Andre de Gouvea – Lecture 2 Questions

Questions marked in green were answered during the Q&A session. No attempt was made to correct grammar/spelling issues. Where a slide number was given it is shown.

Q1: (Matter Effects slide, 1st lecture): Between the 2nd and 3rd equations, why does the m^2 factor change into a deltam^2 factor?

A1: I did not mention this very carefully, but you can always add to the "Hamiltonian" a term proportional the identity. We take advantage of this to subtract off a term proportional to m_1^2/2E and express everything as a function of the mass-squared difference(s).

Q2: Could the lightest neutrino mass eigenstate have zero rest mass?

A2: Yes. This is a question we can't answer with neutrino oscillation experiments.

Q3: Why does CP violation makes oscilation amplitude of neutrinos bigger tham antineutrino ?

A3: (also addressed in lecture). C-violating effects change the oscillation probability of neutrinos relative to those of antineutrinos. They can make it both bigger or smaller, depending on the values of the CP-violating parameter delta.

Q4: What would CP violation being equivalent in the quark and lepton sectors imply? Thank you!

A4: This is a difficult question to qualify, but here are some thoughts. First, in some sense, CP-violation in the quark sector is already known to be different from CP-violation in the lepton sector because the mixing matrices (and possibly the pattern of the masses) are so different. People do speculate about whether these phenomena are related in some way. This is the subject of grand unified theories that postulate that quarks and leptons are, in fact, different components of the same fundamental objects. In these theories, one is required to "explain" why neutrino mixing and quark mixing look so different. In class, I said very quickly that the CP-odd phase in the quark sector is large, almost 90 degrees, and that it would be weird if the CP-odd phase in the lepton sector turned out to be the same! On the other hand, I don't really know what that would imply but I am sure people would come up with lots of possible reasons!

Q5: Why does P(nu_mu -> mu_e) vs P(\bar{nu}_mu -> \bar{mu}_e) let us test CP-violation instead of just C-violation?

A5: This is a very good question. The reaosn is that we are secretly flipping the spins of all the particles in the comparison. Hence, we are really comparing left-handed nu_mu to nu_e oscillations with right-handed anti-nu_mu to anti-nu_e oscillations. We already know that C and P are (maximally) violated in the weak interactions.

Q6 (CP-invariance Violation in Neutrino Oscillations slide): Did you miss a -ve sign in the conjugated amplitude of oscillation, in the exponential parts?

A6: This is an important point and the answer is no. The Exp[i ...] terms are the same for the amplitude of the process and the anti-process. I should have emphasized that A and \bar{A} are not complex conjugates of one another. One is the amplitude for the neutrino process, the other the amplitude for the antineutrino process. If one were the complex- conjugate of the other, there would be no CP-violation since the magnitude of a complex number and the magnitude of the numbers complex conjugate are always identical.

Q7: Why do neutrios should be massive in order to be able to oscillate from physics point of view becaue it is clear from euqations that massless neutrinos do not oscillate

A7: You need the neutrino masses to be different in order to have oscillations. In the language we used, oscillations happen because there are two different ways of defining neutrinos: the flavor basis and the mass basis. If all neutrino masses are the same, you can choose the mass basis to agree exactly with the flavor and hence there is no mixing nor oscillation. If all masses are zero, they are all the same and there are no oscillations.

Q8: If neutrinos happen to be Majorana particles, how will they annihilate? Or What will be the outcome of annihilation of neutrinos if they happen to be Majorana Particles?

A8: If neutrinos are Dirac fermions, a neutrino can annihilate with an antineutrino into the vacuum state, which will then “materilize” into something else, like two photons, an electron-positron pair, etc. If neutrinos are Dirac fermions, however, a neutrino cannot annihilate with an antineutrino since that would violate lepton number. They can still scatter into a different state, but the total lepton number has to be conserved (for example, we could have something like nu + nu -> e^- e^- pi^+ pi^+).

