Experimental test of relativistic quantum state collapse with moving reference frames

2001 J. Phys. A: Math. Gen. 34 7103

(http://iopscience.iop.org/0305-4470/34/35/334)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND GENERAL

J. Phys. A: Math. Gen. **34** (2001) 7103–7109 PII: S0305-4470(01)22310-5

Experimental test of relativistic quantum state collapse with moving reference frames

H Zbinden, J Brendel, W Tittel and N Gisin

Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland

Received 2 February 2000
Published 24 August 2001

Abstract
An experimental test of relativistic wave-packet collapse is presented. The tested model assumes that the collapse takes place in the reference frame determined by the massive measuring detectors. Entangled photons are measured at 10 km distance within a time interval of less than 5 ps. The two apparatuses are in relative motion so that both detectors, each in its own inertial reference frame, are first to perform the measurement. The data always reproduces the quantum correlations and thus rule out a class of collapse models. The results also set a lower bound on the 'speed of quantum information' to $\frac{2}{3}10^7$ and $\frac{3}{2}10^4$ times the speed of light in the Geneva and the background radiation reference frames, respectively. The very difficult and deep question of where the collapse takes place—if it takes place at all—is considered in a concrete experimental context.

PACS numbers: 03.65.Ta, 03.65.Od, 03.67.−a

Entanglement, one of the most important features of quantum mechanics, is at the core of the famous Einstein–Bohr philosophical debate [1] and is the principal resource for quantum information processing [2]. The tension between quantum mechanics and relativity has already received quite a lot of attention in the context of local hidden variables and Bell inequality. There the idea was to complete quantum mechanics with additional variables that would reduce it to a classical theory. Here the intuition is that this tension could be a guide for new physics, beyond quantum mechanics.

Despite the lack of a completely loophole-free test of Bell inequality, the vast majority of physicists is convinced that quantum mechanics correctly describes the atomic world, including the correlation between distant systems, and we fully support this conclusion. Yet, some physicists would like to treat the state vector ψ as describing an objective reality and not merely the physicists' information. We feel that such an approach is of interest, especially when it offers new experimental tests. The difficulty of realistic interpretations comes from the 'wave packet collapse' and there seem to be only two alternatives. The first one assumes that the collapse is only a relative phenomenon: the observer, the measuring apparatus and the quantum system under test all get correlated in a way described by the Schrödinger equation such that all future observations are consistent. In this description there is no real random choice, rather all outcomes happen in different worlds that are in quantum superposition (a so-called many-world or relative state interpretation *à la* Everett [3]). The second alternative assumes a real collapse with a real objective choice. It is generally believed that there is no observable difference between these alternatives. However, this conclusion depends on the exact form of the postulated collapse. For example, the GRW [4] and the primary state diffusion [5] models predict tiny differences, though these are not measurable with today's technology.

In this paper we test the assumption of real collapse in two ways. First, we follow the idea put forward by Suarez and Scarani that the collapse takes place in the reference frame determined by the measuring apparatus [6]. Next, we set experimental limits on the speed of the collapse, both in the reference frame defined by the massive environment of the experiment, that is in the Geneva reference frame, and in the reference frame determined by the cosmic background radiation.

Let us elaborate on the intuition of Suarez and Scarani. Each measuring apparatus defines a reference frame that we call a measuring frame. In each measuring frame some measurements (performed on distant systems) happen before this one, while some happen later. The assumption is that the probabilities of outcomes are determined by the local quantum state (as in standard quantum mechanics) and that the local quantum state is collapsed by all the measurements that happened before in this measuring frame. If there is only one measuring frame, then this is identical to quantum mechanics with the projection postulate, hence the predictions are indistinguishable from those of standard quantum mechanics. In particular, they are compatible with all previous experiments. However, when applied to EPR-like situations with two distant and moving measuring apparatuses, defining different reference frames[1], special relativity implies that the chronology of the measurements can differ from one measuring frame to another. Let us discuss the case of two entangled distant systems that for convenience we attribute to Alice and Bob. Assume first that in both measuring frames Alice's measurement takes place before Bob's. In such a case Alice produces first an outcome with probabilities determined by her local state (obtained by tracing over Bob's system). Next, Bob produces an outcome with probabilities also determined by his local state, but this state takes into account Alice's result (i.e. Bob's state is collapsed). This is quite common reasoning. Assume next that Alice and Bob are in relative motion such that in each of the two measuring frames the local measurement takes place before the distant one. In this case the probabilities of each result are determined by the local state without any collapse and models *à la* Suarez–Scarani predict no correlations at all. This is in strong opposition to the quantum mechanical predictions according to which the correlation should be observed independently of any time ordering. The case that both measurements take place after the distant one is discussed in [8].

