Introduction aux bizarreries quantiques

Paul Caucal

Ecole de Printemps de SUBATECH - Mai 2026

Bibliographie

- Livres et notes de cours :
  - Introduction à la physique subatomique, André Rougé (oscillations des neutrinos et des kaons neutres)
  - Lectures on Quantum Mechanics, Jean-Louis Basdevant
  - Optique quantique 2, tome 1, notes de cours d'Alain Aspect et Philippe Grangier (disponibles en ligne)

- Articles scientifiques :
  - Einstein, Podolsky, Rosen, Physical Review, 47 777, 1935
  - Aspect, Grangier, Roger, Physical Review Letters, 49-2, 1982
  - Bouwmeester, Pan, Mattle, Eibl, Weinfurter & Zeilinger, Nature, 390, (1997)
  - Massar, Popescu, Physical Review Letters, 74-8 (1995)

Plan général des 3 séances

I. Phénomènes d'oscillations quantiques en physique des particules.

II. Intrication et non-localité en mécanique quantique.

III. Information quantique : cryptographie, clonage et téléportation.

Oscillation des neutrinos

First Results from KamLAND: Evidence for Reactor Antineutrino Disappearance

K. Eguchi,[1] S. Enomoto,[1] K. Furuno,[1] J. Goldman,[1] H. Hanada,[1] H. Ikeda,[1] K. Ikeda,[1] K. Inoue,[1] K. Ishihara,[1] W. Itoh,[1] T. Iwamoto,[1] T. Kawaguchi,[1] T. Kawashima,[1] H. Kinoshita,[1] Y. Kishimoto,[1] M. Koga,[1] Y. Koseki,[1] T. Maeda,[1] T. Mitsui,[1] M. Motoki,[1] K. Nakajima,[1] M. Nakajima,[1] T. Nakajima,[1] H. Ogawa,[1] K. Owada,[1] T. Sakabe,[1] I. Shimizu,[1] J. Shirai,[1] F. Suekane,[1] A. Suzuki,[1] K. Tada,[1] O. Tajima,[1] T. Takayama,[1] K. Tamae,[1] H. Watanabe,[1] J. Busenitz,[2] Z. Djurcic,[2] K. McKinny,[2] D.-M. Mei,[2] A. Piepke,[2] E. Yakushev,[2] B. E. Berger,[3] Y. D. Chan,[3] M. P. Decowski,[3] D. A. Dwyer,[3] S. J. Freedman,[3] Y. Fu,[3] B. K. Fujikawa,[3] K. M. Heeger,[3] K. T. Lesko,[3] K.-B. Luk,[3] H. Murayama,[3] D. R. Nygren,[3] C. E. Okada,[3] A. W. P. Poon,[3] H. M. Steiner,[3] L. A. Winslow,[3] G. A. Horton-Smith,[4] R. D. McKeown,[4] J. Ritter,[4] B. Tipton,[4] P. Vogel,[4] C. E. Lane,[5] T. Miletic,[5] P. W. Gorham,[6] G. Guillian,[6] J. G. Learned,[6] J. Maricic,[6] S. Matsuno,[6] S. Pakvasa,[6] S. Dazeley,[7] S. Hatakeyama,[7] M. Murakami,[7] R. C. Svoboda,[7] B. D. Dieterle,[8] M. DiMauro,[8] J. Detwiler,[9] G. Gratta,[9] K. Ishii,[9] N. Tolich,[9] Y. Uchida,[9] M. Batygov,[10] W. Bugg,[10] H. Cohn,[10] Y. Efremenko,[10] Y. Kamyshkov,[10] A. Kozlov,[10] Y. Nakamura,[10] L. De Braeckeleer,[11] C. R. Gould,[11] H. J. Karwowski,[11] D. M. Markoff,[11] J. A. Messimore,[11] K. Nakamura,[11] R. M. Rohm,[11] W. Tornow,[11] A. R. Young,[11] and Y.-F. Wang[12]

(KamLAND Collaboration)

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KamLAND has measured the flux of $\bar{\nu}_e$'s from distant nuclear reactors. We find fewer $\bar{\nu}_e$ events than expected from standard assumptions about $\bar{\nu}_e$ propagation at the 99.95% C.L. In a 162 ton · yr exposure the ratio of the observed inverse β-decay events to the expected number without $\bar{\nu}_e$ disappearance is $0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst})$ for $\bar{\nu}_e$ energies > 3.4 MeV. In the context of two-flavor neutrino oscillations with CPT invariance, all solutions to the solar neutrino problem except for the "large mixing angle" region are excluded.