If the neutirnos are Majorana fermions, two of them can annihilate in the vacuum, i.e., lepton number would not need to be conserved (e.g. something like nu + nu -> W^+ W^- would be allowed).

Q9: In beta-decay measurement of neutrino mass, why people talk about the electron neutrino "mass" instead of the mass eigenstates? Is it because the energy resolution is so small to distinguish the individual masses?

A9: This is correct. At the end point of the beta-spectrum, the way to talk about the neutrino is to consider that either a nu_1 is produced with probability P_1, a nu_2 is produced with probability P_2, etc. The spectrum is then the sum of the different possibilities: P_1 S_1 + P_2 S_2 + P_3 S_3, where the S_i are the spectra for a neutrino with mass m_i. Because the masses are very small, I can write the spectra as S_i = S_0 + m_i^ 2 R_0 (R_0 and S_0 are some functions that do not depend on the neutrino masses). Hence, the spectrum looks like S_0 + (P_1 m_1^2 + P_2 m_2^2 + P_3 m_3^2)R_0. THe object in parenthesis what we call the electron neutrino mass. Incidentally, the P_i are elements of the mixing matrix squared (P_1 = |U_{e1}|^2, etc).

Q10: If we observe neutrinoless double beta decay we can safely eliminate the possibility of the Dirac nature of neutrinos, similarly, is there is any experiment where we can eliminate the possibility of Majorana nature of neutrinos directly?

A10: (also answered in the lecture). The answer is yes, in principle. What you need is to have the result of some experiment only be possible if the neutrinos are Dirac fermions. We looked at this recently in a paper that I think is quite accessible, https://arxiv.org/pdf/1808.10518.pdf and explores hypothetical neutrino decays. In practice, this is very difficult because, and this is the main point, in order to tell Majorana from Dirac neutrinos, you need the neutrino mass to play a role in your experiment, and neutrino masses are very tiny.

Q11: Could it be that the one or two of the mass-eigenstate neutrinos are Majorana and the other(s) are Dirac? How would they mix into flavor-eigenstates if their fermionic nature is different?

A11: The short answer is that, given what we know about mixing, either all neutrinos are Majorana or all neutrinos are Dirac.

Q12: For the Dirac Neutrino, if the Neutrino does have mass, does that mean there is a right handed neutrino (also known as a sterile neutrino)?

A12: Saying things carefully, if the neutrinos are Dirac fermions, then right-handed neutrino and left-handed antineutrino degrees of freedom exist. From a more theoretical point of view, it means there is a new field in the theory, the right-chiral neutrino. This right-chiral neutrino field has no gauge quantum numbers and is what we call a sterile neutrino field. This does not mean that there is a new sterile neutrino particle. The number of neutrino flavors is still three.

Q13: From oscillation experiments we can only conclude that the masses of neutrinos have to be different. Is it possible in the theory for one neutrino to have a mass of 0? What would be the implication for the Majorana Neutrinos in this case? Is it possible in the theory for two being Majorana particles while the third is not?

A13: As I wrote in A2, it is possible that the lightest neutrino mass is zero. If this is the case, we can't ask whether the zero-mass neutrino is a Majorana or a Dirac fermion: whatever you call it, it will behave exactly the same (keep in mind that massless fermions are weird).

Q14: Is neutrino-electron scattering process useful for distinguishing Dirac from Majorana neutrinos?

A14: If you are talking about elastic electron-neutrino scattering, the answer is no. If one is willing to consider more adventurous inelastic scattering processes (something like looking for nu + e^- to W^- Z^0, which would violate lepton number) the answer is theoretically yes but in practice definitely no.

Q15 (slide 40): Can we get constraints on cp violation in neutrino oscillations by limits on cp violation in the charged lepton sector?

A15: (also addressed in the lecture). Strictly speaking, the answer is yes but in practice the answer is no. The reason is that in order to see CP-violation, the physics processes needs to be sensitive to the fact that neutrino masses are different (and hence not zero). This renders the rate for the would-be process ridiculously small (one example is the neutrino contribution to the electric dipole moment of the electron, which is CP-violating obervable).

