The Before–Before Experiment

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The Satigny–Jussy experiment, run by N. Gisin and his group and described in [1, 2], tests one variant of the hypothesis that quantum correlations might be explained by superluminal transfer of quantum information (QI) in some form or another between entangled photons. More specifically, the superluminal transfer is assumed to 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.

The before–before experiment, first proposed by Scarani and Suarez [3] and put to the test by Gisin et al. [4], makes the hypothesis that the superluminal transfer is relative to some frame determined by the experimental setup itself. But which frame exactly? That is something that was definitely not very clear in the original paper [3] and caused me quite a lot of difficulty in grasping what was going on when I read the brief summary of this in [1, p. 88 ff.].

This is my account based on [4]. I use the usual jargon. So we have Left and Right measuring some entangled feature of each wing of an entangled system at spacelike separation. There are two possible outcomes on each wing, denoted $+$ and $-$. Then $P \otimes 1$ is the projector onto one possible outcome (say $+$) for Left and $1 \otimes Q$ likewise for Right. We denote these just by P and Q. The state of the whole system is ψ.

First we assume that the QM value for the probability for getting $++$, viz., $\langle P \otimes Q \rangle_\psi$, will be correct whenever the situation is right with regard to any relative motion the two wings may have (e.g., none) and one of the measurements is before the other. We call these the before–after (ba) and after–before (ab) experiments, without specifying the frame in which we should make this temporal assessment. This QM value for the probability is also written suggestively

$$\langle P \otimes Q \rangle_\psi = \langle Q \rangle_{P\psi} \langle P \rangle_\psi$$

and

$$\langle P \otimes Q \rangle_\psi = \langle P \rangle_{Q\psi} \langle Q \rangle_\psi \ ,$$

these being equivalent because, for example,

$$\langle P \rangle_{Q\psi} := \frac{\langle Q\psi | P | Q\psi \rangle}{\langle Q\psi | Q\psi \rangle} = \frac{\langle P \otimes Q \rangle_\psi}{\langle Q \rangle_\psi} \ .$$

They are suggestive because one might like to think of

$$\text{prob}(++\,|\text{ba}) = \langle Q\rangle_{P\psi}\langle P\rangle_\psi \ ,$$

with the idea that P is first, collapsing ψ to $P\psi$, whence the probability of also getting $+$ on the right *afterwards* is $\langle Q\rangle_{P\psi}$. Likewise, one might think of

$$\text{prob}(++\,|\text{ab}) = \langle P\rangle_{Q\psi}\langle Q\rangle_\psi \ ,$$

with the idea that Q is first, collapsing ψ to $Q\psi$, whence the probability of also getting $+$ on the left *afterwards* is $\langle P\rangle_{Q\psi}$.

This is a bit laborious, but it's better to be clear. We have [4, (17)–(19)]

$$\begin{aligned}\text{prob}(++\,|\text{ba}) &= \langle Q\rangle_{P\psi}\langle P\rangle_\psi \\ &= \text{prob}(++\,|\text{ab}) = \langle P\rangle_{Q\psi}\langle Q\rangle_\psi \\ &= \text{prob}(++\,|\text{QM}) = \langle P\otimes Q\rangle_\psi \ .\end{aligned}$$

Before–Before According to Gisin [1, 4] and Scarani and Suarez [3]

If the two measurements are made in experiments that are suitably moving apart, we can arrange the timing so that each considers in its rest frame to have been done first. Gisin's interpretation seems to be this: the quantum state cannot have collapsed when Left does her measurement so the probability of $+$ is $\langle P\rangle_\psi$. But likewise the quantum state cannot have collapsed when Right does his measurement so the probability of $+$ is $\langle Q\rangle_\psi$. Then the probability of $++$ is the product of these, as though they were independent. So we end up with

$$\text{prob}(++\,|\text{bb})^{\text{Gisin}} = \langle P\rangle_\psi\langle Q\rangle_\psi \ .$$

This is of course different from the QM probability $\text{prob}(++\,|\text{QM}) = \langle P\otimes Q\rangle_\psi$.

We get similar things for outcomes $+-$, $-+$, and $--$, viz.,

$$\text{prob}(+-\,|\text{bb})^{\text{Gisin}} = \langle P\rangle_\psi\langle Q^\perp\rangle_\psi \ ,$$

$$\text{prob}(-+\,|\text{bb})^{\text{Gisin}} = \langle P^\perp\rangle_\psi\langle Q\rangle_\psi \ ,$$

and

$$\text{prob}(--\,|\text{bb})^{\text{Gisin}} = \langle P^\perp\rangle_\psi\langle Q^\perp\rangle_\psi \ ,$$

where $P^\perp$ and $Q^\perp$ are the projectors onto the minus outcomes. These are all products of probabilities, of course. The main message here is that there should be no correlation between the results of the measurements on the left and right if this interpretation is right.

