The Satigny–Jussy Experiment

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This is my account of an experiment run by N. Gisin and his group, described briefly in [1] and published in more detail in [2]. I discuss only the ideas and some of the issues it raises about the fate of Minkowski spacetime. There are no technological details about the experiment here.

We make the hypothesis that there is a particular or 'privileged' frame in which something propagates faster than light. The idea is that, since polarisation measurements on two entangled photons are never perfectly synchronised, correlations between the resulting values could then be explained by very fast transfer of information (quantum information QI) from one to the other in the very short time interval between the measurements, at least if there is such a time interval in the proposed 'privileged' frame. In [1], Gisin calls this a local explanation, i.e., in his definition, a mechanism that propagates from one point to the next through space. One might call this *point-to-point locality*, to be contrasted with what is sometimes called *causal locality*, whereby causes are constrained to operate within future light cones. Presumably, the latter has already been ruled out by experiment.

In [1], Gisin states that a superluminal velocity can only be defined if we make the hypothesis that this velocity is specified relative to a particular inertial frame of reference. Of course, no velocity of any kind is defined until we specify a frame, but the specific assumption here, tested by this experiment, seems to be that the superluminal transfer can only occur as a *physical point-to-point transfer* in one frame which is somehow universal, i.e., independent of the particular entangled system under investigation, similar perhaps to the universal frame of the CMB, or the frame of a kind of quantum ether, which are energy–matter-determined frames, or possibly some extra fundamental spacetime structure. More about this below.

In order to test this hypothesis, and in fact disqualify it, the ideal thing would be if Alice and Bob made their choices and collected their results simultaneously in *this particular* frame, in such a way that the hypothetical influence could not arrive in time. If they cannot achieve simultaneity, and in practice one could never do so, either a greater distance must separate them or they must improve synchronisation in this particular frame, whatever it is, in order to beat the transfer of the superluminal something and show either that there are no longer any correlations, whereupon this hypothesis gains support, or there are still correlations, in which case, the mysteries of 'standard' quantum theory perdure.

I understand the experiment as follows. Because Alice and Bob are located on an east–west axis, viz., the line through the villages of Satigny and Jussy, this axis will rotate through 180 degrees every 12 hours. Let us assume that they are capable of perfect synchronisation. Now there will be some time when the SJ axis is perpendicular to the motion of the putative special frame, so their measurements will be perfectly synchronised in that special frame if they are perfectly synchronised in their own frame. This means that the putative physically transferred something that is possible in that frame won't have time to communicate between them, so that couldn't explain any correlations that violate Bell's inequalities. But Gisin and coworkers found experimentally that Bell's inequalities were always violated during the 12 hours of repetitions of the experiment (a remarkable piece of experimental work once again).

This does not completely debunk the proposed hypothesis, however, because as Gisin explains in [1], they did not achieve perfect synchronisation, the alignment of the east–west axis will have contained some error, and the time required to carry out the Bell experiment will not have been totally negligible, so in these experiments one can only set a lower bound for the speed of the hypothetical superluminal influence. However, it is already much faster than the speed of light ($5 \times 10^3 c$).

Perhaps there is still one thing that needs to be made absolutely clear about this. Suppose spacetime has the Minkowski structure of the special theory of relativity. If QI can transfer point to point between two spacelike separated events, then for any $u > c$, there will be a frame in which it will transfer at speed u, and indeed, there will be a frame in which it transfers instantaneously, and yet others in which it reaches its destination *before* it is sent. So could it be that, when the SJ axis happens to be perpendicular to the motion of the special frame, the frame of the SJ axis is precisely one of those frames where the QI gets to its destination instantaneously, or before it is sent? That looks like it might scupper the above argument.

But the point is that only QI transfers moving with some component in the direction of motion of the SJ axis relative to the special frame could have these attributes, whereas the SJ axis is moving perpendicular to the SJ axis here. If we accept that QI is always transferred at some fixed universal speed $u > c$ relative to the special frame, then QI transfers perpendicular to the direction of motion of the SJ axis, such as those along this axis, could never occur instantaneously or go back in time in the frame of the SJ axis, at least not for this configuration in which the frame of the SJ axis is moving perpendicularly to that axis as viewed from the special frame. To see this simply, note that, if the QI crosses from S to J instantaneously in the frame of the SJ axis, then it will also do so in the special frame, whence it traverses a spacelike separation in the special frame in zero special frame time and its speed in that frame would not be the hypothesised finite value $u > c$.

