The T2K Collaboration (2020), *Constraint on the Matter-Antimatter Symmetry-Violating Phase in Neutrino Oscillations,* Nature, 580, 339–344.

Last week we mentioned the idea of a review article – an article which brings together a whole series of research and provides some form of commentary on it. When writing a review article, the author performs what we call a *literature review* – they read as much as they can about the topic, hunting down different references, to form a complete picture. This is the process that PhD students typically start with when they begin their studies to become accustomed to their research area.

This week, we're going to have a two week deadline, so that you can perform a mini literature survey. This won't be a traditional literature review as you won't be reading papers to find the majority of the information, but useful web pages and videos. We're not going to ask you to hunt for links yourself – we'll provide them – but you might want to look further if something doesn't make sense or you suddenly want to delve into more detail. We're not going to ask you to write one giant piece either, we're going to use our Cornell notes style and give detailed descriptions of the different aspects of our topic.

Our topic is going to be the very recent results from a particle physics experiment called T2K in Japan. It's another huge collaboration of scientists from all over the globe looking to understand one of the most significant questions in modern day physics – *why did the universe come to be filled with matter?* Our current understanding of the laws of physics have quite a big hole in them when it comes to the creation of everything around us – the big hole being that our laws say that the universe should really be empty.

Our aim this week is to:

- Perform a review to understand what each of the basic ideas behind this experiment are below – you can use your own knowledge, or links and videos that you find, but we have given some links too.
- Armed with this knowledge, we're going to read three popular articles about the experiment to give us a rounded view of what's going on.
- Finally, we're going to take some glimpses at the paper that has been published on this work. This will only be glimpses as this paper is not the most readable to non-experts. In truth, I don't understand 75% of it, so I've asked for lots of help from the Particle Physics department at Warwick. We're going to focus on specific bits of the paper that we should be able to understand.

Before we get started, I just want you to think about how far you've come during Journal Club. How would you have felt about reading part of a current particle physics paper? In fact, here's the link now, read the abstract on the webpage and then download the PDF and just flick through the pages *very quickly*. Is it as intimidating as it would have been if I'd given this to you in week one? It probably doesn't look like a stroll in the park – there are some big formulae and some odd looking graphs – but hopefully you can see that it's not as intimidating any more.

We're going to start by looking at some of the general ideas from particle physics that we need to know. We've provided some ideas for answers and some useful links to get you started.

The standard model – useful link; useful video playlist	
Matter-antimatter asymmetry – useful link	
Charge conjugation	A mathematical operation that converts a particle into its antiparticle. If I apply *charge conjugation* to an electron, then the result is its antiparticle – the positron. If I then apply charge conjugation to the positron, I return to the electron.
Parity – useful link	Parity is another mathematical operator that turns a system into its mirror image. If I have a particle moving to the right in the real world, then the parity operator 'flips it' so that it is moving left – so that it is now moving as if 'in a mirrored world' compared to the original. We would tend to think that the laws of physics stays the same whether or not we 'flip the coordinates' and live in the mirrored world or not. This is called parity symmetry, or P-symmetry – a ball will fall in the same way if you throw it to the left or to the right. Parity symmetry applies at the quantum level too (sometimes…) and any interaction that is via the electromagnetic or strong nuclear interaction will look the same whether or not the system is viewed normally or in the flipped mirrored world.
Spin and the 'handedness' of particles – the helicity section of this link is useful.	Fundamental particles have a property called spin. It is analogous to a much larger body spinning. If you imagine a particle moving out of this page, the particle could be spinning in a clockwise or anticlockwise direction as we look at it. Take your hands and point your thumbs towards your face – the fingers of you left hand are curled in a clockwise direction and the fingers of your right hand are curled in an anticlockwise direction. We use this convention to define the handedness of the particle. If the particle is moving towards you and spinning anticlockwise, it is a right-handed particle. If

	the particle is moving towards you and spinning clockwise, it is a left-handed particle. If we look at the particle in a mirror, such that it is moving in the opposite direction, then it's handedness will change (in a similar way to you seeming to be the opposite handedness when you look at yourself in a mirror).
Parity violation – useful link	
CP Symmetry (Charge-Parity symmetry) – useful link	A combined symmetry which is invariant for the majority of fundamental interactions.
CP Violation – useful link	

Now we have this idea that the imbalance that we see in the universe (the dominance of matter over antimatter) may have been caused by some asymmetry in the laws of physics – matter and antimatter may behave ever so slightly differently.

