Special Report

Can Neutrinos be Superluminal? Ask OPERA!

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Abstract

Four days ago a rumour started circulating in the comments at Resonaances that some "6.1 sigma" signal of new physics had been seen at CERN. I reported it in an update on the Seminar Watch post. There had been a seminar titled "Seminar DG" which was listed on indico and removed the day before it was due. The rumour confirmed that this meeting was rescheduled to Friday but as an update on OPERA, the neutrino experiment which a couple of years ago saw its first tau neutrino. The claim now is that they have measured the speed of muon neutrinos and got a result faster than the speed of light!

Key Words: neutrino, superluminal, faster than light, CERN, OPERA.

This is of course a crazy idea because if true it would violate everything we think we know about causality. Even if neutrinos are hard to detect it should be possible to use them to send information into the past if this result holds up. That does not sound very likely (but I am now setting up a neutrino beam to send the news back in time so that it was actually me who leaked the story) .

Hypothetical superluminal particles are known as tachyons and they always move faster than light because they have *imaginary valued* mass, but quantum field theories for tachyons have terrible problems. Aside from the causality issues, the vacuum becomes unstable because you can create neutrino pairs with negative energy out of nothing. You would need a very

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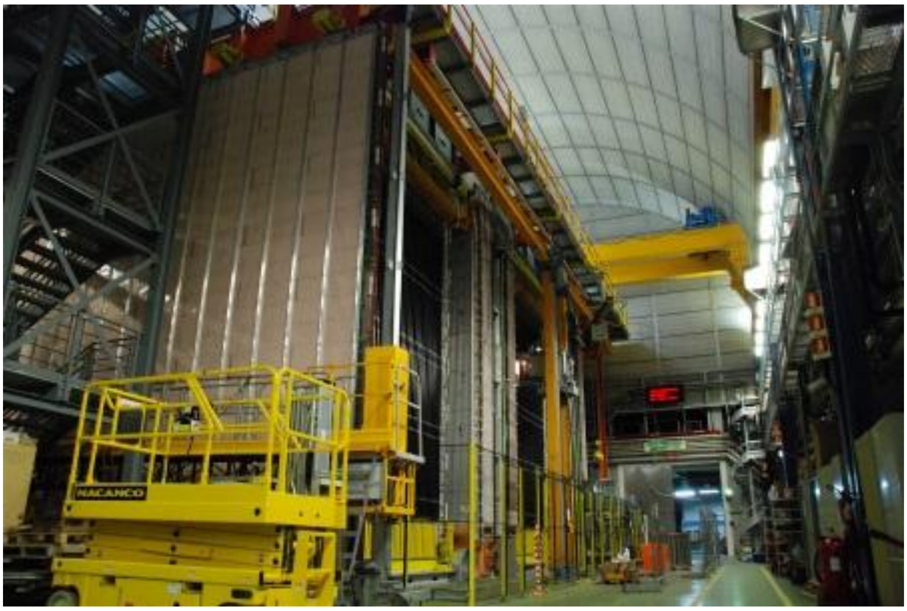
unconventional variation of relativistic quantum field theory to stop the universe degenerating into an instant burst of neutrinos, and we don't have that.

However this is not the first time that superluminal neutrinos have been reported. Some people claimed that observations of neutrinos arriving before gamma rays from supernovae implied that they are superluminal see http://arxiv.org/abs/hep-ph/9712265 . Other people just say that the neutrinos were created before the gamma rays. In fact some "crazy" people believed in superluminal neutrinos well before that. Early attempts to measure the squared mass of the neutrino in the 1990s always seemed to give negative results I have not had time to look back at that old ideas but it may be time to do that.

Of course such extraordinary claims need very good evidence and for now the most likely explanation by far is a systematic error. The rumoured "6.1 sigma" significance is probably a statistical error and it will be important to consider any systematic sources of error before coming to conclusions. For now we will need to wait for the official seminar at CERN on Friday to see what they have to say about that.



