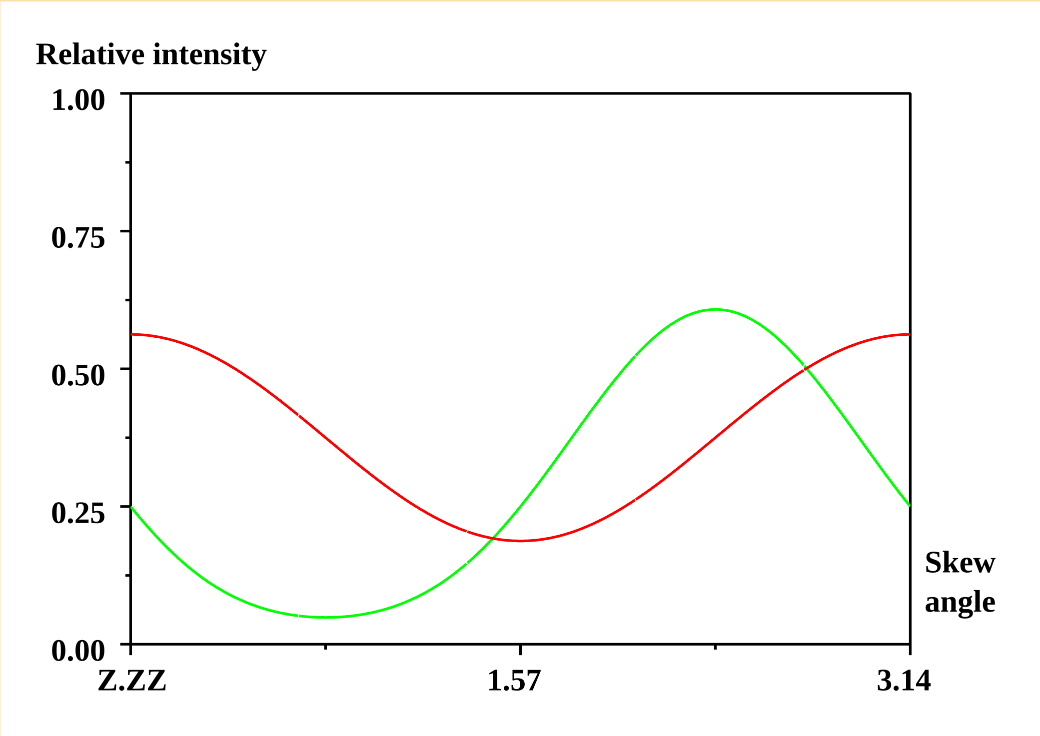


Results of a *classical* calculation of four-fold coincidences. The upper curve, without PBS's, on the left is "prepurified;" the fact that the visibility of the other curve with PBS's is higher is said to exhibit "entanglement purification." Irrespective of terminology, the phenomenon is *nonquantum:* Malus' Law or geometry.



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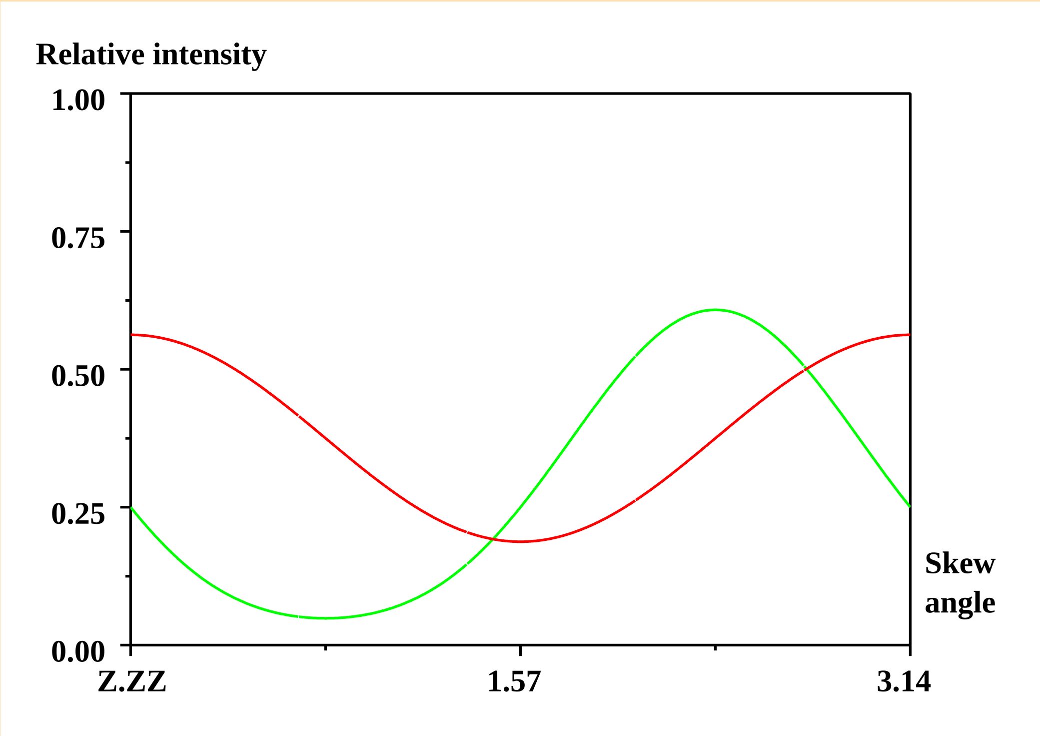
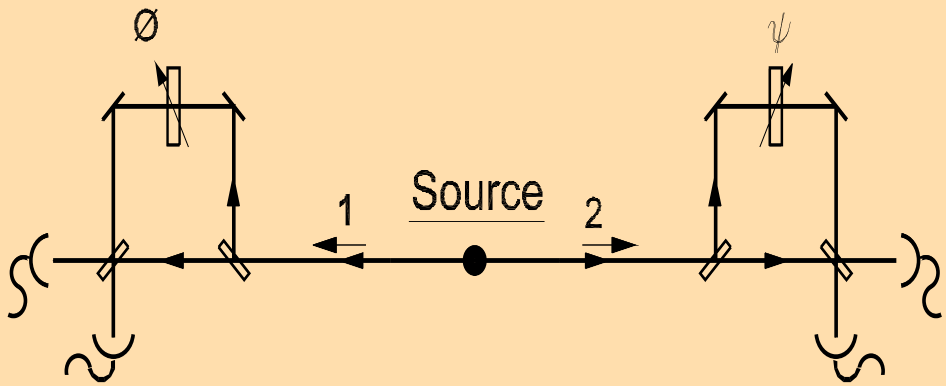


Franson-type experiments

These experiments exploit time-delays between pulses to define the orthogonal states played by the two states of polarization in the setups described above.See Fig. below.