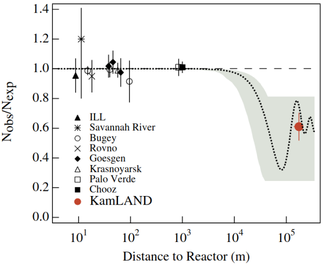
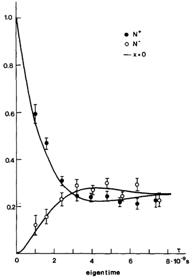


FIG. 4 (color). The ratio of measured to expected $\bar{\nu}_e$ flux from reactor experiments [15]. The solid circle is the KamLAND result plotted at a flux-weighted average distance of ~180 km. The shaded region indicates the range of flux predictions corresponding to the 95% C.L. LMA region from a global analysis of the solar neutrino data [16]. The dotted curve, $\sin^2 2\theta = 0.833$ and $\Delta m^2 = 5.5 \times 10^{-5}$ eV^2 [16], is representative of a best-fit LMA prediction and the dashed curve is expected for no oscillations.

Oscillation des mésons neutres étranges

$$\mathcal{A}(t) = \frac{P_{K^0\to K^0}(t) - P_{K^0\to \bar{K}^0}(t)}{P_{K^0\to K^0}(t) + P_{K^0\to \bar{K}^0}(t)}$$



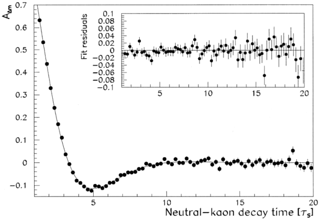
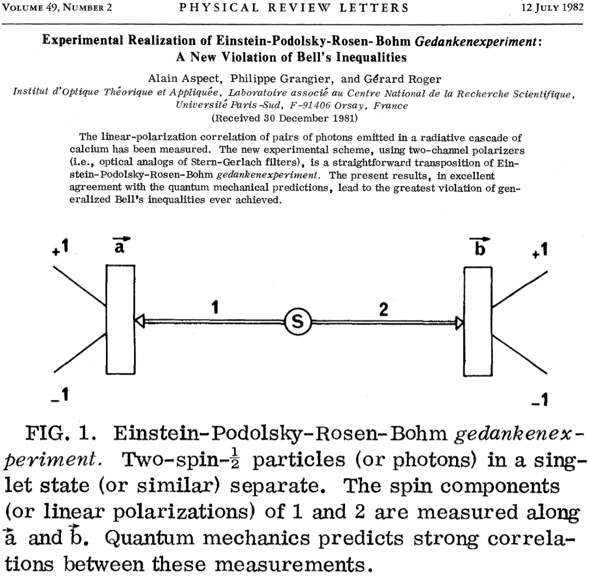


FIGURE 1 – Figure d'après CPLEAR *collaboration, Phys. Lett. 444B (1998) 38.* L'axe des abscisses est gradué en unités de τ_S.

Expérience d'Aspect (1982)



VOLUME 49, NUMBER 2 PHYSICAL REVIEW LETTERS 12 JULY 1982

Experimental Realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: A New Violation of Bell's Inequalities

Alain Aspect, Philippe Grangier, and Gérard Roger
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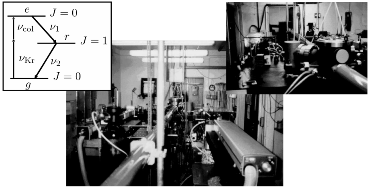
(Received 30 December 1981)

The linear-polarization correlation of pairs of photons emitted in a radiative cascade of calcium has been measured. The new experimental scheme, using two-channel polarizers (i.e., optical analogs of Stern-Gerlach filters), is a straightforward transposition of Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. The present results, in excellent agreement with the quantum mechanical predictions, lead to the greatest violation of generalized Bell's inequalities ever achieved.

FIG. 1. Einstein-Podolsky-Rosen-Bohm *gedankenexperiment*. Two-spin-$\frac{1}{2}$ particles (or photons) in a singlet state (or similar) separate. The spin components (or linear polarizations) of 1 and 2 are measured along $\vec{a}$ and $\vec{b}$. Quantum mechanics predicts strong correlations between these measurements.

Expérience d'Aspect (1982)



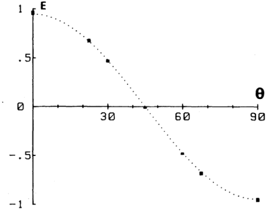
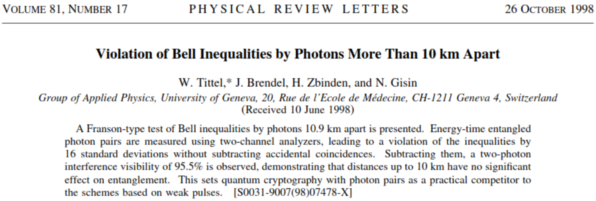


FIG. 3. Correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are ±2 standard deviations. The dotted curve is not a fit to the data, but quantum mechanical predictions for the actual experiment. For ideal polarizers, the curve would reach the values ±1.

