Neutrinos – the next big small thing

10 September 2012 by Robert Adler
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With the Higgs safely in the bag, could ethereal neutrinos guide us towards the new physics we are so keenly seeking?

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(Image: Joshua D. Cox)

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"UNEASY lies the head that wears a crown," wrote Shakespeare. The same could be said today of the standard model of particle physics, our most successful description of the building blocks of matter and their interactions. The recent discovery of a particle that looks very much like the Higgs boson stands as the theory's crowning achievement, validating a prediction made nearly four decades ago and filling the model's last major gap. Yet we are as eager as ever to knock it from its throne, to discover the new physics that must surely supersede it. "The standard model *is* particle physics," says Nobel prizewinning physicist Jack Steinberger. "But there are many unanswered questions that are extremely elusive at the moment."

Those questions include the nature of dark matter - the mysterious, invisible material thought to make up more than 80 per cent of the mass of the universe. Then there is dark energy, the stuff reckoned to be causing the universe's expansion to accelerate. In what must rank as our worst prediction, particle physics overestimates dark energy's magnitude by a factor of 10^{120}. The standard model also cannot explain how matter survived the big bang, or how gravity fits into the picture. It is riddled with so-called "free parameters", troublingly arbitrary numbers that have to be fed into the theory by hand, for example to set the strength of the interactions it describes.

Researchers had hoped that the Higgs would lead to the new physics that is needed to explain away these difficulties. But with the Higgs behaving largely as expected so far, the real key to the kingdom beyond the standard model may lie with a different sort of particle: neutrinos.

Neutrinos hit the headlines in September last year when the OPERA experiment under Gran Sasso mountain in Italy clocked them apparently travelling faster than the speed of light, an activity forbidden by Einstein's special theory of relativity. Six months later, the finding was traced to a glitch in the experiment. Even so, there is plenty more to say and learn about these beguiling particles.

Ghostly, mysterious and antisocial - they rarely deign to interact with the world of common matter around them - much of what is known about neutrinos lies outside the standard model. The three neutrinos we know about fit neatly enough. They pair with the electron and its two heavier cousins, the muon and the tau. A trio of antineutrinos also exists, which pair with the positively charged

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antiparticles of the electron, muon and tau to complete the extended lepton family (see chart). But at the outset, the standard model wrongly assumed neutrinos have no mass, and even now it cannot specify the masses they do have. It did not foresee their ability to shape-shift from one type into another, nor the fact that there might be more than three of them.

Many new theories hope to fill in those gaps, including grand unified theories, supersymmetry and string theory. One of them might gain traction by explaining why neutrinos are so very weird. Neutrinos themselves might in turn tell us which theory is on the right track.

Despite their aloof nature, neutrinos have a long history as problem-solving particles. Physicist Wolfgang Pauli conceived of them in 1930 in order to conserve energy and momentum in radioactive beta decays. More recently, neutrinos have moved to the forefront of our efforts to explain how matter came to dominate antimatter in our universe. "Neutrinos allow you to access another world for the simple reason that they are not so strongly interacting with us in the visible world," says theorist Patrick Huber at Virginia Tech in Blacksburg.

Flavour change

The first cracks in the standard model's description of neutrinos came 15 years ago. Up until then, most physicists assumed - as did the theory - that neutrinos are massless. However in 1998, the Super-Kamiokande experiment in Japan proved that this wasn't the case (see photo). Neutrinos are emitted or absorbed with electron, muon or tau flavour, like single scoops of ice cream. Super-Kamiokande studied muon neutrinos from cosmic rays striking the atmosphere and found they could morph into electron neutrinos on their way through Earth. Other experiments investigating neutrinos created in nuclear reactors, particle accelerators and nuclear decay processes in the sun have confirmed that, however they start out, neutrinos shape-shift into a tutti-frutti mixture of flavours on their journey, with each scoop containing a hint of all three. According to quantum mechanics, the only way such morphing can happen is if neutrinos have mass. Indeed, we now understand that each of the three neutrino flavours propagates through space as a different, constantly changing mixture.