We're now going to look at the specific particles that are measured by the T2K experiment – neutrinos. Remember, from a quantum mechanical point of view (the laws that apply to the smallest of particles) particles can behave as waves. We describe their behaviour with a wavefunction which encapsulates all of the information about the state of the particle. Specifically, the square of the wavefunction gives us the probability of finding that particular particle at a particular point at a particular time. This wavefunction changes or evolves over time and that is going to be crucial for this experiment.

Neutrinos – useful link; useful long panel discussion	
Neutrino oscillations – useful link one; useful link two; very useful video (particularly towards the end)	

T2K – useful link one; useful video	
Cherenkov radiation	

You might hear articles talk about the ‘mixing angle’ of neutrinos – this isn’t a physical angle at all, but a way of quantifying the probability of a neutrino swapping flavours.

With our mini literature review complete, we’re in a much better position to read our popular articles. We’ll provide some comprehension questions for each one. We also have some example answers for the more difficult questions which Professor Gary Barker has kindly agreed to give. He is part of the T2K team.

Natalie Wolchover (2020), *Neutrino asymmetry passes critical threshold* can be accessed at this link.

Comprehension questions:

1. Are antineutrinos the ‘mirror image twins’ of neutrinos?

   A mirror flips spatial components of an object. An antiparticle is typically more than merely an upside-down particle, instead all of the quantum numbers of a particle are flipped e.g. a electron has a charge of -1 and a positron has a charge of +1. However, as neutrinos are such an odd sort of particle, there are very few differences between a neutrino and an antineutrino. The have opposite lepton number - a quantum number which is conserved in interactions and is in some sense just an accounting mechanism. The only other difference is that they have opposite chirality – you can think of this as the ‘handedness’ of a particle – and this naturally flips in a mirror. So antineutrinos, owing to the oddness of neutrinos themselves, seem very much the mirror twin of the neutrino. But in the truest sense, they are not, and we must consider them the CP opposites of one another.

   Prof. Gary Barker’s answer: “*The important point is that neutrinos and antineutrinos are not really just mirror images of each other but “CP opposites” i.e. all internal quantum numbers are reversed (the `charges) and all spatial properties are mirrored (e.g. momentum). Note that a spin vector does not change sign in a mirror but momentum does and so e.g. a left-handed state will change into a right-handed* *state under parity. Couple this with the C -operator changing the sign of all the charges and you have changed the quantum mechanical description of a neutrino into an antineutrino."*

2. Why is this measurement so important?

    Because it's one of the purported mechanisms that led to the dominance of matter over antimatter. From our current understanding of the laws of physics, pure energy can turn into mass if the mass produced comes in the form of equal amounts of matter and antimatter. The downside of this is that the antimatter and matter can then mutually annihilate to form pure energy again. There must have been a mechanism that tipped the balance ever so slightly in the favour of mass to allow the universe to exist in its current state today.

3. What is the difference between 'evidence' and a 'discovery'?

    It's to do with the level of statistical significance within your data. If there is only a 0.3% chance of your signal being due to chance, then you have *evidence*. If there's a 0.00006% of the signal being due to chance, you are much more certain and can therefore claim a *discovery*. These limits are not, though, rigorous limits but guidelines.

4. Why are further experiments necessary?

    As more data is needed to claim a discovery, to ensure that the 'evidence' was definitely not due to chance. Note that the sensitivity of a measurement can be improved by taking more data with the same experiment – so using T2K for longer - or designing a more precise experiment or (even better) doing both, which is what the next generation of neutrino oscillation projects will do (e.g. DUNE).