Mesure expérimentale

$$S_{\text{exp}} = 2.697 \pm 0.015$$

Non-localité quantique sur ∼ 10 km !



VOLUME 81, NUMBER 17 PHYSICAL REVIEW LETTERS 26 OCTOBER 1998

Violation of Bell Inequalities by Photons More Than 10 km Apart

W. Tittel,* J. Brendel, H. Zbinden, and N. Gisin
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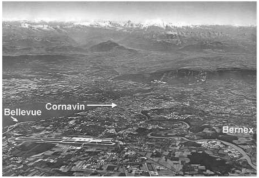
(Received 10 June 1998)

A Franson-type test of Bell inequalities by photons 10.9 km apart is presented. Energy-time entangled photon pairs are measured using two-channel analyzers, leading to a violation of the inequalities by 16 standard deviations without subtracting accidental coincidences. Subtracting them, a two-photon interference visibility of 95.5% is observed, demonstrating that distances up to 10 km have no significant effect on entanglement. This sets quantum cryptography with photon pairs as a practical competitor to the schemes based on weak pulses. [S0031-9007(98)07478-X]



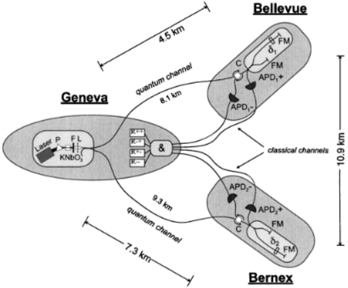
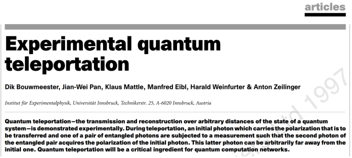


FIG. 1. Setup for experiment 1. See text for detailed description.

Expérience de Zeilinger (1997)



articles

Experimental quantum teleportation

Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger

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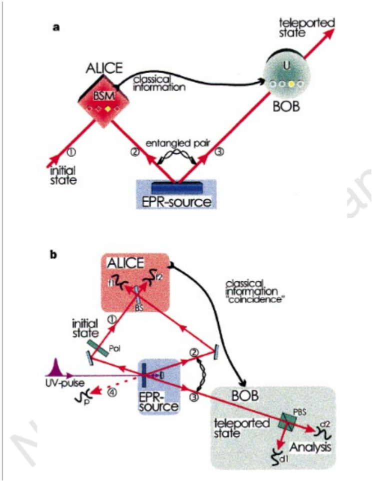
Quantum teleportation—the transmission and reconstruction over arbitrary distances of the state of a quantum system—is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks.



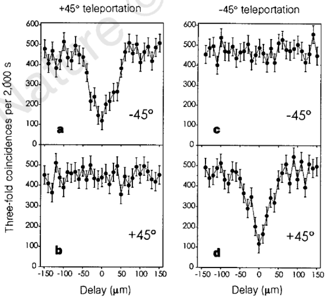
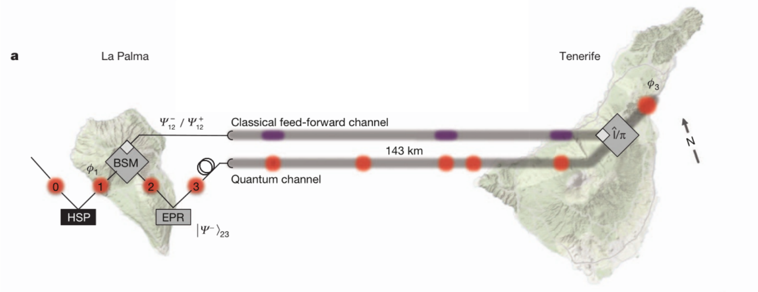
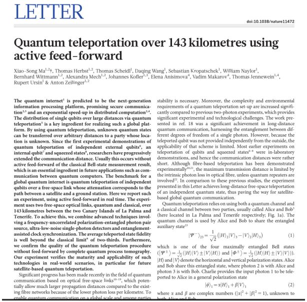


Figure 4 Experimental results. Measured three-fold coincidence rates d1f1f2 (–45°) and d2f1f2 (+45°) in the case that the photon state to be teleported is polarized at +45° (**a** and **b**) or at –45° (**c** and **d**). The coincidence rates are plotted as function of the delay between the arrival of photon 1 and 2 at Alice's beam splitter (see Fig. 1b). The three-fold coincidence rates are plotted after subtracting the spurious three-fold contribution (see text). These data, compared with Fig. 3, together with similar ones for other polarizations (Table 1) confirm teleportation for an arbitrary state.