To model them, a simple tactic is to assign the signals in the long and short paths to orthogonal dimensions of a vector space; the resulting calculations are transparent and devoid of irrelevant, gratuitous complexity. For example:

$$\begin{aligned} E_r &= (\exp(-i(kx-\omega t)+\phi), \exp(-i(kx-\omega t))/\sqrt{2} \\ E_l &= (\exp(-i(kx-\omega t)+\varphi), \exp(-i(kx-\omega t))/\sqrt{2} \end{aligned} , \quad (8)$$

where ϕ and φ are the extra phase shifts introduced in the long paths. Then, using Eq. (4), with the convention that the tensor product in be replaced by a vector inner product; i.e.,

$$P(\phi, \varphi) = \frac{(E_r^* \cdot E_l^*)(E_l \cdot E_r)}{(E_r^* \cdot E_r)(E_l^* \cdot E_l)}, \quad (9)$$

(to algebraically enforce the orthogonality in calculations that time-delay enforces in the experiment) quickly gives the observed correlation as a function of the phase shifts:

$$P(\phi, \varphi) \propto 1 + \cos(\phi - \varphi), \tag{10}$$

which exhibits the oscillation with 100% visibility characteristic of idealized versions of these experiments.

Brendel type experiments

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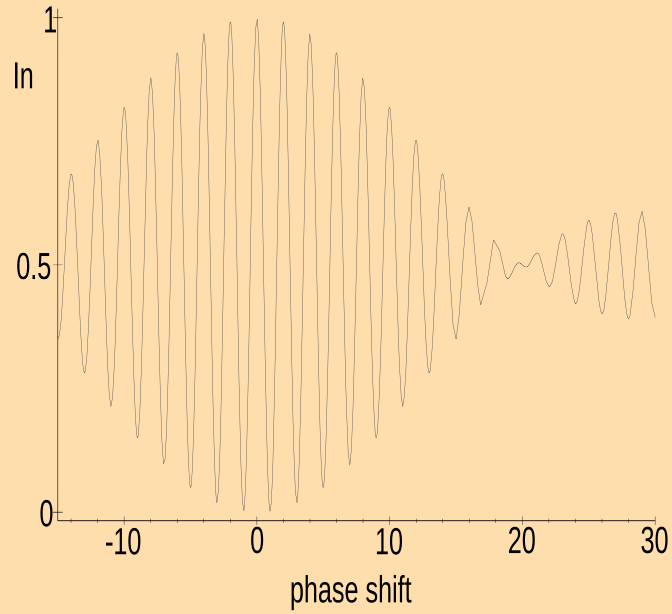
In the above experiment the radiation source was taken to be ideal, that is, it produced two signals of exactly the same frequency with no dispersion. In some experiments, the source used was a nonlinear crystal generating two correlated but not necessarily identical pulses, which satisfy ‘phase matching conditions’ so that if one signal in frequency is above the mean by s (spread), the other is down in frequency by the same amount. This leads to an additional phase difference at the detectors which is also proportional to those already there; i.e., $s\varphi$ and $s\phi$, so that:

$$\begin{aligned} E_r &= (\exp(-i(kx-\omega t)+\phi(1+s)), \exp(-i(kx-\omega t)) \\ E_l &= (\exp(-i(kx-\omega t)+\varphi(1-s)), \exp(-i(kx-\omega t)) \end{aligned} . \tag{11}$$

Since the value of s is different for each pulse (photon) pair, the resulting signal is an average over the relevant values of s:

$$\frac{1}{2s}\int_{-s}^{s} P(\phi, \varphi, s)\,ds, \tag{12}$$

where $P(\phi, \varphi, s)$ was computed as for ‘Franson’ experiments. The final result closely matches that observed by Brendel et al. See following fig.



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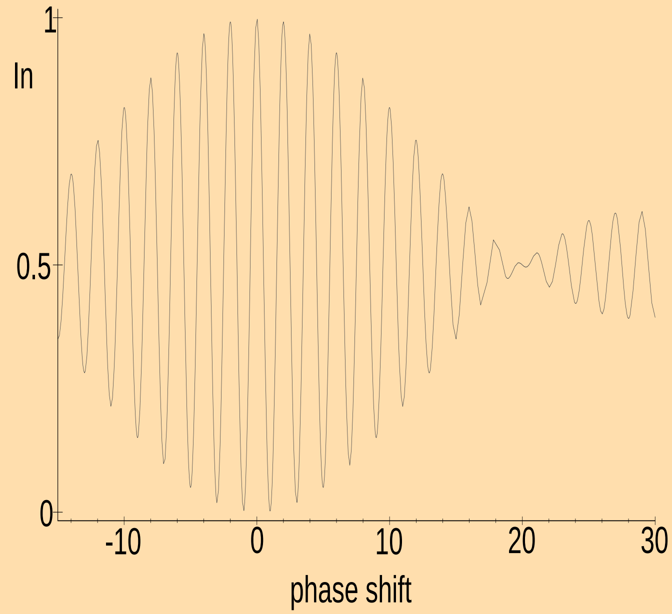
phase shift



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Suarez-Gisin type experiments

In experiments of this type one of the detectors is set in motion relative to the other. By doing so with appropriately chosen parameters, it is possible to arrange the situation such that each detector precedes the other in its own frame. Thus, not only is the ‘collapse’ of the wave packet “nonlocal,” it occurs such that there is also “retrocausality.” In the model proposed herein, however, this complication (paradox) can not arise in the first instance. All the properties of each pulse are determined completely at the common point at which the signals are generated. Properties measure at one detector in no way determine those at the other detector, regardless of the order in which an observer receives reports of the results from the two detectors, or regardless of what conditional probabilities he might write to describe the state of his hypothetical or real knowledge as determined by the time order of his receipt of information from the detectors.