We have to make the above statements about the collapsing state very carefully, more carefully than I have done. We should say that the quantum state cannot yet have collapsed when Left does her measurement, as judged in the frame that is relevant for this assessment, viz., the frame moving with the experiment (or the observer, or the relevant part of the apparatus, etc.), so the probability of $+$ is $\langle P\rangle_\psi$. But why is that the relevant frame?

Before–Before According to Lyle

When I read Chap. 9 of [1], I had a rather different idea about what was supposed to be happening here. On p. 88, he speaks about something (quantum information) travelling superluminally:

> [...] when Alice's box produces a result, it informs the rest of the Universe, and in particular, Bob's box, at a superluminal speed. And conversely from Bob to Alice. Hence the first to produce a result informs the second, which then takes it into account to win Bell's game [...]

Of course, he doesn't say here who decides which measurement is first. But my reaction is this. When I draw the Minkowski spacetime diagram for the two experiments moving apart, with measurement at event L on the left and measurement at event R on the right, I can draw a straight line from L to R which is of course everywhere spacelike but moving forward in time for the person who made the measurement at L, and likewise, I can draw a straight line from R to L which is also everywhere spacelike but still moving forward in time for the person who made the measurement at R.

In my causal way of thinking, the measurement at R has been informed of the outcome at L and must somehow take it into account. In this view, the QI goes from L to R and collapses ψ by the time Right makes his measurement. But QI has also gone from R to L and collapsed ψ by the time Left makes her measurement. This seems to be a reasonably objective view of what might happen, especially with the talk about something crossing space, albeit faster than light, and it considers the transmission of that something to be caused by the measurement experiments and to have a motion determined in the frame of those experiments.

Of course, it depends on the superluminal something being sent forward in time in the frame of the measurement that somehow triggers it, whereas the view in [1, 3, 4] is that the superluminal something would have to be going forward in time in the frame of the measurement/experiment/observer that somehow receives it, which is not the case for the straight lines mentioned in the last paragraph – each is going backward in time for the measurement/experiment/observer that receives it.

Actually, my view of the before–before experiment is precisely the view of the after–after experiment in [1, 3, 4].

After–After According to Gisin [1, 4] and Scarani and Suarez [3]

If the two measurements are made in experiments that are suitably moving toward one another, we can arrange the timing so that each considers in its rest frame to have been done after the other. Gisin's interpretation seems to be this: Right does his measurement at event R after the event L of Left's measurement *as assessed in his frame*, so he assumes that the quantum state on his wing must be either $P\psi$ or $P^{\perp}\psi$, one of the two possible collapsed states. Likewise

Left does her measurement at event L after the event R of Right's measurement *as assessed in her frame*, so she assumes that the quantum state on her wing must be either $Q\psi$ or $Q^{\perp}\psi$, one of the two possible collapsed states.

Of course, we have a problem in suggesting probabilities here, because what Left or Right assume, or think, or believe, is clearly irrelevant to those probabilities. (This is physics after all, not psychology.) So here is what Scarani and Suarez suggest [3], and not unreasonable, except that I think one could equally attribute it to the outcomes in the before–before experiment if one considers that the important frame for assessing QI transfer is *not* the one *receiving* the QI but the one *emitting* it! They propose

$$\begin{aligned}\mathrm{prob}(++|\mathrm{aa})^{\mathrm{Gisin}} = {} & \langle P\otimes Q\rangle_{\psi}\langle P\rangle_{Q\psi}\langle Q\rangle_{P\psi} + \langle P\otimes Q^{\perp}\rangle_{\psi}\langle P\rangle_{Q^{\perp}\psi}\langle Q\rangle_{P\psi} \\ & + \langle P^{\perp}\otimes Q\rangle_{\psi}\langle P\rangle_{Q\psi}\langle Q\rangle_{P^{\perp}\psi} + \langle P^{\perp}\otimes Q^{\perp}\rangle_{\psi}\langle P\rangle_{Q^{\perp}\psi}\langle Q\rangle_{P^{\perp}\psi}\ .\end{aligned}$$

What is the thinking behind this? In Gisin's subjective terms [4, p. 15]:

> The idea is that Alice's system evaluates the projector P in either the state $Q\psi$ or $Q^{\perp}\psi$ depending on its guess for the outcome of Bob's system.