Téléportation entre les îles Canaries (2012)

Zeilinger et al., Nature, 489-269, 2019





LETTER

doi:10.1038/nature11472

Quantum teleportation over 143 kilometres using active feed-forward

Xiao-Song Ma[1,2]†, Thomas Herbst[1,2], Thomas Scheidl[1], Daqing Wang[1], Sebastian Kropatschek[1], William Naylor[1], Bernhard Wittmann[1,2], Alexandra Mech[1,2], Johannes Kofler[1,3], Elena Anisimova[4], Vadim Makarov[4], Thomas Jennewein[1,4], Rupert Ursin[1] & Anton Zeilinger[1,2]

The quantum internet[1] is predicted to be the next-generation information processing platform, promising secure communication[2,3] and an exponential speed-up in distributed computation[2,4]. The distribution of single qubits over large distances via quantum teleportation[5] is a key ingredient for realizing such a global platform. By using quantum teleportation, unknown quantum states can be transferred over arbitrary distances to a party whose location is unknown. Since the first experimental demonstrations of quantum teleportation of independent external qubits[6], an internal qubit[7] and squeezed states[8], researchers have progressively extended the communication distance. Usually this occurs without active feed-forward of the classical Bell-state measurement result, which is an essential ingredient in future applications such as communication between quantum computers. The benchmark for a global quantum internet is quantum teleportation of independent qubits over a free-space link whose attenuation corresponds to the path between a satellite and a ground station. Here we report such an experiment, using active feed-forward in real time. The experiment uses two free-space optical links, quantum and classical, over 143 kilometres between the two Canary Islands of La Palma and Tenerife. To achieve this, we combine advanced techniques involving a frequency-uncorrelated polarization-entangled photon pair source, ultra-low-noise single-photon detectors and entanglement-assisted clock synchronization. The average teleported state fidelity is well beyond the classical limit[9] of two-thirds. Furthermore, we confirm the quality of the quantum teleportation procedure without feed-forward by complete quantum process tomography. Our experiment verifies the maturity and applicability of such technologies in real-world scenarios, in particular for future satellite-based quantum teleportation.

Significant progress has been made recently in the field of quantum communication based on optical free-space links[10–19], which potentially allow much larger propagation distances compared to the existing fibre networks because of the lower photon loss per kilometre. To enable quantum communication on a global scale and among parties

stability is necessary. Moreover, the complexity and environmental requirements of a quantum teleportation set-up are increased significantly compared to previous two-photon experiments, which provides significant experimental and technological challenges. The work presented in ref. 18 was a significant achievement in long-distance quantum communication, harnessing the entanglement between different degrees of freedom of a single photon. However, because the teleported qubit was not provided independently from the outside, the applicability of that scheme is limited. Most earlier experiments on teleportation of qubits and squeezed states[6–8] were in-laboratory demonstrations, and hence the communication distances were rather short. Although fibre-based teleportation has been demonstrated experimentally[20,21], the maximum transmission distance is limited by the intrinsic photon loss in optical fibre, unless quantum repeaters are involved[22]. In comparison to these previous studies, the experiment presented in this Letter achieves long-distance free-space teleportation of an independent quantum state, thus paving the way for satellite-based global quantum communication.

Quantum teleportation relies on using both a quantum channel and a classical channel between two parties, usually called Alice and Bob[5] (here located in La Palma and Tenerife respectively; Fig. 1a). The quantum channel is used by Alice and Bob to share the entangled auxiliary state[23]

$$|\Psi^-\rangle_{23}=\frac{1}{\sqrt{2}}(|H\rangle_2|V\rangle_3-|V\rangle_2|H\rangle_3) \quad (1)$$

which is one of the four maximally entangled Bell states ($|\Psi^\pm\rangle=\frac{1}{\sqrt{2}}(|H\rangle|V\rangle\pm|V\rangle|H\rangle)$ and $|\Phi^\pm\rangle=\frac{1}{\sqrt{2}}(|H\rangle|H\rangle\pm|V\rangle|V\rangle)$). $|H\rangle$ and $|V\rangle$ denote the horizontal and vertical polarization states. Alice and Bob share this entangled state, where photon 2 is with Alice and photon 3 is with Bob. Charlie provides the input photon 1 to be teleported to Alice in a general polarization state

$$|\phi\rangle_1=\alpha|H\rangle_1+\beta|V\rangle_1 \quad (2)$$

where α and β are complex numbers ($|\alpha|^2+|\beta|^2=1$), unknown to both Alice and Bob