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Is 'entanglement' always entangled?

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Abstract
Entanglement, including 'quantum entanglement', is a consequence of correlation between objects. When the objects are subunits of pairs which in turn are members of an ensemble described by a wavefunction, a correlation among the subunits induces the mysterious properties of 'cat-states'. However, correlation between subsystems can be present in purely non-quantum sources, thereby entailing no unfathomable behaviour. Such entanglement arises whenever the so-called 'qubit space' is not afflicted with Heisenberg uncertainty. It turns out that all optical experimental realizations of the Einstein, Podolsky and Rosen (EPR) Gedanken experiment in fact do not suffer Heisenberg uncertainty. Examples will be analysed and non-quantum models for some of these described. The consequences for experiments that were to test EPRs contention in the form of Bell's theorem are drawn: valid tests of EPR's hypothesis have yet to be done.

Keywords: Entanglement, non-locality, EPR correlations, Bell's theorem, quantum mechanics

1. Introduction

The above title needs 'disentangling'. The quantum

Now, in QM, according to the Born interpretation, the modulus squared of a wavefunction, i.e. $\psi^*(x)\psi(x)$, is the probability that the object to which it pertains will be found

Local-realistic simulation of “Bell” (EPR-B) experiment.

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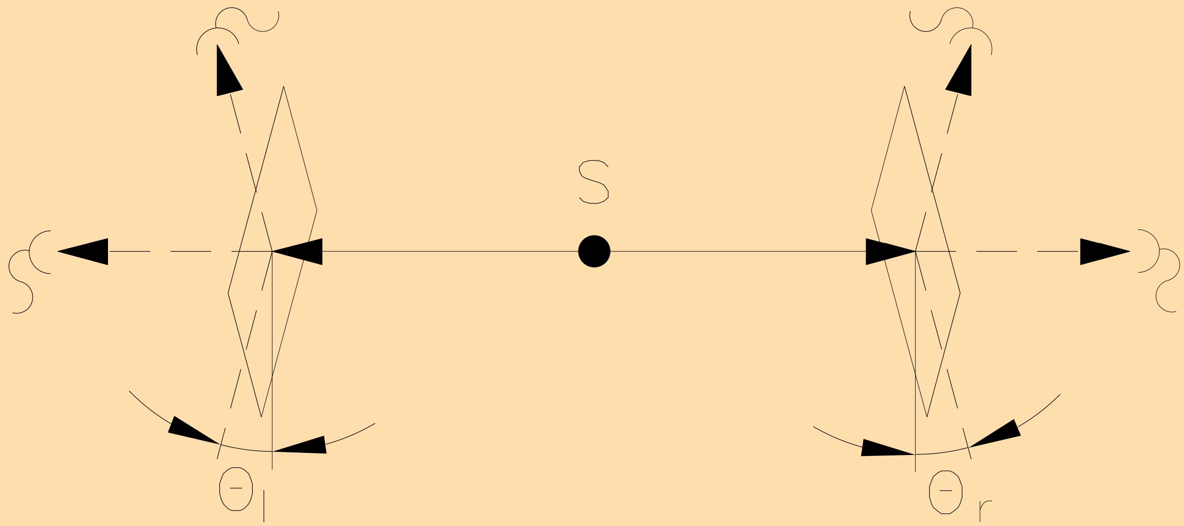

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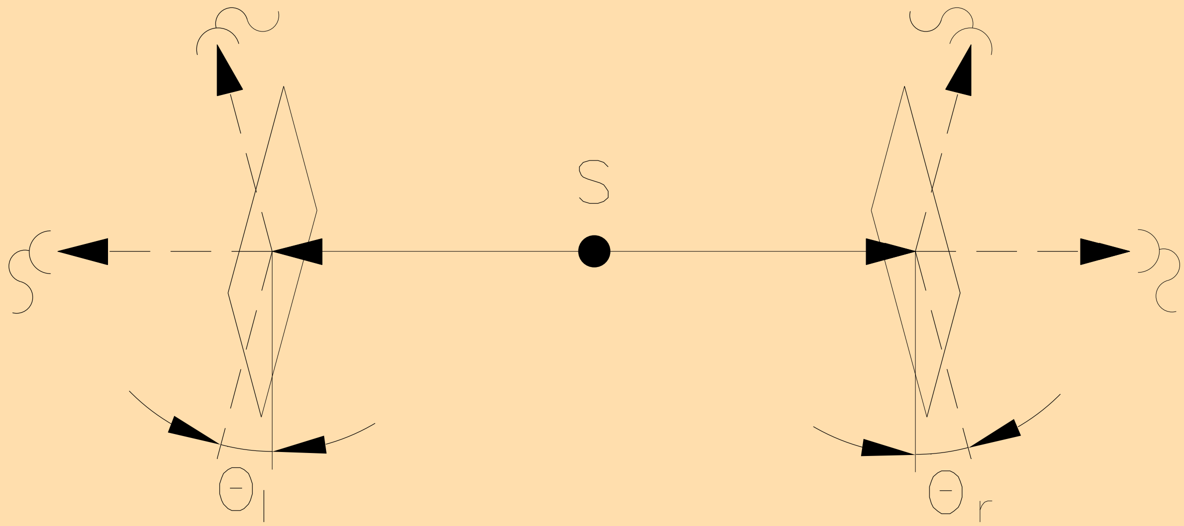

- Source: two randomly selected pairs of classical pulses: vertical::horizontal

or visa versa.