5. Why do we not notice the 'trillions [of neutrinos] each second" that pass through our bodies?

    Because they don't strongly interact with matter. Neutrinos only interact by the weak interaction (which has a relatively weak coupling). Neutrinos do not carry any electric or strong charge.

6. Describe what is being shown by the diagram in "A Window on the Asymmetric Universe".

    The symmetry side shows oscillations in both neutrino and antineutrino flavours happening in the same time period – the oscillations are symmetrical. In an asymmetric scenario, on the other hand, neutrinos and antineutrinos oscillate between flavours at different rates.

    In the box 'Primordial Universe' the difference in decay rates is suggested as a reason for the dominance of matter in the universe today. Primordial, supermassive neutrinos and antineutrinos may also have oscillated at different rates. Remembering that they are also annihilating if neutrino meets an equally flavoured antineutrino, in the second step of the diagram, we start to see an imbalance occur.

7. Looking at the numbers of electron neutrinos and electron antineutrinos detected, explain why this finding is only ‘evidence’ rather than a ‘discovery’.

    Whilst the data certainly shows a deviation from the expected numbers in a symmetrical universe, the numbers remain small so the difference between measured and expected is not that large – they found 12 more electron neutrinos and 5 fewer electron antineutrinos than expected. Whilst this is significant in showing there is an imbalance, there is still some margin for error – a couple of electron antineutrinos more or less has a significant difference on the result. With more data, the discrepancies will become clearer.

8. How are charge conjugation and parity symmetry linked to the discussion of the ‘handedness’ of the neutrinos?

    When viewed through a charge conjugation mirror, a neutrino becomes an antineutrino. Charge conjugation is the mathematical operation that can convert a neutrino wavefunction into an antineutrino wavefunction.

    When viewed through a parity mirror, a left handed particle becomes a right handed particle.

    Combining both together, a left handed neutrino viewed through a CP symmetry mirror will turn into a right handed antineutrino.

Silvia Pascoli and Jessica Turner (2020), ***Matter-antimatter symmetry violated*** can be accessed at this link.

Comprehension questions:

1. What are fermions?

    They are spin half fundamental particles. The fermions can be split into two families: quarks and leptons. There are six members of each of these families (so 12 matter fermions). There are antiparticle counterparts to all of them (so 12 antimatter fermions).

2. What are leptons?

    One of the branches of fermions. Unlike the quark branch, leptons don’t take part in the strong interaction. They interact via the electromagnetic and weak interactions (as well as the gravitational interaction). There are 6 matter leptons: electron, muon and tau all have a charge of -1; the electron neutrino, muon neutrino and tau neutrino are electrically neutral and have a much smaller mass. All of these matter leptons have antimatter counterparts.

3. What is leptogenesis?

The umbrella term given to the physical process that led to the dominance of leptons over antileptons. In the bible, Genesis tells the story of creation (genesis is the Greek word for beginning), so leptogenesis is the idea behind the creation of leptons (instead of antileptons).

4. What is meant by the neutrino flavour being described as a quantum superposition of the different mass states?

   Schrodinger's cat describes the hypothetical situation in which a cat trapped in a box with a sealed vial of poison that is opened via a random, quantum mechanical process. As you don't know whether the cat is alive or dead, it is considered to be a superposition of both. When you make a measurement (when you lift the lid), this superposition collapses into one state or the other. The same is true of neutrinos – they live as a mixture of different states and can collapse into either one when measured.

5. Describe what is shown in Figure 1.

   This diagram aims to show the that as the mass states of the neutrino change over time in different ways (the three wave like structures), then at different points, the neutrino is composed of different 'portions' of each mass state. If a measurement were to be taken, the proportions of the mass states at that given moment may lead the neutrino to be seen as a flavour different to its original one.

   The figure further demonstrates that the oscillation for neutrinos and antineutrinos may be different and thus break CP symmetry. In the figure, the antineutrinos evolve at different times to the neutrinos, despite them being in a mirror (which is meant to show the hypothetical CP symmetry that we would naively expect).