Let us emphasize how natural our tests are in the context of assumed real collapses. Indeed, since the collapse is non-local, if it is a real physical phenomenon it must happen in some privileged frame. It is then natural to assume that the latter is either defined by the measuring apparatus, or by the massive environment, or by the background radiation field [9]. The attractive aspect of these ideas is that they lead to difficult but feasible experiments which could severely reduce the room for 'real collapse models'. They also set the question of what

---

[1] For space-like separated measurements there are always reference frames such that in the first frame one measurement happens first, while in the second frame it is the other measurement which is first, see e.g. [7]. But generally these frames are arbitrary, contrary to models *à la* Suarez–Scarani where the frames are naturally determined by massive devices.

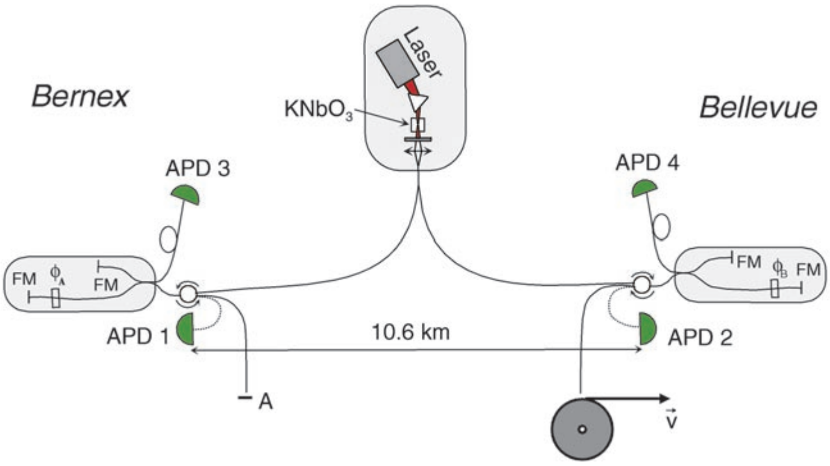

Figure 1. Schematic of the experiments that consist of a photon pair source and two analysers separated by 10.6 km, see [11]. The absorbing surface A and the rotating wheel are at equal distances from the source. The detectors APD3 and APD4 are connected with longer fibres such that each photon meets first the absorber, next the detector. In a second experiment the absorbers are replaced by two photon counters APD1 and APD2, again at exactly the same distance. We obtain typically 2 kcts s^{-1} single count rates and a mean value of about three coincidences per second (including two accidentals). For details, see text and [8].

is a measurement in a concrete context, since the measuring device determines the relevant measuring frame.[2]

The general idea of collapse models *à la* Suarez–Scarani is clear. However, in order to design feasible tests, a more specific model has to be elaborated. Indeed, to test the general idea an entire measurement apparatus would have to be put in relativistic motion. Fortunately, in any collapse model there is an assumed intrinsic irreversible choice after which the collapse has happened. It thus suffices to speed up the device where this happens. We call this device the *choice device*. In their original work, Suarez and Scarani [6] assumed that the beam-splitters are the choice devices, inspired by Bohm's model. The experiment described in this paper tests the more conventional assumption that collapses are produced by all detectors and absorbing materials. The motivation for the latter is that the relevant physics in detectors happens in the first layers where the irreversible absorption takes place in less than a picosecond. Note that negative results, i.e. particle not detected or not absorbed, also produce a collapse. In summary, the first detector or absorber encountered by any particle acts as the *choice device*. In a binary choice, as in our experiment, when a particle encounters a second detector or absorber in the absolute future of the *choice device*, then the collapse already happened and there is no longer any alternative: the second device merely reveals the choice made by the *choice device*.

In order to test the above model, we took advantage of our long-distance Bell-experiment presented earlier in more detail [10, 11], see figure 1. A source of energy–time entangled photons is located in a Swisscom terminal in the centre of Geneva. The photons are sent through the optical fibre telecom network to two villages, Bellevue and Bernex, separated by 10.6 km. There, the photons are analysed by two identically imbalanced fibre optic

---

[2] *Measurements* are here considered as physical processes, without any anthropomorphic flavour.