That leaves us with a conundrum. "Neutrino mass tells us that the standard model needs to be extended, but it doesn't tell us how," says theoretical physicist Lawrence Krauss at Arizona State University in Tempe. In contrast, some grand unified theories - which go further by attempting to unite all the forces of nature except gravity - do predict neutrinos with mass, so pinning down the actual masses could tell theorists which theory to pursue. "There have been decades where people have speculated about grand theories which can explain the masses in various ways," says Joe Formaggio at the Massachusetts Institute of Technology, "but if you're going to come up with a theory that explains masses, you'd better have the masses."

Measuring the mass of an invisible particle that can sail unhindered through a slab of lead a light year thick is easier said than done. Catching neutrinos is a matter of patience, of watching long enough with big enough detectors until one eventually interacts. To do it, we have been stalking neutrinos at two radically different scales - the subatomic and the cosmic. Seventy years ago, Enrico Fermi envisioned measuring neutrino mass by measuring radioactive beta decays. In a typical beta decay, a neutron inside an atomic nucleus turns into a proton while spitting out an electron and an electron antineutrino. Although the antineutrino is undetectable directly, Fermi outlined how its mass could be inferred from the energy and momentum of the accompanying electron. Neutrinos, however, are so light that it has been impossible to achieve the sensitivity needed. An exquisitely sensitive experiment being built at the Karlsruhe Institute of Technology in Germany, called KATRIN, may yet win the race to accomplish that in the next few years.

Meanwhile, the tightest limits on neutrino mass come from the cosmos: the particles' fingerprints can be found on the mix of elements created in the big bang and supernovae, on the expansion rate of the universe, on the cosmic microwave background (CMB), and on how matter coalesced into galaxies and galaxy clusters.

A combination of cosmological measurements reveal that the sum of the three neutrino masses cannot exceed more than about 0.3 electronvolts (eV) - more than a million times smaller than the next lightest particle, the electron. "To me it's exhilarating that you can look at all the galaxies and clusters in the universe and detect the mass of this tiny particle," says Scott Dodelson, a cosmologist at Fermilab in Batavia, Illinois. Frank Close of the University of Oxford thinks that message should be taken to heart. "We don't appreciate the magic of what we're doing," he says. Early next year, analysis of observations of the CMB from the Planck space observatory should significantly hone our limits on the sum of the

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neutrino masses.

Breaking that sum down into the masses of the individual mass states is made difficult by their constant shape-shifting. Measuring the shifts allows us to draw inferences, and an analysis of the best existing data puts the mass of the lightest state at about 0.05 eV.

That still leaves a puzzle. "Why it is that neutrinos are so anomalously light compared with everything else is bizarre," says Close. "It's as if they want to be nothing and yet weren't allowed to be."

As if the three "normal" neutrinos were not antisocial enough, one theory suggests they may be shadowed by one or more "sterile" neutrinos. Unlike regular neutrinos, which feel the weak force inside nuclei and so occasionally interact with particles contained there, sterile neutrinos feel only gravity and so fail to interact with ordinary matter at all. Sterile neutrinos fascinate theorists since their discovery would break away from the standard model, and help explain not only dark matter but perhaps why there is matter at all (*New Scientist*, 18 February, p 8). "They may well participate in forces beyond the standard model that we have not discovered yet," says theoretical physicist Boris Kayser of Fermilab.

Matter wins

Over the years, experiments have spun off a string of anomalies that point to one or more sterile neutrinos with a small mass of about 1 eV (see "Strange surplus"). Predicted neither by the standard model nor by grand unified theories, their confirmation would hand researchers just the kind of new physics they are looking for.