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- Measurement stations: polarizing beams splitters feeding two each photodetectors.

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- Data collection & analysis: “coincidence circuitry:” also per Malus’ Law get relative intensity:

$$\kappa^* = \cos^2(\theta_r - \theta_l) - \sin^2(\theta_r - \theta_l), \tag{13}$$

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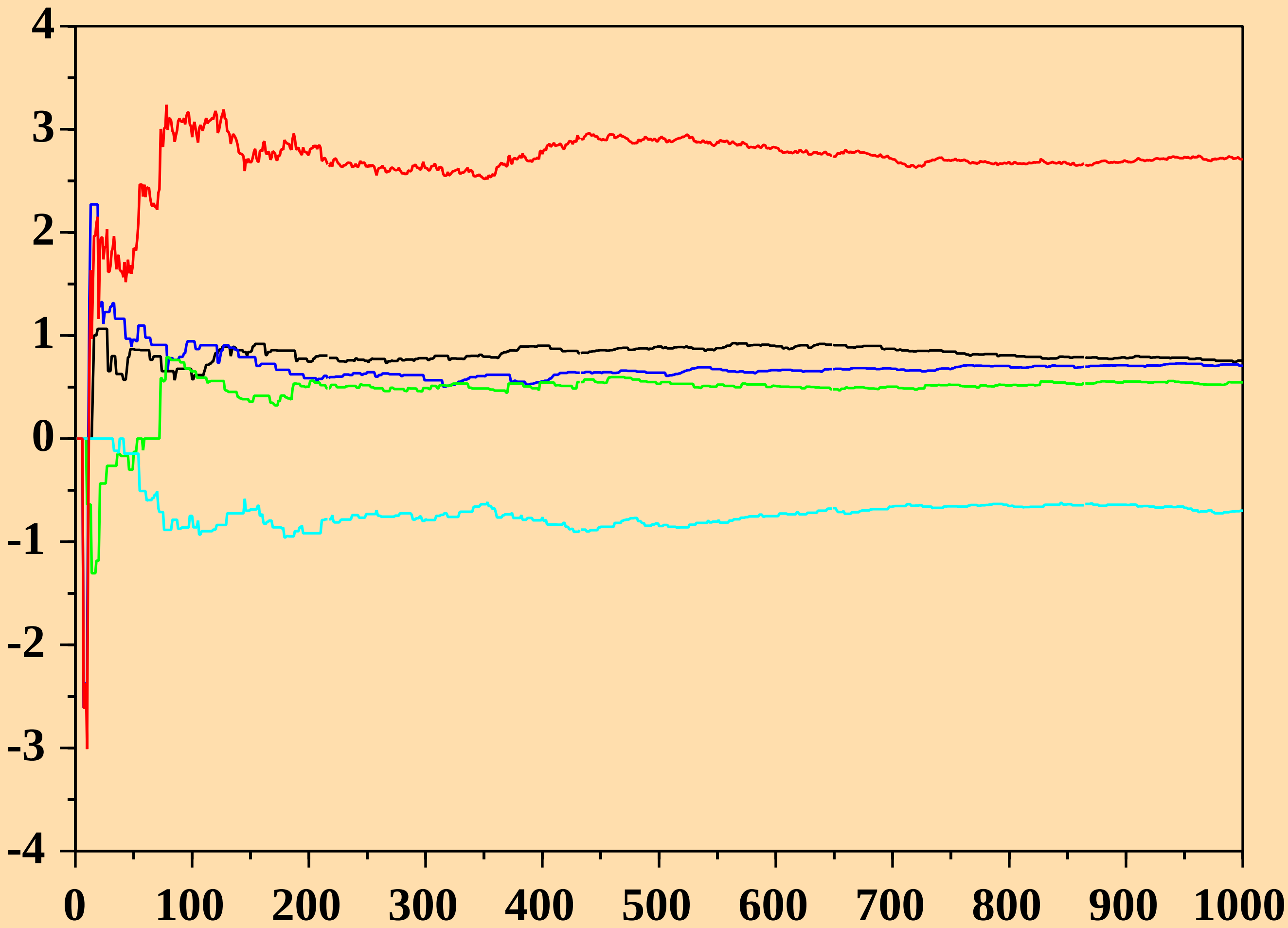
- Expand with:

$$\begin{aligned} \cos(\theta_r - \theta_l) &= \cos(\theta_r)\cos(\theta_l) + \sin(\theta_r)\sin(\theta_l), \\ \sin(\theta_r - \theta_l) &= \sin(\theta_r)\cos(\theta_l) - \cos(\theta_r)\sin(\theta_l); \end{aligned} \tag{14}$$

- Get values of individual terms from Malus' Law:

$$\begin{aligned}\cos(\theta_l) &= \sqrt{N_{hl}/N},\\ \sin(\theta_l) &= \sqrt{N_{vl}/N}.\end{aligned}$$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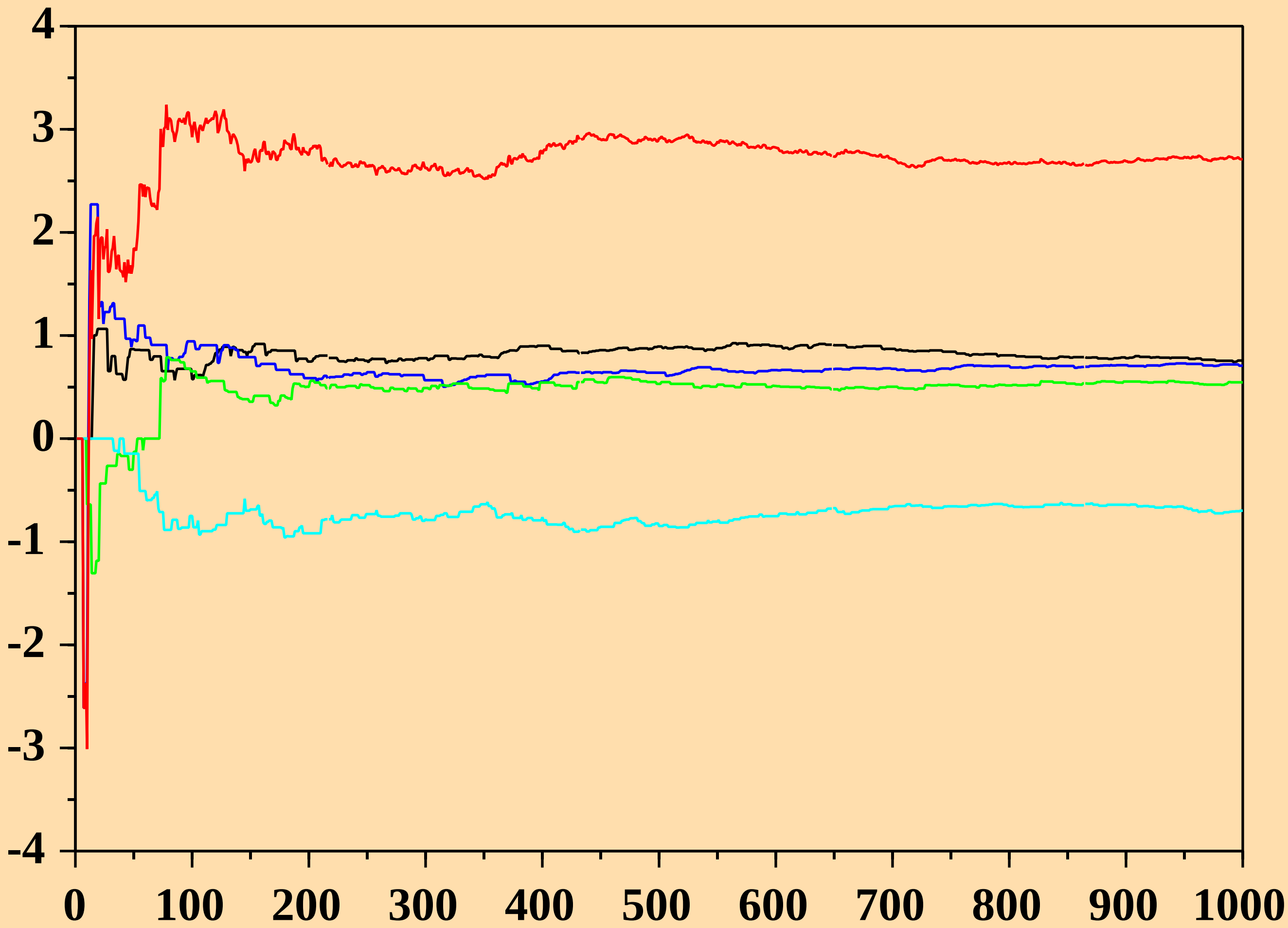

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EPR-B correlations: quantum mechanics, or just geometry?

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Abstract
Based on the observation that polarization phenomena of EM waves are geometric rather than quantum mechanical in nature, it is argued that experiments involving 'entangled polarization' do not address the issues brought up by EPR. A fully classical explanation is offered for a recent experiment of this type, and a fully classical (local and realistic) photoelectron-by-photoelectron simulation is described of ordinary two-fold experiments thought to prove Bell's 'theorem'.

Keywords: polarization entanglement, Bell's theorem, GHZ correlations, quantum mechanics, non-locality

(Some figures in this article are in colour only in the electronic version)

1. Background facts

Any object can be viewed from various angles. When such changes in view-point are restricted to the surface of a sphere

of the wavevector. It is easy to see that this noncommutativity is not due to anything except the rotation on the sphere, *as passed along*. In mathematics all this structure too is codified, in terms of the group $SU(2)$. From these considerations it is absolutely

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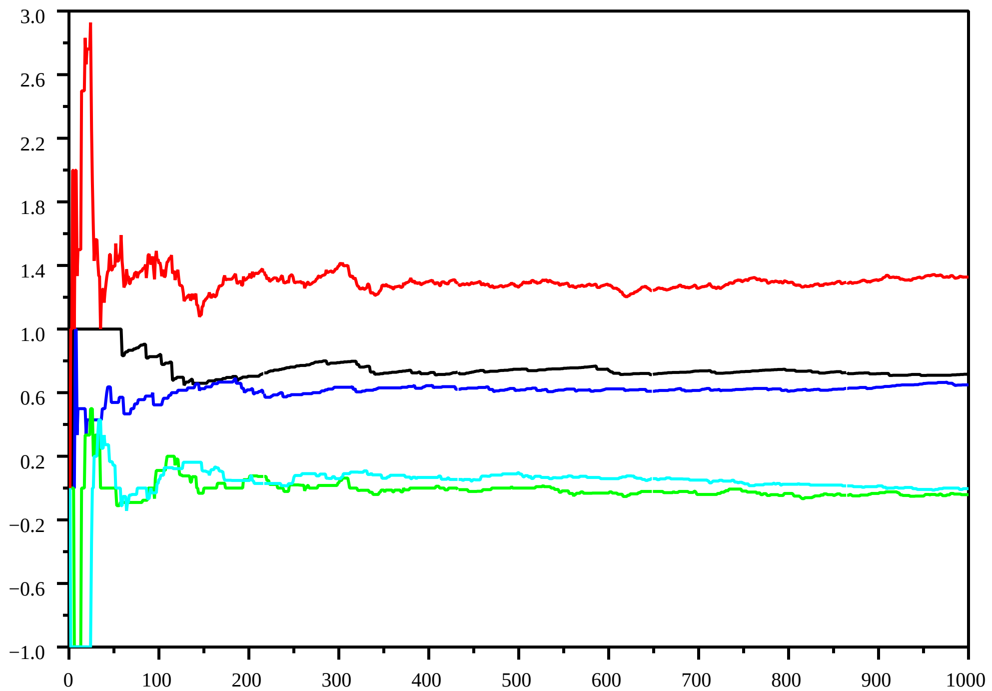