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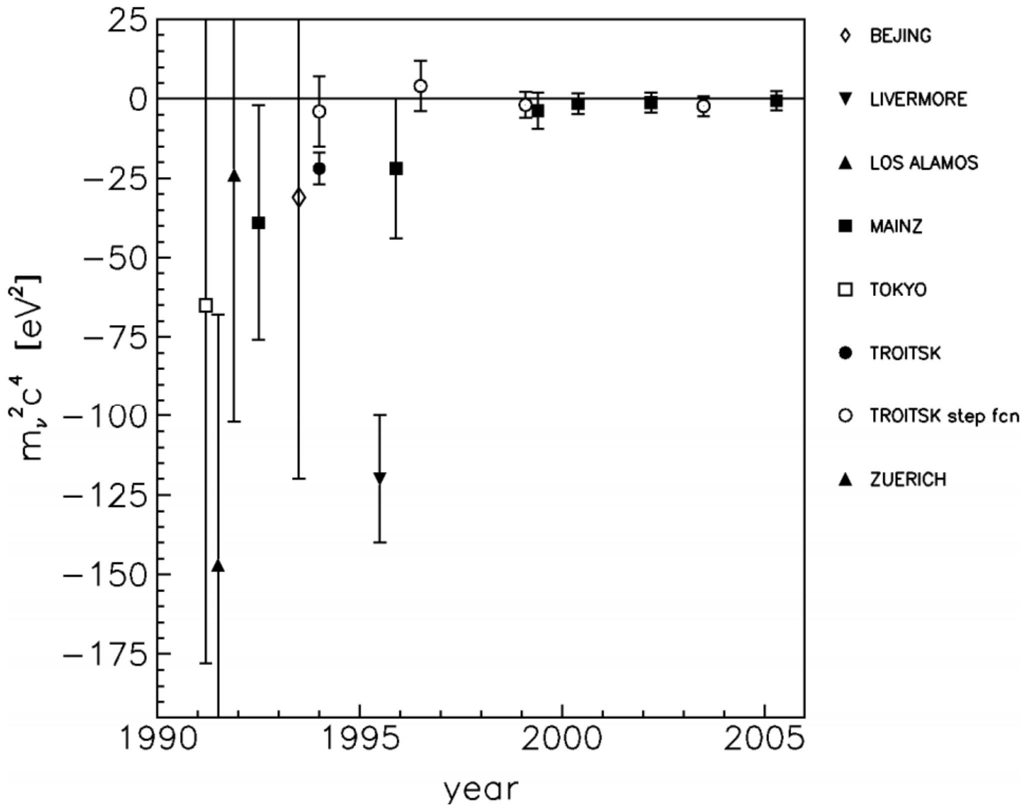
Update: It is of course worth recalling that the MINOS experiment also measured the neutrino speed and got a result faster than the speed of light at 1.7 sigma see http://arxiv.org/abs/0706.0437 If the OPERA measurements are consistent with this measurement it will have to be taken seriously. As far as I can tell no measurement of neutrino speed or mass refutes the claim that they are tachyons, it's just the theory that's a problem.

Measurements of mass-squared from beta decay in Tritium have tended to give negative value results with error bar consistent with zero or positive values. This plot from http://arxiv.org/abs/0909.2104 shows how the measurements have developed over time. The latest result I can find is -0.6 ± 2.2 (stat) ± 2.1 (syst) eV^2 from http://arxiv.org/abs/hepex/0412056. These are measurements for the lectron anti-neutrino, not the muon neutrino that OPERA is looking at.



If you are wondering about theories that allow tachyonic neutrinos the least wacky one I can find is that neutrinos can take "shortcuts off the brane through large extra dimensions"

What about the Supernovae observations? The timing of neutrinos vs light from supernova 1987a constrains the speed of neutrinos to be within one part in 10^{-8} of the speed of light, while the MINOS measurement had a speed of about $(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$ so this seems inconsistent, even taking into account any differences of energy. Since neutrinos oscillate between different flavours we can't make the excuse that one case looks at electron neutrinos and the other muon neutrinos, can we?

That said, neutrino physics has many unknowns. Other experiments hint at sterile neutrinos and even differences in mass between neutrinos and their anti-particles, even though we don't even know what kind of spinors they are yet. If the large extra dimension theory has any bearing they may only travel faster than light in the presence of a gravitational field. It all sounds too crazy to be true but I am reserving judgement until at least we have heard from OPERA to see what they are actually claiming and how confident they are.