The recent publication by an international group of almost 200 neutrino physicists of a "white paper" on sterile neutrinos reflects the interest they have stirred up. It describes some 21 experiments that are running, planned or proposed to try to track them down. "A large number of institutions are getting very excited about this," says Carlo Rubbia, a Nobel prizewinning particle physicist at CERN. "We hope progress is coming fast."

Along with sterile neutrinos, researchers are stalking another prize - a difference between neutrinos and antineutrinos that could help explain why our universe is dominated by matter, and so why we are here to notice. According to our best understanding of cosmology and particle physics, matter and antimatter were created in equal amounts at the big bang. What followed was a maelstrom of interactions, and in this melee matter and antimatter should have annihilated to leave nothing but a cosmos full of light. Clearly this hasn't happened. "We have no good explanation for why the universe is made entirely of matter," says Janet Conrad at MIT. "It's a very embarrassing problem."

"It's perhaps the most fundamental question we can ask about the universe, and neutrinos can provide a window into that question," says Alexandre Sousa at Harvard University.

That window is a theory called leptogenesis, and it relies on a phenomenon called CP violation. What this means is that if you look at a particle reaction, and then the same reaction viewed in a mirror and with particles swapped for their antiparticles, you will see the two reactions proceeding at slightly different rates. It has been spotted in lab experiments with composite particles made up of quarks, but the imbalance seen there is not sufficient to explain why the antimatter created in the big bang vanished. The idea of leptogenesis is that in the first microseconds after the big bang, the young, hot universe contained extremely heavy, unstable sterile neutrinos that soon decayed, some into leptons and the remainder into their antimatter counterparts, but at unequal rates. This imbalance need only be tiny - one part in a billion. But it would mean that when the matter mopped up all the antimatter, enough leptons remained behind to eventually transform into the protons and neutrons that went on to form stars, galaxies and planets.

Heavy sterile neutrinos and their standard-model counterparts are thought to have been inextricably linked in the early universe: according to a theoretical process known as the see-saw mechanism, neutrinos acquired their puzzlingly light masses by interacting with their heavyweight counterparts when the universe was extremely hot. If the picture of leptogenesis is true, we should see neutrinos and antineutrinos behaving in a slightly imbalanced way too.

So far, experimentalists have not uncovered any convincing neutrino CP anomalies. Fermilab's MINOS experiment created a buzz in 2010 when it found slight differences in the way that muon neutrinos and their antineutrino counterparts shape-shift as they travel over long distances, but by 2012, with more data, the difference disappeared.

Still, the prospects for glimpsing CP violation are good. Earlier this year, researchers at the Daya Bay Reactor Neutrino Experiment, based in southern China, measured a crucial parameter called theta13, which describes how neutrinos change flavour. A low theta13 would have made CP violation hard to find, and zero would have ruled it out. To the researchers' delight, however, the value turned out to be surprisingly large, implying that future experiments have a good chance of finding CP violation. "We now think we have the big picture," says André de Gouvêa, a theorist at Northwestern University in Evanston, Illinois. A first glimpse of the detail may come from Fermilab's Nova experiment, touted to have the best chance yet to detect neutrino CP violation. "It's the one experiment that can look at this over the next decade," says Sousa.

Even if neutrinos show CP violation, it is only part of the story. Leptogenesis only works if neutrinos, including the sterile variety, are so-called Majorana particles. This means that, unlike most other particles in the standard model, they are identical to their antiparticles and get their mass through the see-saw mechanism.

If this is indeed the case, we would expect to observe a process known as neutrinoless double beta decay that the standard model frowns upon. In normal beta decay, a neutron changes into a proton and emits an electron and an electron antineutrino. Some nuclei can undergo two such decays at once, in which case we would expect two antineutrinos to be emitted. If these antineutrinos are identical to neutrinos, however, they will annihilate each other on emission, and the reaction will produce just two protons and two electrons.