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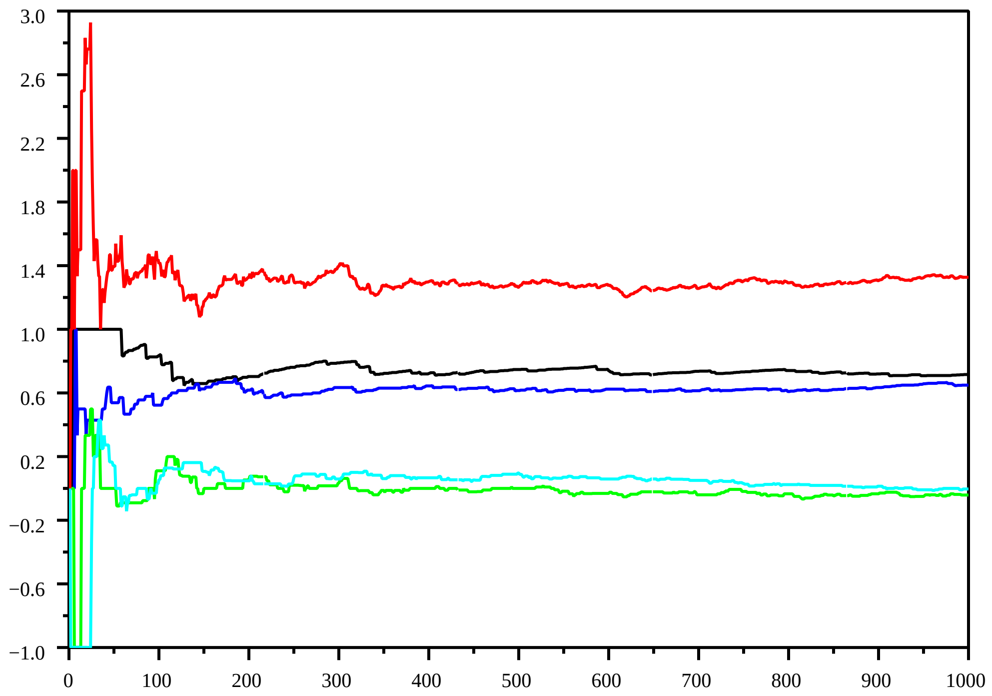
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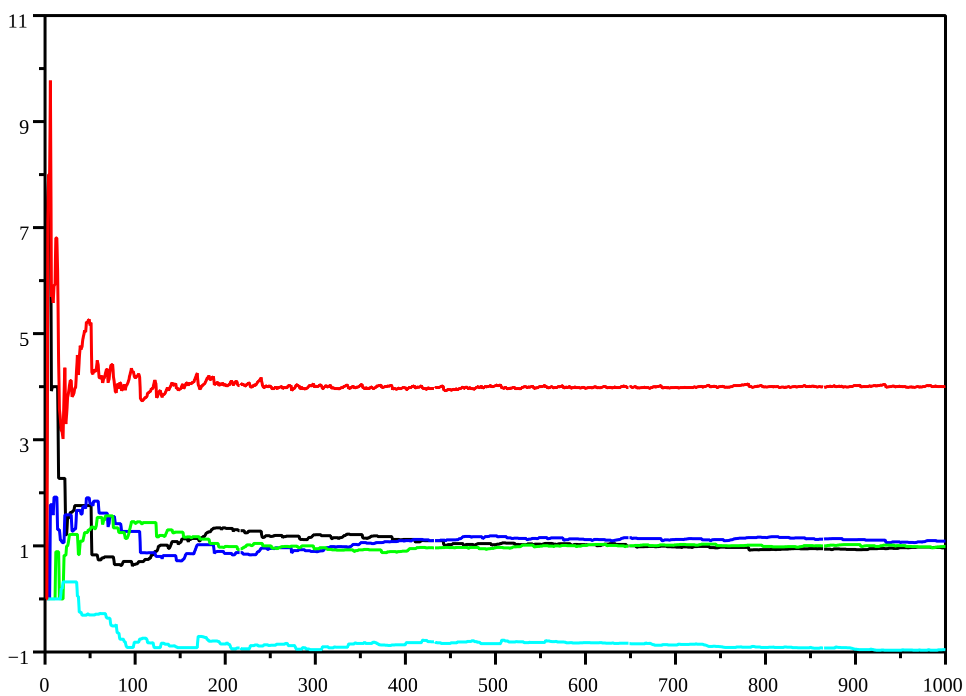
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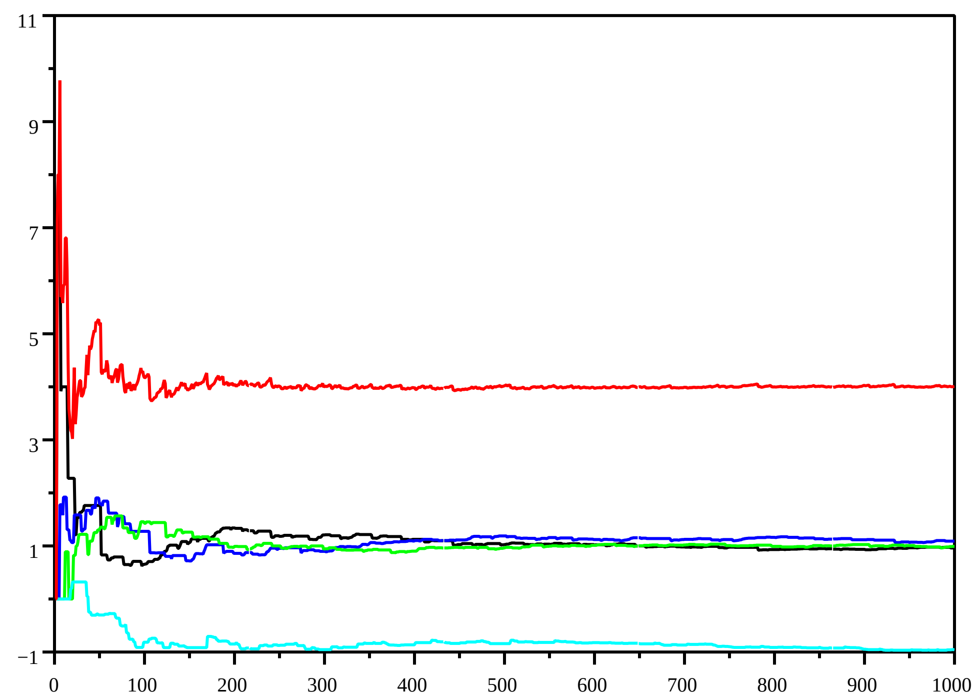