Meanwhile we have other views from Motl, Strassler and Kea.

Update 23-Sep-2011: The news is now officially out with a CERN press release and an arxiv submission at http://arxiv.org/abs/1109.4897 The result they have obtained is that the neutrinos arrive ahead of time by an amount 60.7 ns ± 6.9 ns (statistical) ± 7.4 ns (systematic). On the face of it this is a pretty convincing result for faster than light travel, but such a conclusion is so radical that higher than usual standards of scrutiny are required.

The deviation for the speed of light in relative terms is $(v-c)/c = (2.48 \pm 0.28 \pm 0.30) \times 10^{-5}$ for neutrinos with an average energy of 28.1 GeV The neutrino energy was in fact variable and they also split the sample into two bins for energies above and below 20 GeV to get two results.

13.9 GeV: $(v-c)/c = (2.16 \pm 0.76 \pm 0.30) \times 10^{-5}$

42.9 GeV: $(v-c)/c = (2.74 \pm 0.74 \pm 0.30) \times 10^{-5}$

These can be compared with the independent result from MINOS, a similar experiment in the US with a baseline of almost exactly the same length but lower energy beams.

3 GeV: $(v-c)/c = (5.1 \pm 2.9) \times 10^{-5}$

If we believe in a tachyonic theory, with neutrinos of imaginary mass the value of (v-c)/c would decrease in inverse square of the energy. This is inconsistent with the results above where the velocity excess is more consistent with a constant independent of energy, or a slower variation.

We also have a constraint from supernova SN1987A where measurement of neutrino arrival times compared to optical observation sets $|v-c|/c < 2 \times 10^{-9}$ for neutrino energies in the order of 10 MeV. For smaller energies we should expect a more significant anomaly so this is important, but perhaps the energy dependence is very different from this expectation.

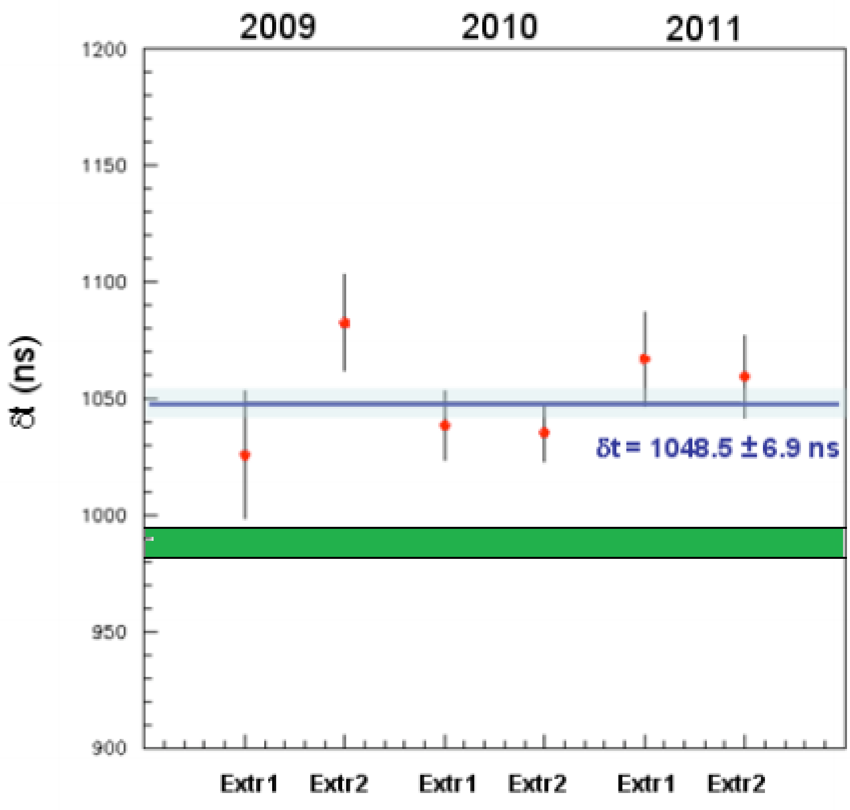
So if this is a real effect it has to be something that does not affect the cosmic neutrinos in the same way. For example it may only happen over short distances or in the presence pf a gravitational field. It would still be a strong violation of Lorentz invariance of a type for which we do not really have an adequate theory.

