オーストリア　チロル、アルプバッハにある聖オズワルド・カソリック教会

お墓

２００９年　長谷川裕司さんの好意による

シュレーディンガーの墓標

リフォームされている

現在のもの

ドイツ語が私には難しく、東工大の山崎太郎先生の日本語訳を引用する。

存在するものは、私たちがその存在を今感じているがゆえに存在するのではなく、
私たちがその存在をもはや感じないゆえに存在しなくなったわけでもない。
存在するものが在り続けるがゆえに、私たちは存在し、持続して存在し続けるのである。
したがって、あらゆる存在は唯一の「存在」から発している。
人が死んでなお「存在」は在り続けているという事実が
死者の「存在」が途絶えたわけではないということを、あなたに告げているのである
E・シュレディンガー 1942年

山崎太郎先生のお父様の山崎敏光先生は著名な実験核物理学者で私は学生実験を指導していただいた。

２粒子のスピンの相関を実験できる形で
定量化しよう。

粒子１のスピン（の２倍）をσ_1, 粒子2 のスピンをσ_2 として、各々を軸a、b とc、d を量子化の軸にして観測しよう。

観測量を$a = a \cdot \sigma_1$、$b = b \cdot \sigma_2$、$c = c \cdot \sigma_1$、$d = d \cdot \sigma_2$
と定義しよう。

観測すればa, b, c, d は±1 の価を取ることに
注意しよう。

a, b, c, d を実験する前から決まっている”実在”の量
であると仮定して、さらに２つの粒子は遠く離れている
の
でそれらのスピンの測定は互いに影響を
及ぼさないという局所性を仮定しよう。

少し考えると、次の等式が恒等的に成立することがわかる

$$(-a + c)b + (a + c)d = \pm 2$$

観測を**N** 回繰り返して、a_j , $_j b_j$、c_j d_j $_j$ **j = 1, 2, . . . N**
を得たとしよう。
粒子１、２の観測が独立に行われたとすると
ab の平均値**< ab >** は

$$< ab >= \Sigma_j a_j b_j / N$$

したがって、”ベルの不等式“（正確には、**CHSH** 不等式）

$$|- < ab > + < bc > + < ad > + < cd > \ | \leq 2$$

EPR 状態

$$|s > = | \uparrow > | \downarrow > - | \downarrow > \ | \uparrow >$$

は、全角運動量$\boldsymbol{\sigma_1 + \sigma_2 = 0}$ の状態であるから

$$< s| \ a \otimes b | \ s >= < s|a \ . \ \sigma_1 \otimes b \ . \ \sigma_2 | \ s >$$
$$= - \ < s|a \ . \ \sigma_1 b \ . \ \sigma_1 | \ s >= -a \ . \ b$$

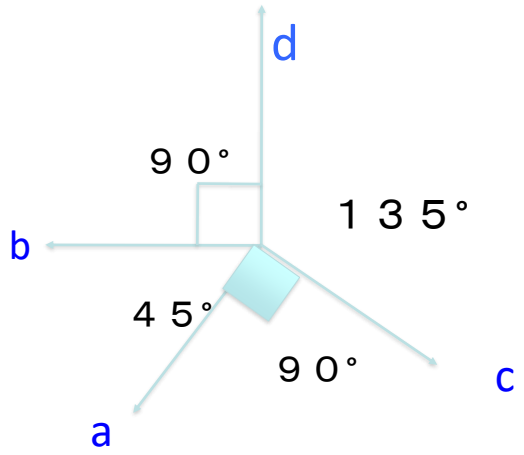
CSSH correlation operator

$$C := a\otimes b - b\otimes c - a\otimes d - c\otimes d$$

$$|C| = |-a.b+b.c+a.d+c.d| \leq 2\sqrt{2}$$

上限を実現する配位?

最適の配位



に対して、Cの固有値は　$\pm 2\sqrt{2}$　（谷村）

アスペたちの実験により、ベルの不等式の破れが示された。

このことは、物理量の値が予め決まっている、という物理量の実在を否定した。

物理量の値は測定によって与えられる。

Aspect et al の実験

Experimental Test of Bell's Inequalities Using Time-Varying Analyzers

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(Received 27 September 1982)

Correlations of linear polarizations of pairs of photons have been measured with time-varying analyzers. The analyzer in each leg of the apparatus is an acousto-optical switch followed by two linear polarizers. The switches operate at incommensurable frequencies near 50 MHz. Each analyzer amounts to a polarizer which jumps between two orientations in a time short compared with the photon transit time. The results are in good agreement with quantum mechanical predictions but violate Bell's inequalities by 5 standard deviations.

PACS numbers: 03.65.Bz, 35.80.+s

Bell's inequalities apply to any correlated measurement on two correlated systems. For instance, in the optical version of the Einstein-Podolsky-Rosen-Bohm Gedankenexperiment,[1] a source emits pairs of photons (Fig. 1). Measurements of the correlations of linear polarizations are performed on two photons belonging to the same pair. For pairs emitted in suitable states, the correlations are strong. To account for these correlations, Bell[2] considered theories which invoke common properties of both members of the

FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm Gedankenexperiment. The pair of photons γ_1 and γ_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