Michelson interferometers. The cases when the photons either both take the short arm of their interferometers, or both take the long arm, are indistinguishable, leading to interference according to Feynman's criterion. One interferometer is kept at a constant temperature, while the temperature of the other one is scanned, producing a phase variation. We can thus continuously measure the correlation as a function of the phase.

According to special relativity the time ordering of the measurements differ between the two measuring frames only if their relative speed v and their time difference δt satisfy:

$$\delta t \leqslant \frac{Lv}{c^2} \qquad (1)$$

where $L = 10.6$ km is the straight line distance between Alice and Bob. Consequently, assuming a speed v of 100 m s^{-1} and a safety margin of 2, a $\delta t \approx 5$ ps timing accuracy is necessary. Note that achieving this automatically provides a bound on the speed of the assumed collapse. Indeed, if both measurements take place before the quantum information from the distant measurement result reaches them, then no correlation would be observed.

The technical challenges are thus, first to achieve a speed of 100 m s^{-1}, next to adjust the fibres' relative lengths below 5 ps (corresponding to 1 mm, each fibre being about 10 km long), third to master the dispersion such that the pulse spreading remains below 5 ps.

To achieve an absorber speed of 105 m s^{-1} we use a 20 cm diameter black-painted aluminium disk of 1 cm thickness directly driven by a brushless 250 W DC motor (Maxon EC) turning vertically at 10 000 rpm. During the absorption, the circular motion provides a good approximation to a linear one, defining thus the inertial reference frame. It is oriented with a compass to make it run away from or towards the other observer.

We now describe the fibre length adjustment and dispersion management. To adjust roughly the distances from the source to the detectors we add 1.5 km of optical fibre on a spool on the link to Bellevue. Furthermore, in order to equilibrate the chromatic dispersions, we add about 500 m of dispersion-shifted fibre on the link to Bernex, this is necessary because the dispersion of this link is higher (dispersion-shifted fibres have relatively high negative dispersion around 1300 nm). Finally, each fibre link measures in total about 10 km and has about 9 dB losses. Next, the fibre lengths are measured with a home-made OTDR (optical time domain reflectometer) with a precision of a few cm. Short fibre pigtails are used for this adjustment. In a further step, we use another home-made low-coherence interferometer [12] with 100 μm resolution (using a LED with a 2 nm FWHM interference filter). Fine tuning is realized by pulling on a 2 m long fibre on a rail with a micrometer-screw (optical fibres have 1% elasticity).

The dispersion-induced spreading of the wavepackets may easily be larger than the achievable precision of the positioning. To limit the spreading we take advantage of the two-photon chromatic dispersion cancellation phenomena [13, 14]: if the central wavelength of the down-converted photons is precisely at the (average) zero chromatic dispersion wavelength of the two fibres, then, in the domain where chromatic dispersion varies linearly, both photons undergo exactly the same delay. We thus measured accurately and equilibrated the chromatic dispersion of the fibre links and found the zero chromatic dispersion wavelength with a precision of ± 0.2 nm. This uncertainty together with nonlinear chromatic dispersion determines the width of the two-photon wave-packet. Reducing the bandwidth of the down-converted photon with a 10 nm filter, we estimate that the resulting spread is below 5 ps (for a detailed analysis, see [8]).

Due to daily thermal expansion, the optical lengths between Geneva and each of the villages change by several mm over the day. We observe that Bernex is drifting further away during the daytime, since this link is more exposed to temperature variations. The drift proves