"Neutrinoless double-beta decay is the smoking gun that neutrinos are Majorana particles," says Alan Poon of Lawrence Berkeley National Laboratory in California. "It would give lots of tips to theorists on how to update the standard model, and it ties back to the very early universe - how we got more matter than antimatter."

Chasing the dream

Another allure of neutrinoless double-beta decay experiments is that the mass of the neutrino influences the reaction rate, allowing us to pin down this quantity too. "You get two very interesting pieces of physics - the mass of the lightest neutrino and the fact that neutrinos are Majorana particles," says Art McDonald, a particle astrophysicist at Queen's University in Kingston, Ontario, Canada.

So far, only one group claims to have seen neutrinoless double-beta decay, a Russian-German collaboration that first published their study of germanium decays in 2002. No other experiment has replicated their results. New findings from the Enriched Xenon Observatory, near Carlsbad, New Mexico, using a bath of liquid xenon, show that if neutrinoless double-beta decay exists at all, it is extremely rare - perhaps vanishingly so (*Physical Review Letters*, vol 109, p 032505). Nevertheless, so great would be the prize of observing it that it remains the object of multiple research projects.

Many questions about neutrinos remain open. Sheldon Glashow, a Nobel prizewinning theorist at Harvard University, says what is needed are more and better experiments. "I don't think there's much to do until we have some experimental guidance," he says.

Francis Halzen, who heads the IceCube Neutrino Observatory, an experiment to measure cosmic neutrinos passing through Earth that is situated under the ice at the South Pole, agrees. "We chase new physics connected with neutrino oscillation. We may discover that neutrinos have non-standard-model interactions. We may discover there are sterile neutrinos mixing in with the three standard neutrinos," he says, "or something totally out of the blue."

The problem, they point out, is resources. Among the next experiments that have been proposed is the Long Baseline Neutrino Experiment, managed by Fermilab. It would be an intense neutrino beam fired hundreds of kilometres through Earth's mantle to a large detector weighing many thousands of tonnes. Another is the UK-to-Japan Neutrino Factory, which would create an intense beam of neutrinos and ping it to a detector on the other side of the world. Both would take decades to build and cost many billions of dollars.

It's worth the money and effort, says Rubbia. "This is one of the areas in which new discoveries are possible, but we don't know from which direction these discoveries will come. So we have to take a very courageous view to find out what's coming next."

Strange surplus

It was a few flashes of light two decades ago that started the story of the biggest neutrino anomaly of them all. They occurred at the Liquid Scintillator Neutrino Detector (LSND) at Los Alamos National Laboratory in New Mexico, and each represented the passage of a neutrino through the detector's massive tank of mineral oil. Those flashes revealed that more muon antineutrinos than expected had changed into electron antineutrinos en route from a particle accelerator 30 metres away.

The leading explanation for the surplus is that on their way they briefly morph into undetectable "sterile" neutrinos, giving them another route to effect their transformation. By 1998, when LSND ended, the excess was still there and had reached a significance of 3.8 standard deviations - not enough to claim an outright discovery of sterile neutrinos, but sufficient to claim hints of them at work. "We were left with a very surprising result," says Bill Louis at Los Alamos, who worked on the experiment.

Still, the LSND anomaly would probably have faded into oblivion had it not been bolstered by a series of similar findings.

Researchers at Fermilab in Batavia, Illinois, built the MiniBooNE experiment to check LSND's results. It started by looking for muon neutrinos morphing into electron neutrinos, although at higher energies and over a longer distance than LSND. Then it switched to antineutrinos like LSND, The details are complicated, but it too found hints that sterile neutrinos might exist.

A completely different experiment has also suggested the existence of sterile neutrinos. One of the early experiments to detect neutrinos streaming from the sun used tanks of gallium, which solar neutrinos could transmute into a detectable germanium isotope. Researchers calibrated their detectors using known radioactive sources. In two separate projects, based underground in Italy and Russia, detectors snared 15 per cent fewer neutrinos than expected from models of how many should have been produced - the so-called GALLEX and SAGE anomalies. Again, a likely explanation is that some neutrinos shape-shifted into an undetectable form.