For a detailed, hence more complete analysis, let special frame coordinates be unprimed and let the coordinates of the frame moving with the SJ axis be primed. Suppose the origins of the two coordinate systems coincide just when the QI is emitted from S at the then coincident space origins of the two systems and that the x and x' axes coincide. Then the worldline of the QI will be described by

$$x = u_x t \;, \quad y = u_y t \;, \quad z = 0 \;, \qquad x' = \gamma_v(-vt + u_x t) \;, \quad y' = u_y t \;, \quad z' = 0 \;.$$

Here the three-velocity of the QI has components u_x and u_y in the special frame, so

$$u_x^2 + u_y^2 = u^2 > c^2 \;,$$

and the frame of the SJ axis moves with speed v in the positive x direction in the special frame. The SJ axis is taken to lie along the y' axis in its frame of motion. On the worldline of the QI, we have

$$t' = \gamma_v(t - u_x vt/c^2) \;,$$

whence the three-velocity in the frame of the SJ axis is

$$u'_x = \frac{u_x - v}{1 - u_x v/c^2} \;, \qquad u'_y = \frac{u_y}{\gamma_v(1 - u_x v/c^2)} \;, \qquad u'_z \;.$$

Now the QI is supposed to go from S to J, which lies along the y' axis, so we know that $u'_x = 0$, i.e., $u_x = v$. Hence, $u'_y = \gamma_v u_y$. So if u'_y were infinite, so would be u_y, contradicting the hypothesis. Likewise, if u'_y were negative (QI travelling back in time in the frame of the SJ axis), so would be u_y, once again contradicting the hypothesis.

Gisin gives an interesting discussion of these results [1, p. 86 ff]. According to him, physicists conclude that there can be no superluminal influence of the kind hypothesised above. In his view, the nonlocal correlations seem to emerge somehow from outside spacetime. However, he then adds [1, p. 86]:

> But fifty thousand times the speed of light may not be enough. Perhaps we need to repeat the experiment with greater accuracy in order to exclude speeds up to a million times the speed of light. Of course, we only get a lower estimate for the speed in the version of the privileged frame in which the Earth is stationary in the direction of motion of the superluminal transfers. Recall that the ratio of the speed of light to the speed of sound in air is about one million (340 m/s as compared with 300 000 km/s), so why shouldn't the next significant speed be once again a million times greater?

So in a sense, we're back to square one.

At this point there are some rather dismissive remarks about Bohmian mechanics, but it is interesting to see how that theory might be relevant to this discussion [1, p. 87]:

> One might also consider an influence able to travel at infinite speed, still as defined relative to some privileged frame. This is indeed possible mathematically, as was shown by David Bohm in 1952.

For Gisin, this hypothesis implies that “influences can instantaneously connect arbitrary regions of space”. He complains that we could not then understand space, because “influences could instantaneously connect arbitrarily remote regions”. But isn’t it distinctly possible that this is what is observed in the experiments? On the other hand, perhaps his problem is that these ‘influences’ are, in his understanding, due to some physical thing moving between the measurements by Alice and Bob? But then he says that, accepting such influences as an explanation for nonlocal correlations means that one accepts that these influences do not in fact propagate in our space, but follow some short cut of zero length outside our space. So it’s not absolutely clear what the problem is there.

For Gisin, and many others, the explanatory power of the ontological hypothesis of Bohmain mechanics seems weak. In a footnote, he comments [1, p. 87]:

> To avoid having communication without transmission, the Bohm model assumes that certain variables are forever inaccessible to us.

But it is important to note that this is not actually an assumption of Bohmian mechanics: in fact a key aspect of this theory is that it actually *explains why* the aforementioned variables must remain inaccessible to us. In actual fact, the assumption of a particle ontology does not in this case avoid having communication without transmission. As I understand it, non-relativistic Bohmian mechanics *does* have communication without transmission in the sense that some minimum amount of information about one measurement does in fact reach the other instantaneously in whatever frame one assumes the theory to be operative.

Gisin also raises the important question as to whether intrinsically and forever inaccessible variables could possibly be ‘physical’ [1, p. 87]. But surely the Bohm variables, if they correspond to something, would be as physical as anything ‘submicroscopic’? Are the xenon atoms spelling out IBM on a nickel surface physical? How was the famous image created? Do we see what there really is there? And if not, does that make the xenon atoms less physical? It seems to me that we see only what we can somehow boost up to our macroscopic level, and the same goes for the consequences of Bohm’s particles, if that theory happens to be right. Why should we ‘get rid of’ or reject the very entities that explain what we see? We return to Bohmian mechanics in a moment.

The last paragraph of this section [1, pp. 87–8] is intriguing. It seems to be making big claims:

> Some theoreticians try to get around the difficulty of experiments that will never be able to do other than establish a lower bound on the speed of these hypothetical influences by showing that, under suitable assumptions, any hidden superluminal influence must necessarily lead in the end to the possibility of faster-than-light communication.