So obviously there could be some error in the experiment, but where? The distances have been measured to 20cm accuracy and even earthquakes during the course of the experiment can only account for 7cm variations. The Earth moves about 1m round its axis in the time the neutrinos travel but this should not need to be taken into account in the reference frame fixed to Earth. The excess distances by which the neutrinos are ahead of where they should be is in the order of 20 meters, so distance measurements are unlikely to be a source of significant error.

Timing is more difficult. You might think that it is easy to synchronous clocks by sending radio waves back and forward and taking half the two way travel time to synchronise, but these experiments are underground and radio waves from the ground would have to bounce off the upper atmosphere or be relayed by a series of tranceivers. This is not a practical method. What about taking atomic clocks back and fourth between the two ends of the experiment? the best atomic clocks lose or gain about 20 pico seconds per day, but portable atomic clocks at best lose a few nanoseconds in the time it would take to get them from one end to the other. This could be a good check to carry out if a good atomic clock could be flown on a helicopter, but as far as I know this has not been done.

Instead the best way to synchronise clocks over such distances is to use GPS which sends signals from satellites in low earth orbit. Each satellite has four atomic clocks which are constantly checked with better groundbased clocks. The ground positions are measured very accurately with the same GPS and in this way a synchronisation of about 0.1 ns accuracy can be obtained at ground level. The communication between ground and experiment adds delay and uncertainty but this part has been checked several times over the course of the experiment with portable atomic clocks and is good to within a couple of nanoseconds. The largest timing uncertainties come from the electronic systems that are timing the pulses of neutrinos from the source at CERN. The overall systematic error is the quoted 6.9 ns, well within the 60 nanosecond deviations observed. Unless a really bad error has been made in the calculations these timings must be good enough.

The rest of the error is statistical so it is worth looking at the variations in timings to see if another error could be hidden there. Here is a plot from the paper of some of the timings over the years the experiment has run. The blue band shows the average delay relative to timing delays assuming travel at the speed of light that were calculated later to be 987.8 ns. I have added a green band at this time plus or minus the 6.9 ns systematic error so that we can see how cleanly the measurements are displaced.



It looks pretty consistent. I think the only conclusion we can draw at this point is that further independent results are required. Perhaps MINOS could upgrade their timing measurements to see if they get a similar result with increased precision. T2K might also be able to attempt a measurement but their baseline is 295km compared with 730km for OPERA and MINOS. Otherwise a new experiment with shorter neutrino pulses and superaccurate timers may be the only way to resolve it. OPERA could also remove possible systematic timing errors at the source end by installing a second (much smaller) neutrino detector much nearer to CERN.

Some more reports: arstechnica , BBC, and of course Dorigo whose earlier post was ordered off line by big cheeses at CERN. Look out for his repost of his interesting review of where he thinks problems may lie.

Post-talk update: The webcast talk at CERN was very interesting with lots of good questions. The most striking thing for me was the lack of any energy dependence in the result, a confirmation of what I noted this morning. The energy of the neutrinos have a fairly wide spread. If these were massive particles or light being refracted by a medium there would be a very distinct dependence between the speed and the energy of the particles but no such dependency was observed. The speeker showed how the form of the pulse detected by OPERA matched very nicely the form measured at CERN. If there was any kind of spread in the speed of the neutrinos this shape would be blurred a little and this is not seen.

Most physical effects you could imagine would have an energy dependence of some sort. A weak energy dependence is possible in the data but that would still be hard to explain. On the other hand, any systematic error in the measurement of the time or distance would be distinguished by just such a lack of energy dependence.

The only physical idea that would correspond to a lack of energy dependence would be if the universe had two separate fixed speeds, one for neutrinos and one for photons. I don't think such a theory could be made to work, and even if it did you would have to explain why the SN1987A neutrinos were not affected. I think the conclusion has to be that there is no new physical effect, just a systematic error that the collaboration needs to find.

References

1. http://blog.vixra.org/2011/09/19/can-neutrinos-be-superluminal/