BIG SPLASH

Then there are the newly discovered anomalies at nuclear reactors. Improved calculations of the way nuclei capture neutrinos, and how many neutrinos nuclear reactors generate, indicate that several experiments over the past three decades should have found on average 7 per cent more neutrinos than they actually did. "When we discovered this anomaly, we were not looking for sterile neutrinos at all," says Thierry Lasserre, a neutrino physicist at CEA, in Saclay, France. "It was a big surprise to us."

Louis checks off MiniBooNE, SAGE, GALLEX and the reactor anomalies. "All of those appear to be consistent with LSND," he says. "This has given additional incentive to look into sterile-neutrino models."

Janet Conrad at the Massachusetts Institute of Technology and her colleagues have just published a very promising model which proposes three sterile neutrinos paralleling the three flavoured ones. The new model explains most of the anomalies found close to neutrino sources. "You can't assume that there's just one sterile neutrino," Conrad says. "We put in three plus three and get a very good fit for both the disappearance and appearance data. We think that's going to be very big and splashy."

Lasserre proposes more experiments to settle the problem. He wants to insert an intense radioactive source into the heart of an existing detector. If light sterile neutrinos with a mass of about 1 electronvolt are produced by such a source, they should oscillate relatively fast into and out of detectable flavours. "You would see these beautiful oscillating patterns," says Lasserre. "If you manage to do this, either you find something or you are sure there is no sterile neutrino." He hopes to see those oscillations or "kill the anomalies" within five years.

Robert Adler *is a writer in Santa Rosa, California*

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The Most Fundamental Question

Thu Sep 06 18:12:02 BST 2012 by **Eric Kvaalen**

"We have no good explanation for why the universe is made entirely of matter," says Janet Conrad at MIT. "It's perhaps the most fundamental question we can ask about the universe" says Alexandre Sousa.

No, not at all. The most fundamental question is why the universe exists at all (and why it has the laws that it has).

If you "run the film backwards" to time zero, starting from what we see today and using standard physics, you get a scenario in which there is more and more matter and antimatter, but always the same excess of matter. We can't really rule that out.

I would also like to point out (again) that neutrinos going faster than light does not contradict Relativity, according to a letter published by NS: (long URL - click here)

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The Most Fundamental Question

Mon Sep 10 14:55:09 BST 2012 by **Mark Bridger**

"We have no good explanation for why the universe is made entirely of matter,"

The answer to that is very simple. Things always start with one, not two, A cosmos can only come into existence with asymmetry. I've described a scenario.

"The most fundamental question is why the universe exists at all (and why it has the laws that it has)."

That's two different questions. My answer to the first is because an (infinite eternal) universe cannot not exist and/or it's beyond the realm of science to know a reason why a cosmos exists.

Why the cosmos has the laws it has is I believe explicable given a theory that starts with the right precept (that the greater universe is infinite and eternal)

"I would also like to point out (again) that neutrinos going faster than light does not contradict Relativity, according to a letter published by NS: (long URL - click here) "

Unless the neutrino has mass, in which case it won't be able to get past the speed of light - being released from an inertial particle.

But this article kind of clarifies that there is very little understanding of what neutrinos really are.

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The Most Fundamental Question

Tue Sep 11 14:35:44 BST 2012 by **Mark Bridger**

The article says; " Then there is dark energy, the stuff reckoned to be causing the universe's expansion to accelerate. In what must rank as our worst prediction, particle physics overestimates dark energy's magnitude by a factor of 10 to the power of 120"

So, there's an elephant in the Cosmos!

That figure suggests not only that 'dark energy' is not the explanation for the accelerating expansion of the cosmos but that space can't be an expanding context (or it would be expanding much faster). So, the accelerating expansion is objects moving apart, against the context of space, rather than space expanding and carrying objects with it (nflation).