Of course, these physical systems do not really make guesses about what happened to their entangled partners!

I have another, but I think objective, description of what might be happening if this kind of calculation is relevant, but let us see how it could be attributed to the before–before experiment.

Before–Before According to Lyle Again

Concerning the above probability calculation, perhaps one could put things like this. This is a picture in which information is sent superluminally from each measurement *in the frame in which the measurement is made*. In the before–before experiment, each measurement is made before the other in the relevant frame because the measurements are made in frames that are suitably moving apart. This means that, by the time L is made, information from R has already caused the wave function to collapse; but also, by the time R is made, information from L has already caused the wave function to collapse. But then one might wonder which collapse is operative.

The suggestion is that there might be different effective collapses in each wing. So we have things like this: with probability $\langle P\otimes Q\rangle_{\psi}$, L is informed of a collapse to $Q\psi$ and R a collapse to $P\psi$, whence the probability of ++ gets a contribution $\langle P\otimes Q\rangle_{\psi}\langle P\rangle_{Q\psi}\langle Q\rangle_{P\psi}$. But with probability $\langle P\otimes Q^{\perp}\rangle_{\psi}$, L is informed of a collapse to $Q^{\perp}\psi$ and R a collapse to $P\psi$, whence the probability of ++ gets a contribution $\langle P\otimes Q^{\perp}\rangle_{\psi}\langle P\rangle_{Q^{\perp}\psi}\langle Q\rangle_{P\psi}$. And so on. In this view, the usual quantum joint probabilities $\langle P\otimes Q\rangle_{\psi}$, $\langle P\otimes Q^{\perp}\rangle_{\psi}$, etc., serve merely to inform as to how often such and such information is transferred (superluminally) between the measurements about the putative collapse of the wave function, and this regardless of what collapse *actually* occurs in each wing.

After–After According to Lyle

Then in this alternative view of the after–after experiment, in which it is the frame of the photon *emitting* the QI that counts, there is no time for such information to pass in the relevant frames, and the relevant wave function for each measurement ought to be just the uncollapsed wave function ψ. In this case, we predict complete independence of measurement results at L and R and we expect *no correlation*.

Summary

There are in fact *two* possible alternative theories here, not just the one discussed in [1, 3, 4]. If we consider that quantum information (QI) is shared between the photons, or rather between the measurement events, we might imagine that to be transferred at superluminal speed from one to the other, even travelling somehow point-to-point through space. In that case, Suarez and Scarani's Principles I and II in [3] assume that this superluminal transfer occurs in the frame of the photon *receiving* the QI. Then in the before–before experiment, neither photon could have received QI from the other, so one expects no correlation.

However, one might also assume that the superluminal transfer occurs in the frame of the photon *emitting* the QI. Then in the before–before experiment, each photon would have time to inform the other, in its frame, of what had happened to it. The interpretation of the before–before experiment in this theory would be precisely the interpretation of the after–after experiment (if only one knew what that should be) in the previous theory. In fact the interpretation of the aa and bb experiments would be reversed between these two theories.

I note that both Scarani and Gisin agree with this possibility (private communication). Scarani notes that he and Suarez have already recognised the existence of this second theory in their paper [5].

Results of Experiment

Gisin and coworkers were able to run this astonishing experiment with the beam-splitters moving apart in such a way that each measurement was made prior to the other as viewed in its own frame. The quantum correlations were observed as usual. This rules out the theory that QI is transferred superluminally in the frame of the photon receiving the QI.

However, according to a footnote in Gisin's book [1, p. 89]:

> When Suarez learnt of our result, he immediately came to Geneva and observed that the student had set up the experiment the wrong way round: the mirrors were moving toward one another rather than moving apart! And none of us had noticed. We were not proud of ourselves! The experiment was corrected and repeated, but the result was the same.

If the results were the same, i.e., the quantum correlations persisted, they also falsified the second theory here! That is, they ruled out the theory that QI is transferred superluminally in the frame of the photon emitting the QI.

Future Posts

I hope to comment on other papers by the authors mentioned here, and in particular [5]. Note also a wealth of information and commentaries at the website [6]. Since references to Bohmian mechanics crop up in Gisin's book [1] in relation to the Satigny–Jussy and before–before experiments, it will be interesting to see what is going on there. Indeed it is in Bohmian mechanics that the potential conflict between quantum nonlocality and Minkowski spacetime structure stands out most clearly. Useful references here would be [7, 8].

References

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