SNOLAB and the OPERA results

September 28, 2011 - Neutrinos are a type of sub-atomic particle, which have no electrical charge, interact very weakly with normal material and have a very small, but non-zero, mass. When they were first postulated to resolve a problem in studies of radioactive decay, where energy apparently disappeared from certain reactions, they were assumed to be impossible to detect - indeed Pauli who proposed them wrote, 'I have done a very bad thing, and proposed a particle that cannot be observed'.

Since that time, through studies of nuclear reactions in the Sun, cosmic ray interactions in the atmosphere, nuclear reactions in the Earth and in nuclear power plants, we now know much more about the neutrino. We know it comes in three 'flavours' that interact weakly (called electron, muon and tau neutrinos), we know they have a non-zero mass, we know they can change from one flavour to another. There are billions of neutrinos from many sources streaming through your body every second as you read this. Almost all pass through you, the Earth and the Sun, without noticing anything.

The Sudbury Neutrino Observatory was one of the key instruments developed to study neutrinos from the Sun, and solved the 'solar neutrino problem' where earlier measurements had shown there was apparently fewer electron-type neutrinos coming from the Sun than we expected. This could be interpreted as not understanding the nuclear fusion reactions in the Sun, or not understanding the neutrino itself. SNO proved that we didn't understand the neutrino well enough, and the electron-type neutrinos created in the Sun had changed flavour by the time they reached the Earth, giving a deficit of this particular type of neutrino. This proved categorically that neutrinos have mass and are not massless, one of the major steps of contemporary particle physics, showing physics beyond our current standard model is most likely required.

There are still many questions remaining, such as the exact mass of the neutrino particles, whether the neutrino has an antiparticle, the probability that one changes to another and whether it can help explain the matter-antimatter asymmetry seen in the Universe. Many studies therefore continue to look at the physics of neutrinos, and are helping to push the boundaries of our current understanding of the Universe.

One of these studies is the CNGS beam. A beam of neutrinos is created at CERN, fired through the Earth from Geneva to the Gran Sasso underground facility in Italy, where it is detected by several large particle detectors. The OPERA experiment is one such device, and has recently published a pre-print showing that the neutrinos from CERN are traveling faster than the speed of light.

If true, this overturns one of the cornerstones of modern physics. The theories of relativity developed by Einstein at the start of the last century are predicated on the belief that the speed of light is the limit at which particles can travel. All massless particles, such as the photon, travel at this speed when in a vacuum, and this defines the maximum speed at which information can be conveyed between two points. The Special Theory is derived from this basic assumption, which then leads into the General Theory of Relativity which describes the interplay between matter and space-time. Both of these theories have been tested extensively through experimental observation and are now the basis for modern technology such as the GPS system where both theories need to be applied to determine accurately one's position in time and space. If true, this result would immediately point to the requirement for new physics to understand space and time, areas which physicists have been working on for several decades such as quantum gravity and string theory, which may provide avenues to explain this result. It should be stressed that we know General Relativity works as a description of space-time at certain energies, but these descriptions are further refinements. This is similar to the way in which Newtonian gravity can put man on the moon, even though we know this is an approximation refined by General Relativity.

Another consequence of this result would be that we break causality, the statement that cause precedes effect. This is because information is carried at the speed of light, and so having massive particles travel faster than light would allow effect to precede cause. Indeed, this is contrary to expectation for massive particles, where sub-luminal speeds are expected due to the interactions of neutrinos with matter.

To overturn this basic assumption of modern physics would therefore be totally revolutionary, and hence needs extreme care and scrutiny applied. The scientific methodology does not just dismiss or accept this claim out-of-hand, but requires careful study of the results, the systematic errors that may effect the experiment, and confirmatory evidence from other projects.

To measure the speed of the neutrinos between CERN and Gran Sasso, three things are needed: the distance between the source and detector, the time of each pulse leaving CERN and arriving at Gran Sasso, and knowledge of the statistics of each pulse. Individual neutrinos are not tracked from CERN to Gran Sasso, as they are so weakly interacting, rather bunches of neutrinos are tracked and so knowledge of what each bunch looks like is required. The measurement of time and distance relies on careful study of timing signals from GPS, and propagation of these signals to the underground facility. Significant study has been done by the OPERA team to ensure this measurement is robust, although cross-checks will need to be done. To put the result in context the distance between CERN and Gran Sasso is 730km, the shift needed to bring the speed of the neutrinos back to the speed of light is only 20 m. However, these types of measurements are well understood and so will be cross-checked by the scientific community. The knowledge of the neutrino beam bunches themselves also needs to be studied, as here there are many effects than could come in to play - the neutrino beam fans out from CERN, so OPERA may be sampling a part with a different characteristic to that at Geneva, the production of neutrinos is via a proton beam slammed into a target, so a clear understanding of the production mechanisms and stability will be required.

Confirmatory evidence is also possible from other 'long-baseline' neutrino experiments around the world. Two that could provide immediate input would be the MINOS experiment in the US and T2K in Japan, both using neutrino beams fired through the Earth to large detectors. Analysis and further studies will no doubt be conducted by these collaborations.

Another problematic indicator for super-luminal neutrinos is that neutrinos have already been seen in 1987 from a Supernove (SN1987A) in the Large Magellanic Cloud. These neutrinos arrived a few hours earlier than the light pulse from the supernova, which is entirely consistent with expectation from our understanding of supernova explosions. If the neutrinos were superluminal they should have arrived many years before the light. However, a cautionary statement here is that the energy of supernova neutrinos is a factor of 1000 lower in energy that those seen by OPERA, and so the superluminal process may only turn on at these higher energies, although there is no theoretical reason to understand why this energy is so fundamentally important to space-time.

And so, the OPERA result illustrates the scientific process at work. One group have found an experimental result which would have great importance for physics and our understanding of the Universe. This result will now be assessed, checked, studied for subtle systematic effects and tested by other projects. It will probably go away as these additional tests are applied, but if it doesn't then physics will never be the same.

For more information please review “New Constraints on Neutrino Velocities” by Cohen and Glashow found here: http://arxiv.org/pdf/1109.6562