If that's the case then space/ the greater universe is always eternally infinite, making the big bang a local event probably surrounded by infinite others. That then provides an explanation for the accelerating expansion of the cosmos (as an effect of it's relationship with the surrounding infinite universe) in terms of gravity and the conservation of overall momenta.

This explanation (which predicted (in 94) the observations (of post 98) also explains the 'clumping' that is too advanced for the standard model, and a dark matter effect.

I've elborated elsewhere see; (long URL - click here)

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The Most Fundamental Question

Mon Sep 10 20:41:20 BST 2012 by **Karl**

If neutrinos shift between flavours with different rest masses, then by determining the times between shifts we ought to be able to put a strict upper limit on the differences in mass. If all three are different we ought to be able to determine the ratios between them from the times spent in different flavours.

Combining the two should give an independent measure of the upper limit on neutrino mass.

Why is this never mentioned? Is it common knowledge that never makes to the popular press?

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The Most Fundamental Question

Tue Sep 11 06:43:16 BST 2012 by **Eric Kvaalen**

I don't think it's correct that "if all three are different we ought to be able to determine the ratios between them from the times spent in different flavours". As I understand it, the mass difference tells you the rate of conversion, but we can't determine the actual masses. It's like having two independent linear equations and three unknowns.

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The Most Fundamental Question
Tue Sep 11 16:29:31 BST 2012 by **Karl**

Why not? The uncertainty principle principle puts an upper limit on time x deviation from average mass. Unless of course the missing mass is going somewhere, but where would that be?

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The Most Fundamental Question
Tue Sep 11 19:08:43 BST 2012 by **Eric Kvaalen**

Yes, we can figure out the deviations from the average mass. But we can't figure out the average mass. That's what I was trying to say.

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The Most Fundamental Question
Wed Sep 12 01:30:41 BST 2012 by **Karl**

Unfortunately I think you're right. We can't get the ratio of masses this way, only the ratio of the differences.

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Surprise Is Likely
Mon Sep 10 20:44:55 BST 2012 by **Dirk Pons**
http://cordus.wordpress.com/2012/05/23/exciting-things-for-neutrinos-to-do/?preview=true&preview_id=312&preview_nonce=5a29f800f7

Neutrinos are great wee beasts! Thank you for an interesting article Robert.

The article ponders from which direction the next discoveries will come. Well, while others are building large machines, some of us are taking the conceptual approach, and we have some early results that may be of interest to neutrino-watchers.

Our work, which is conjectural, suggests neutrinos are leading characters in the drama of fundamental physics. We have a non-local hidden-variable (NLHV) solution that predicts their structure, explains their mass & speed, identifies why they have left-hand spin (and right for antineutrinos). It also explains CP violation along the way.

Neutrinos are also incriminated in the asymmetrical baryogenesis problem, but with an unexpected twist in the plot. The workflow is proposed to be as follows: the antielectron from pair-production is remanufactured into matter, more specifically the proton, and the unwanted handedness is carried away from the scene by the antineutrino.

This is a bold and radical proposal, and we acknowledge its validity is uncertain, but when it comes to neutrinos nothing seems too exotic to be considered. Whatever the truth about neutrinos, they seem likely to surprise.

Thank you

http://vixra.org/abs/1111.0022

http://vixra.org/abs/1111.0035

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Question On Flavour Change
Tue Sep 11 15:47:28 BST 2012 by **Mike**

Where does the difference in mass go when neutrinos flip to a different flavour?

Am I assuming correctly that the energies (velocities) of the neutrinos will change spontaneously via E=mc^2 ?

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Question On Flavour Change
Tue Sep 11 16:37:19 BST 2012 by **Karl**

I was assuming the difference is temporary, as allowed by the uncertainty principle. That's why I think you can determine the ratios between masses from the times spent in each flavour.

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