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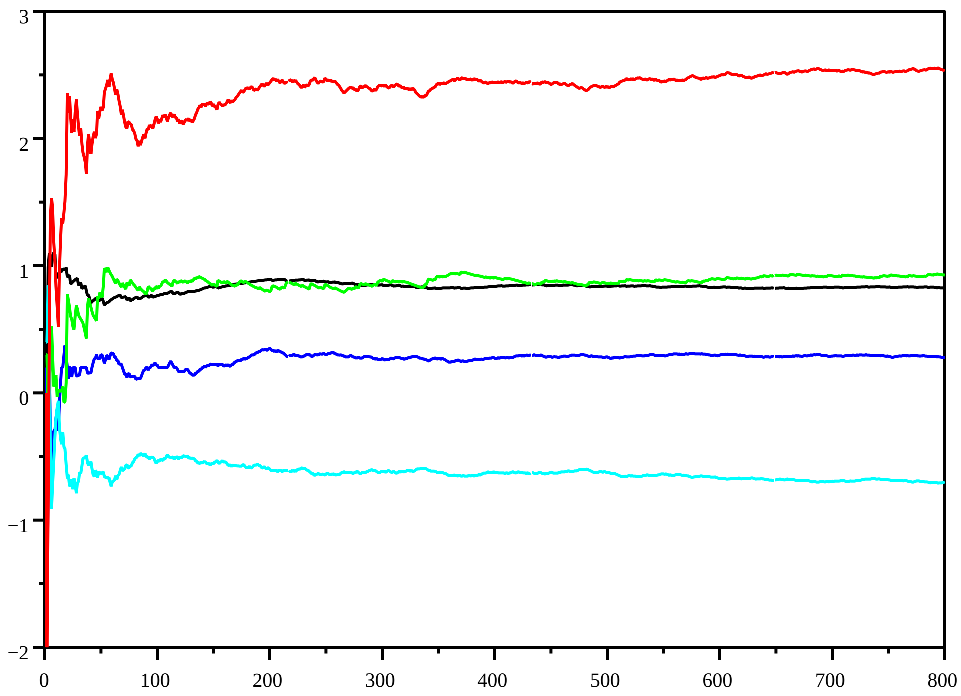

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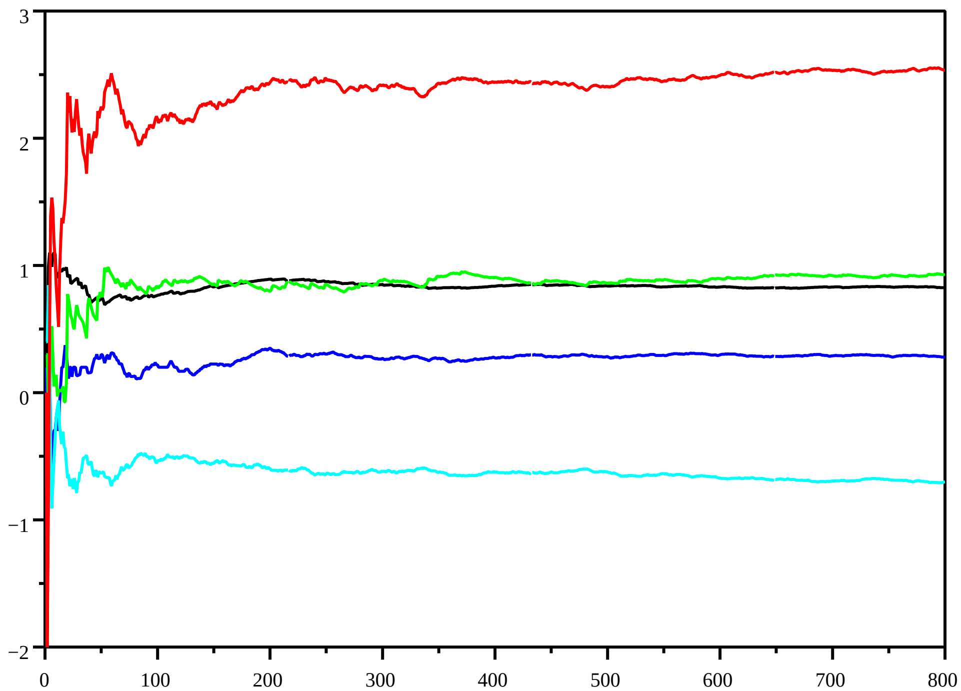

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- What goes into the extraction of a Bell Inequality?

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The derivation of a Bell Inequality starts from BELL's fundamental *Ansatz*:

$$P(a,b) = \int d\lambda \rho(\lambda) A(a,\lambda) B(b,\lambda), \tag{16}$$

where, per *explicit assumption:* A is not a function of b; nor B of a; and each represents the appearance of a photoelectron in its wing, and a and b are the corresponding polarizer filter settings. This is motivated on the grounds that a measurement at station A, if it respects 'locality,' so argues Bell, can not depend on remote conditions, such as the settings of a remote polarizer. By definition:

$$|A| \leq 1, \;\; |B| \leq 1, \tag{17}$$

which in this case effectively restricts the analysis to the case of just one photoelectron per time window per detector. Eq. (16) expresses the fact, that when the hidden variables are integrated out, the usual results from QM are to be recovered.