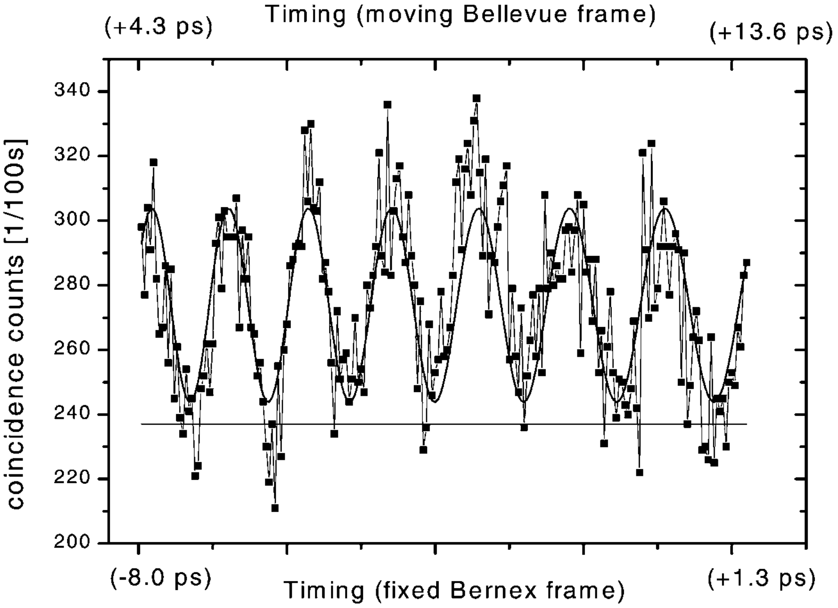

Figure 2. Two-photon interference fringes measured over 6 hours, each data point corresponds to a time interval of 100 s. The difference of the optical path lengths varies from −8 to +1.3 ps. Negative values mean that the detection occurs first in Bernex in the Geneva–Bernex reference frame. In the moving Bellevue reference frame the detections happen first in Bellevue over the entire scan range, as indicated on the upper time scale. Despite this different time ordering no reduced visibility is observed.

to be monotonic, in one direction during the day and in the other during the night. Accordingly, we aligned the paths taking into account the daily drift such that the optical distances from the source to the two interferometers will be perfectly equal some time later. During these few hours we continuously record the two-photon interference fringes, scanning the phase of the Bellevue interferometer. After an acquisition we confirm with a second measurement that the path lengths really passed through the equilibrium point. In this way we are sure that some fringes are collected when the fibre length difference is smaller than 1 mm (corresponding to 5 ps). Many interferograms were collected over various day and night periods and measurement times. Figure 2 displays typical data taken over 6 hours while the optical link to Bernex lengthened by 2 mm with respect to the one to Bellevue and the wheel was rotating, such that both measurements were 'before the other' over almost the entire scan. Inevitably, the curves show high statistical fluctuations due to the low count rate. In spite of this, one can state that the visibility of the two-photon interferogram remains constant. Especially, a reduced visibility over a scan span of 5 ps, as predicted by the model under test, should easily be noticed. After subtraction of the 237 ± 5 cts/100 s accidental coincidences (which are caused by the well understood phenomenon of dark counts and which we measured independently), the fit of figure 2 shows a constant fringe visibility of 83%.[3]

We also measured interferograms corresponding to the 'after–after' configuration by reversing the rotation of the wheel, again with no evidence for a breakdown of the correlations.

---

[3] This visibility is large enough for a violation of Bell's inequality. However, a violation of Bell inequality is not necessary in our context, since we do not test local models, but, quite the opposite, non-local collapse models.

We like to mention that with the detectors as ‘choice device’, a breakdown of the correlations would allow to exploit ‘non-locality’ for superluminal communication by slightly adapting the setup [8].

Our results also demonstrate quantum correlation measurements quasi-simultaneous in the natural Geneva reference frame, setting a conservative, nevertheless impressive lower bound on the speed of any hypothetical quantum influence, with c the speed of light:

$$\frac{10.6\,\mathrm{km}}{5\,\mathrm{ps}} \approx 2 \times 10^{15}\,\frac{\mathrm{m}}{\mathrm{s}} = \frac{2}{3} \times 10^{7} c \tag{2}$$

This speed remains superluminal in all reference frames, in particular in that defined by the cosmic background radiation (CBR). Our Earth moves at a mean speed of 371 km s^{-1} relative to this single-out frame. Due to the Earth’s rotations, both around its axis and around the sun, the date and time when the data were taken and the orientation of the experiment are relevant to establish the corresponding bound. A detailed analysis will be presented elsewhere [15]. Taking into account the Bellevue–Bernex orientation (almost exactly north–south), the worst case corresponds to a delay of 37 ns in the CBR frame and we get a conservative bound close to $10^3 c$. We also performed this experiment without the rotating wheel and with two aligned detectors (APD 1 & 2 on figure 1). Note that for this bound, the 5 ps timing in the Geneva reference frame is unnecessary since anyway the timing in the background radiation frame is much less precise. Hence, we could relax the constraint on the spectral width of the photons, accepting larger dispersion and performed this experiment without the rotating wheel and with two aligned detectors (APD 1 & 2 on figure 1). This provides much higher counting rates, improves the signal to noise ratio and sets a bound of $1.5 \times 10^4 c$ to the speed of quantum information in the CBR frame [15].