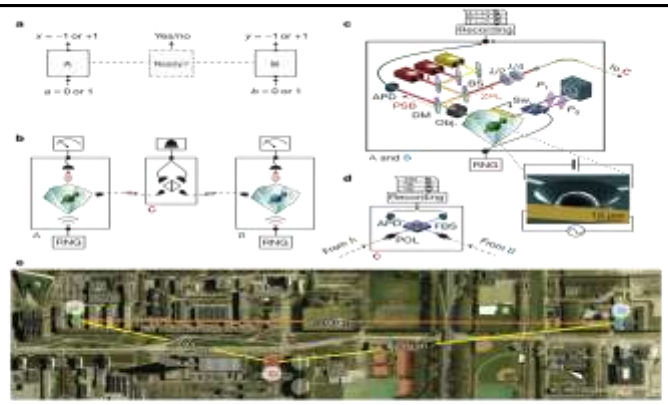


Figure 1 | Bell-test schematic and experimental realization. a. Bell-test set-up: two boxes, A and B, accept binary inputs (x, y) and produce binary outputs (a, b). In an event-ready scenario, an additional box C gives a binary output signalling that A and B were successfully prepared. **b.** Experimental realization. The set-up consists of three separate laboratories, A, B and C. The boxes at locations A and B each contain a single NV centre in diamond. A quantum random-number generator (RNG) is used to provide the input. The NV electronic spin is read out in a basis that depends on the input bit, and the resultant signal provides the output. A box at location C records the arrival of single photons that were previously emitted by, and entangled with, the spins at A and B. **c.** Experimental set-up at A and B. The NV centre is located in a low-temperature confocal microscope (Obj.). Depending on the output of the RNG, a fast switch (Sw.) transmits one of two different microwave pulses (P_1 and P_2) into a gold line deposited on the diamond surface (inset, scanning electron microscope image). Pulsed red and yellow lasers are used to resonantly excite the optical transitions of the NV centre. The emission (dashed arrows) is spectrally separated into an off-resonant part (phonon side band, PSB) and a resonant part (zero-phonon line, ZPL), using a dichroic mirror (DM). The PSB emission is detected with a single-photon counter (APD). The ZPL emission is transmitted through a beam-sampler (BS, reflection ≈4%) and wave plates ($\lambda/2$ and $\lambda/4$), and sent to location C through a single-mode fibre. **d.** Set-up at location C. The fibres from A and B are connected to a fibre-based beam splitter (FBS) after passing a fibre-based polarizer (POL). Photons in the output ports are detected and recorded. **e.** Aerial photograph of the campus of Delft University of Technology indicating the distances between locations A, B and C. The red dotted line marks the path of the fibre connection. Aerial photograph by Slagboom en Peeters Luchtfotografie BV.

close the locality loophole. So far, no experiment has closed all the loopholes simultaneously.

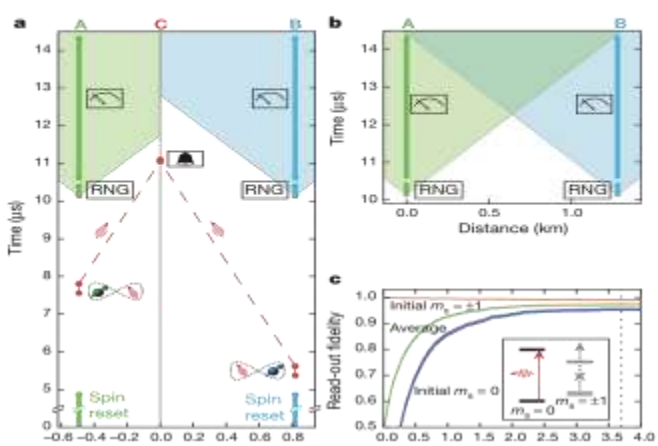
A Bell test that closes all experimental loopholes at the same time—commonly referred to as a loophole-free Bell test[15,17]—is of foundational importance to the understanding of nature. In addition, a loophole-free Bell test is a critical component for device-independent quantum security protocols[22] and randomness certification[23,24]. In such adversarial scenarios, all loopholes are ideally closed because they allow for security breaches in the system[25].

One approach for realizing a loophole-free set-up was proposed by Bell himself[17]. The key idea is to record an additional signal (dashed box in Fig. 1a) to indicate whether the required entangled state was successfully shared between A and B, that is, whether the boxes were ready to be used for a trial of the Bell test. By conditioning the

We implemented an event-ready Bell set-up[16,17] with boxes that use the electronic spin associated with a single nitrogen–vacancy (NV) defect centre in a diamond chip (Fig. 1b). The diamond chips are mounted in closed-cycle cryostats ($T = 4$ K) located in distant laboratories named A and B (Fig. 1c). We control the electronic spin state of each NV centre with microwave pulses applied to on-chip striplines (Fig. 1c, inset). The spins are initialized through optical pumping and read out along the Z axis via spin-dependent fluorescence[27]. The read-out relies on resonant excitation of a spin-selective cycling transition (1.2-ns lifetime), which causes the NV centre to emit many photons when it is in the bright $m_s = 0$ spin state, while it remains dark when it is in either of the $m_s = \pm 1$ states. We assign the value $+1$ ($m_s = 0$) to the output if we record at least one photo-detector count during the read-out window, and the value -1 ($m_s = \pm 1$) otherwise. Read-out in a rotated

space–time diagram in Fig. 2a, we ensure that this event-ready signal is space-like separated from the random input-bit generation at locations A and B.

The separation of the spins by 1,280 m defines a 4.27-μs time window during which the local events at A and B are space-like separated from each other (see the space–time diagram in Fig. 2b). To comply with the locality conditions of the Bell test, the choice of measurement bases and the measurement of the spins should be performed within this time window. For the basis choice we use fast random-number generators with real-time randomness extraction[30]. We reserve 160 ns for the random basis choice, during which time one extremely random bit is generated from 32 partially random raw bits (Supplementary



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