The λ above in Bell's analysis are to be the hypothetical "hidden variables", which, if they exist, should render QM deterministic. As is customary, the single symbol λ represents actually a set of such 'hidden variables' that may include many different characters, such as discrete, continuous, tensor or whatever.

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Extraction of inequalities proceeds by considering differences of two such correlations where (a, b), *i.e.*, the polarizer axis of measuring stations left and right, differ:

$$\begin{aligned} &P(a, b) - P(a, b') = \\ &\quad \int d\lambda \rho(\lambda)[A(a, \lambda)B(b, \lambda) - A(a, \lambda)B(b', \lambda)] = 0, \end{aligned} \tag{18}$$

to which one adds ± 0 in the form:

$$\begin{aligned} &A(a, \lambda)B(b, \lambda)A(a', \lambda)B(b', \lambda) - \\ &\quad A(a, \lambda)B(b', \lambda)A(a', \lambda)B(b, \lambda) = 0, \end{aligned} \tag{19}$$

to get:

$$\begin{aligned} &P(a, b) - P(a, b') = \\ &\quad \int d\lambda \rho(\lambda)A(a, \lambda)B(b, \lambda)[1 \pm A(a', \lambda)B(b', \lambda)] - \\ &\quad \int d\lambda \rho(\lambda)A(a, \lambda)B(b', \lambda)[1 \pm A(a', \lambda)B(b, \lambda)], \end{aligned} \tag{20}$$

which, in turn, upon taking absolute values and in view of Eqs. (17), Bell wrote as

$$\begin{aligned} &|P(a,b)-P(a,b')| \leq \\ &\quad \int d\lambda \rho(\lambda)[1 \pm A(a',\lambda)B(b',\lambda)] + \\ &\quad \int d\lambda \rho(\lambda)[1 \pm A(a',\lambda)B(b,\lambda)]. \end{aligned} \tag{21}$$

Then, using Eq. (16), and the normalization condition $\int d\lambda \rho(\lambda) = 1$, he got, for example:

$$|P(a,b)-P(a,b')| + |P(a',b') + P(a',b)| \leq 2, \tag{22}$$

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Now, however, if the λ are a complete set, thereby rendering everything deterministic so that all probabilities become Dirac or Kronecker delta distributions, then the A's and B's in Eq. (20) are pair-wise, that is as individual events comprising the generation at the source of one pair, non-zero for distinct values of λ, which, by virtue of completeness, do not coincide for distinct events, *i.e.*, for different pairs. That is, for each pair of settings (a, b) and iteration of the experiment, there exists a unique value (or set of values), $\lambda_{(a,b)}$ say, for which $A(a|\lambda_{(a,b)})B(b|\lambda_{(a,b)})$ is non-zero (± 1 in the discrete case, $\pm\infty$ in the continuous case). In other words, each product $A(a|\lambda_{(a,b)})B(b|\lambda_{(a,b)})$ can be written in the form $f(x)\delta(x-\lambda_{(a,b)})$, so that all quadruple products

$$A(a|\lambda_{(a,b)})B(b|\lambda_{(a,b)})A(a|\lambda_{(a',b')})B(b|\lambda_{(a',b')}), \tag{23}$$

are of the form:

$$f(x)\delta(x-\lambda_{(a,b)})g(x)\delta(x-\lambda_{(a',b')}), \tag{24}$$

where x is a dummy variable of integration to run over all admissible values of

λ. Therefore, such terms with pair-wise different values of $\lambda_{(ab)}$ in Eq. (20), *i.e.*, when either $a \neq a'$ or $b \neq b'$, are, in accord with Eq. (15), identically zero under integration over λ. This annihilates two terms on the left of eq. (22), so that the final form of this Bell Inequality, *resulting from the above complex of hypotheses,* is actually, for example, the trivial identity[**?**]:

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Suppose there is a string of data available from an experiment. It will be comprised of four virtually equal length subsets, one for each setting combination; let the term-wise product series of the first subset be denoted a_1b_1, the second $a_2b'_2$, etc. (and where another serial subscript is understood). With this notation, Eq(22) becomes:

$$|<a_1b_1>+<a_2b'_2>|+|<a'_3b'_3>-<a'_4b_4>|\leq 2. \qquad (26)$$

Now, it is obvious that for a particular polarizer setting, the percentage of $+1$'s in the total of long enough samples will be equal; *i.e.*, the number for a_1 equals the number for a_2 etc.; so that one can imagine re-sorting a_2 so that it has nearly the identical serial pattern as a_1. Denote the re-sorted version as $\tilde{a}_2$.

Thus, the re-sorted second term in Eq. (**??**), for example, becomes

$$a_2 b'_2 \Rightarrow \tilde{a}_2 \tilde{b'_2} \cong a_1 \tilde{b'_2}$$

the resorted third term becomes:

$$a'_3 b'_3 \Rightarrow \tilde{a'_3} \tilde{b'_3} \cong \tilde{a'_3} \tilde{b'_2}$$

and then the fourth term:

$$a'_4 b_4 \Rightarrow \tilde{a'_4} \tilde{b_4} \cong \tilde{a'_3} \tilde{b_4}.$$

So that Eq. (26) converts to:

$$< |a_1||(b_1 + \tilde{b}'_2)| > + < |\tilde{a}'_3||(\tilde{b}'_2 - \tilde{b_4})| > . \qquad (27)$$

Obviously, as $b_1 \cong \tilde{b}_4$ is not necessarily true identically, that is by physical requirements from the experiment, the loop can not be closed and the whole expression can not be limited identically to being $\leq |2|$.

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- “Photoelectron” picture:
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- Details: quant-ph/01 08 057; (+more on arXiv;
  search: Kracklauer — all categories/all years)

- e-file with MAPLE or SCILAB routines for the above available upon request.
  kracklau@fossi.uni-weimar.de