   Prof. Gary Barker's answer: "*This is a rather difficult situation to paraphrase. Flavour states are those that take part in the weak interaction i.e. the ones we measure with T2K. You can consider each flavour state to be composed of 3 `mass states' which are states of definite energy (and hence mass). As the flavour states propagate, the mass states get out of phase with each other because they propagate at different velocities due to their different masses. This different mixture of mass states, at any particular future time, corresponds to a particular mixture of the 3 flavour states and so, on measurement, it is possible that a flavour state other than the flavour state you started with, is the result of the measurement*."

6. What is unique about this particular finding?
   It is the first time that a significant difference has been seen between the oscillation rate involving neutrinos c.f. anti-neutrinos.

7. How is the neutrino beam produced in Tokai?

High energy protons are directed at a graphite target. In the collision, pions and kaons are produced – these are examples of mesons, particles composed of a particle and an antiparticle (of different flavours so annihilation doesn't instantly occur). The pions and kaons eventually decay, via the weak force, leading to the formation of neutrinos (or antineutrinos).

8. What do the neutrinos travel through to get to the Kamioka observatory?

   The neutrino beam is simply directed through the earth. As neutrinos barely interact with matter, they don't need to be sent down an evacuated tunnel like we would traditionally expect of a particle physics experiment.

9. In 9 years of data, we still haven't got enough information to warrant a discovery – why is this?

   Because neutrinos interact so infrequently that not enough events have been detected so far. Particle physics relies on huge numbers of detections so that we can have some statistical certainty in what has happened. Seeing one neutrino oscillation proves that they happen, but we need to measure lots to understand how often they happen and therefore if there is a difference between neutrino oscillations and antineutrino oscillations.

Dennis Overbye (2020), *Why the universe produced something rather than nothing* can be accessed at [this link](#).

1. The path to this experiment seems to be littered with Nobel prizes – what have they been won for?

   Andrei Sakharov, a nuclear physicist by day, won the Nobel Peace Prize for his work on human rights and his opposition to the abuse of power.

   Tsung-Dao Lee and Chen Ning Yang won the Nobel prize in Physics for suggesting the existence of parity violation (later detected by Chien-Shiung Wu).

   James Cronin and Val Fitch won the Nobel prize in physics for demonstrating that CP symmetry could be violated when looking at kaon decays.

   Frederick Reines won the Nobel prize in physics for first detecting neutrinos. He shared his prize with Martin Perl who first detected the tau neutrino.

   Leon M. Lederman, Melvin Schwartz and Jack Steinberger won the Nobel prize in physics for detecting the muon neutrino.

   Takaaki Kajita and Arthur McDonald won the Nobel prize in physics for the discovery of neutrino oscillations.

2. Why is this experiment alone not sufficient?

   Andrei Sakharov set three conditions that must be fulfilled to explain the genesis of the universe: CP symmetry violation is one, but he also required baryon number violation and for interactions to occur out of thermal equilibrium. This paper only provides further evidence of CP violation by demonstrating it for leptons.

3. Why are we continuing to look for CP violation in leptons when it's been seen in kaons and b mesons?

   The amount of CP violation seen in B mesons and kaons is not large enough to explain the level of matter dominance over antimatter. Also, further experiments in different situations are always useful in physics to allow us to understand where the limits of our theories lie.

4. Discuss the merit of describing neutrinos as "the most tiny quantity of reality ever imagined by a human being".

   Neutrinos are incredibly small in terms of their mass. For a long term it was thought that they had no mass at all. Equally, their lack of interaction makes them seem even smaller. Thinking of them as 'imagined' is also an interesting idea as neutrinos are certainly a physical object – but by considering them as something almost plucked from a thought, it gives them an even weaker grip on reality.

5. Why were neutrinos first suggested?

   They were suggested as a mechanism to conserve energy in radioactive decays. Measurements showed Wolfgang Pauli that energy seemed to disappear in beta decays so he suggested this additional particle as the carrier of this energy.

6. What is being described by Dr Reines when he mentions a "cat turning into a dog"?

   He is trying to convey the strangeness of neutrinos changing their flavour during neutrino oscillations. It seems utterly remarkable that a subatomic particle can simply change what it is, without any interactions, as it simply lives its life.