Relevant papers here are [3, 4]. Since superluminal signaling is forbidden by relativity theory, Gisin then concludes [1] that there is no hidden influence at any speed whatever. Of course, this assumes that relativity theory is correct, i.e., that superluminal signaling ought to be forbidden. These are important claims that need to be reviewed carefully. I shall try to comment on this in later posts.

Finally, he tells us that this "rich research programme would exclude once and for all any hypotheses involving superluminal hidden influences". He then claims that a group of theoreticians has managed to exclude all explanations of nonlocality that appeal to influences propagating at any finite speed (discussed further in [1, Chap. 10] and I return to that below). So he seems to be talking about physical somethings that go from point to point through space to set up the correlations. As I understand it, that would not be problematic for non-relativistic Bohmian mechanics, which does not propose any such thing in its ontology. According to that theory, photons would be real things that go from the source to each measurement box, but it is not suggested that anything physical goes point to point through space from one box to the other.

One might ask why there should be be only *one* frame in which the proposed superluminal something can propagate superluminally. What we are testing with the SJ experiment is the idea that there's only one frame for this in the universe and only one possible superluminal transfer speed for this physical thing to transfer at relative to that frame, even though it will appear to transfer faster than light in any other inertial frame, in fact faster and slower in various other frames. As mentioned before, in Minkowski spacetime, if that's the right one here, and for any $u > c$, there will be a frame in which it will be transferred at speed u. Indeed, there will be a frame in which it is transferred instantaneously, and yet others in which it reaches its destination *before* it is sent, although one could just interpret that as a transfer in the opposite space direction, disregarding one's intuitions about cause and effect. This is the nature of spacelike separations in the Minkowski structure.

But we might imagine that spacetime is not Minkowskian, or is not *just* Minkowskian [5]. Then there could be something like a preferred 'slicing' of the spacetime into timelike 'leaves'. This might be thought of as providing a notion of absolute simultaneity. Then when we say, for example, that something is transmitted at 10^6c, we mean precisely that it is propagating at 10^6c with respect to *this* frame provided by the leaves. This would be what is called (I think confusingly) a *privileged* frame. There will still be observers for whom (in so far as the purely Minkowski structure is concerned) such a transmission would appear to arrive before it is sent, or would arrive instantaneously. But unless they were ignorant of this additional spacetime structure, they should not feel bothered. They should not try to explain these apparent anomalies, but just recognize it as a kind of illusion that an effect was preceding its cause, or simultaneous with it. They should simply agree that the actual causation is perfectly forward-in-time in the privileged frame that really matters for such things.

This way of putting things suggests that spacetime might be Minkowskian *plus* some extra structure, but one might also say that, by following this route, one is simply rejecting relativity and going back to some pre-Einsteinian view of spacetime, e.g., a Lorentzian view, where there is some 'ether' or privileged frame, and then the illusion of a Minkowski spacetime structure emerges from the accident that the laws of nature, i.e., the laws of electromagnetism, etc., happen to have a Lorentz symmetry [6, Chap. 9]. In a sense then, we have fooled ourselves into thinking that there is no true notion of absolute rest (or absolute time) because we cannot figure out any way to measure our motion with respect to the ether [5].

Another option whereby one might explain quantum correlations with superluminal transfer of QI, thereby implying that point-to-point locality is maintained while causal locality is not, is to make the hypothesis that the superluminal transfer is relative to some frame determined by the experimental setup itself. One such proposal has led to the so called before–before experiment first proposed by Scarani and Suarez [7] and put to the test by Gisin et al. [8]. I discuss this in a separate post.

References

[1] N. Gisin: *Quantum Chance. Nonlocality, Teleportation and Other Quantum Marvels*, Springer, Heidelberg (2014)

[2] D. Salart Subils, A. Baas, C. Branciard, N. Gisin, H. Zbinden: Testing the speed of 'spooky action-at-a-distance', Nature **454**, 861–4 (2008)

[3] V. Scarani, N., Gisin: Superluminal hidden communication as the underlying mechanism for quantum correlations. Constraining models, Brazilian Journal of Physics **35**, 328–332 (2005)

[4] J.D. Bancal, S. Pironio, A. Acin, Y.C. Liang, V. Scarani, N., Gisin: Quantum nonlocality based on finite-speed causal influences leads to superluminal signaling, Nature Physics **8**, 867 (2012)

[5] I am grateful to T. Norsen for the following remarks

[6] J.S. Bell: *Speakable and Unspeakable in Quantum Mechanics*, revised edn., Cambridge University Press (2004)

[7] A. Suarez, V. Scarani: Does entanglement depend on the timing of the impacts at the beam-splitters? Phys. Lett. A **232**, 9–14 (1997)

[8] H. Zbinden, J. Brendel, N. Gisin, W. Tittel: Experimental test of nonlocal quantum correlation in relativistic configurations, `arXiv:quant-ph/0007009v1 4 Jul 2000`