Let us emphasize again that the above bound on the speed of ‘quantum information’ (quantum state preparation)[4] is not in conflict with relativity. What can be said is that Alice can predict with certainty the quantum state of a photon 10 km away which was still in a completely mixed state some ps before. Whether this implies the transmission of some kind of information (or influence) is a matter of debate and models [16]. In this respect the recent progress on evaluating the cost of classical communication for the simulation of quantum correlation is interesting [17, 18]: to simulate our experiment with classical communication one would not only need superluminal communication, but the extreme speed of 10 million time the speed of light.

We presented results of two experiments that go beyond the standard tests of Bell inequality. Their objectives are to explore experimentally the possible limits of quantum mechanics, to test the most peculiar predictions of quantum physics and to open the road for further experimental investigations of these no-longer purely philosophical questions. Our results fully support the quantum predictions, re-enforcing our confidence in the possibility to base future understanding of our world and future technology on quantum principles. They also contributes to the renewed interest for experimental challenges to the interpretation of quantum mechanics. ‘Experimental metaphysics’ questions [19] like ‘what about the concept of states’, ‘the concept of causalities’ will have to be (re)considered taking into account the results presented in this letter. For example, our results make it more difficult to view the ‘projection postulate’ as a compact description of a real physical phenomenon [4, 20, 21]. However this is only a first example of this new class of tests and further experiments are needed before general conclusions can be made.

---

[4] What we call speed of ‘quantum information’ is probably better known as ‘speed of the spooky-action at a distance’, in Einstein’s term.

Acknowledgments

This work would not have been possible without the financial support of the Fondation Odier de psycho-physique. It also profited from support by Swisscom and the Swiss National Science Foundation. We would like to thank A Suarez and V Scarani for very stimulating discussions and H Inamori for preparing work during his stay in our lab.

References

[1] Wheeler J A and Zurek W H (ed) 1983 *Quantum Theory and Measurement (Princeton Series in Physics)* (Princeton, NJ: Princeton University Press)

[2] Lo H K, Popescu S and Spiller T P (ed) 1998 *Introduction to Q Computation and Information* (Singapore: World Scientific)

[3] Everett H III 1957 *Rev. Mod. Phys.* **29** 454

[4] Ghirardi G C, Rimini A and Weber T 1986 *Phys. Rev.* D **34** 470

[5] Percival I C 1994 *Proc. R. Soc.* A **447** 189

[6] Suarez A and Scarani V 1997 *Phys. Lett.* A **232** 9

[7] Aharonov Y and Albert D Z 1981 *Phys. Rev.* D **24** 359

[8] Zbinden H *et al* 2000 *Phys. Rev.* A **63** 022111

[9] Lineweaver C*et al* 1996 *Astrophys. J.* **470** 38

[10] Tittel W *et al* 1998 *Phys. Rev. Lett.* **81** 3563

[11] Tittel W*et al* 1999 *Phys. Rev.* A **59** 4150

[12] Gisin N, Pellaux J P and Von Der Weid J P 1991 *J. Lightwave Tech.* **9** 821

[13] Steinberg A M, Kwiat P and Chiao R Y 1992 *Phys. Rev. Lett.* **68** 2421

[14] Larchurk T S, Teich M V and Saleh B E A 1995 *Phys. Rev.* A **52** 4145–54

[15] Scarani V *et al* 2001 *Phys. Lett.* A **276** 1

[16] Eberhard Ph H 1989 *Quantum Theory and Pictures of Reality* ed W Schommers (Berlin: Springer) pp 169–216

[17] Brassard G, Cleve R and Tapp A 1999 *Phys. Rev. Lett.* **83** 1874

[18] Steiner M 1999 *Preprint* quant-ph/9902014

[19] Cohen R S, Horne M and Stachel J(ed) 1997 *Experimental Metaphysics* (Dordrecht: Kluwer Academic)

[20] Pearle Ph 1985 *Annals Acad. Sci. NY* **480** 539

[21] Gisin N 1989 *Helv. Phys. Acta* **62** 363