   Prof Gary Barker's answer: "*It is wrong to think of the neutrino changing type without any interaction having occurred. Each neutrino is a quantum superposition of 3 states (albeit changing in time) but until a measurement is made i.e. an interaction, there is no sense in which the neutrino could be considered to have spontaneously changed into another type. This is a subtle but important point because it is the essence of quantum mechanics.*"

7. How are the neutrinos and antineutrinos detected in Kamioka?

The neutrinos are detected if they interact with the large amount of pure water stored underground at Kamioka. If an interaction occurs, the products of the interaction will be travelling quickly to conserve momentum. If they are travelling faster than the speed of light in water (but not the speed of light in air of course), then light is emitted in a cone-like shape – called Cherenkov radiation. The water tank is surrounded with sensitive light detectors which look for these rings of light.

8. How might the detector at Kamioka differentiate between neutrinos coming from Tokai and the trillions of other neutrinos around?

    They're looking at the light emitted to get a sense of which direction the neutrino came from – they know that 'their neutrinos' came from a specific direction. They also monitor the production of neutrinos (indirectly as they can't measure the neutrinos themselves) at the production site and so know when to expect them.

    Prof. Gary Barker's answer: "*The most important aspect of reliably measuring only neutrinos from the beam is that the beam is produced in very short bursts and so only interactions inside a well-defined time-window are recorded. This hugely reduces the background from cosmic rays which are anyway suppressed by the experiment being under more than a kilometer of rock.*"

GLIMPSES AT THE MAIN PAPER

The main paper can be found here.

We should now be able to look through the introduction of the paper and understand a little more.

Prof Gary Barker: "*Much of the introduction section of the paper can now be understood from the earlier studies. Note that there are 2 solutions/interpretations of the oscillation data according to the two different possibilities for the `mass hierarchy' which alludes to whether neutrino mass state 3 has a mass that is higher or lower than the masses of states 1 and 2. This is currently unknown and so both possibilities must be considered but an experiment like DUNE will be able to quite easily determine from the data what the correct mass hierarchy is.*"

We can attempt to understand Figure 1 as well.

- The top panel shows the neutrino events.
- The lower panel shows antineutrino events.
- The x-axis shows the energy of the neutrinos and the y-axis shows how many have been seen – so we have a spectrum where the

experiment is counting the number of electron neutrinos seen with different energies (bearing in mind we started with muon neutrinos).

- The coloured histogram in each panel shows the scenario in which there is no CP violation.
- The measured events are shown as data points with the error bars. The error bars are large because T2K sees so few events.
- The data points, even taking into account the error bars, do not nicely fit the scenario in which there is no CP violation (i.e. the data points don't fit the coloured bars).
- The parameter governing the amount of matter/antimatter symmetry breaking in neutrino oscillations, called δ_{cp}, can take a value from -180º to 180º. There are two dotted lines added on each panel to show the values of δ_{cp} for which CP violation is *maximal*. Looking carefully, you can see the data is more aligned to the δ_{cp}= -90º= -π/2 scenario than the δ_{cp}= 90º= π/2 scenario.
- For the first time, T2K has disfavoured almost half of the possible values at the 99.7% (3σ) confidence level, and is starting to reveal a basic property of neutrinos that has not been measured until now.
- Not only that, but the statistical agreement between the data and the *extremal* situation of δ_{cp}= -90º= -π/2 indicates that the amount of CP violation seen may be close to the maximum that could be seen, which would be extremely interesting.

Think back to when you glanced over this paper, have you understood more of it now? We don't expect you to completely comprehend the paper, but hopefully you can see a better glimpse of it.

SUMMARY QUESTIONS (submit these, along with your SKIM-READ answers to thomas.millichamp@warwick.ac.uk)

What is the significance of the T2K experiment?

The history of neutrinos is filled with Nobel prizes – what makes them such a fascinating subject do you think?

Describe, as clearly and simply as you can, what the T2K experiment does and what it is looking for.

FURTHER READING

If, after all that, you still want something more to read then you’ll just have to apply to start a physics degree because even I’m worn out at this point.