Q16: Can you touch on how sphaleron processes work and how they relate breaking lepton number and baryogenesis/matter-antimatter imbalance?

A16: These are non-perturbative electroweak phenomena at finite temperature that allow one to violate both baryon-number and lepton-number (but preserves baryon number minus lepton number). The reason this is important is as follows. Imagine that lepton number violating processes exist. This means I can start with a universe that has as many electrons as antielectrons and as many neutrinos as antineutrinos (one has to be careful about what an "antineutrino" means, but I will gloss over that) and end up, after some time, with more leptons that antileptons (or vice-versa). The spheleron processes allow me to convert some of the excess of antilepton number into an excess of baryon number (more baryons that antibaryons). One cartoon is the following. If I have a box with 10 positrons in it, the sphaleron process can help convert some of the these into protons (e.g. 5 positrons and 5 protons). This way, I transform a lepton asymmetry into a baryon asymmetry.

Q17: Could neutrinos talk to a different Higgs boson and still be Dirac?

A17: Yes. Strictly speaking, you can add a Higgs boson for each fundamental fermions (this is constrained by what we are learning concerning the SM Higgs boson, but this is a different story). The reason we don't like this idea is that these different Higgs bosons all have the same quantum numbers. Here is a reference on the collider phenomenology of this. There are more interesting references inside: https://arxiv.org/pdf/1009.4413.pdf

Q18: If neutrinos talk to the standard Higgs, does this mean that the standard model gauge group is not correct?

A18: No, neutrinos would talk to Higgs just like everyone else, in a way that preserves the SM gauge symmetry. In order to do that, we need a new fermion - the right-chiral neutrino fields (or variants thereof).

Q19: If neutrinos were Dirac particles acquiring mass through the standard Higgs mechanism, wouldn't Higgs decays populate the "sterile" states (right-handed neutrinos or left-handed antineutrinos) in the early universe?

A19: Strictly speaking yes, but the neutrino Yukawa coupling are so tiny that these interactions never thermally populate the right-handed neutrino and left-handed antineutrino degrees of freedom. If that were to happen - and it happens in some new physics scenarios - the effective number of neutrinos (N_{eff}) would be larger than 3 and possibly ruled out by cosmic surveys.

Q20: If Neutrinos are majorana, does that mean that sterile neutrinos, which are right handed, don't have to be discovered because they are just the antineutrinos that we already know?

A20: The hypothesis that there are sterile neutrinos is consistent with both Majorana or Dirac neutrinos (in this case, the sterile neutrino would be either a Majorana or Dirac fermion as well). The source of the confusion is that if neutrinos are Dirac, right-handed neutrino particles and left-handed antineutrino particles exist, but these are not sterile neutrinos. They are just different spin-projections of the massive neutrino and antineutrino. It is true that a right-chiral field, which does not have any gauge quantum numbers (and is hence sterile) exists, but there are no sterile neutrino particles to be found in the lab. See also A12.

Q21 (CP-invariance violation in neutrino oscillations slide): Sorry--silly question--why doesn't unitarity require, instead, (U1)(U1*) = 1 - (U2)(U2*) - (U3)(U3*)?

A21: unitarity means that U^dagger U = 1 (the identity matrix). Some of the components of this matrix equation say that (Ualpha1)(Ubeta1*) = - (Ualpha2)(Ubeta2*) - (Ualpha3)(Ubeta3*) when the flavors (alpha, beta = e mu tau) are different. The one you are asking about applies when the flavors are the same (alpha = beta).

Q22: Could Majorana nature be ruled out if neutrinos have nonzero dipole moment?

A22: This is a good question. Majorana fermions cannot have a nonzero dipole moment. However, they can have what is refereed to as a transition dipole moment; where one neutrino species interacts with a photon and turns into a different neutrino species. Experiments that are sensitive to the neutrino dipole moment cannot, in practice, tell a bona fide dipole moment from a transition one and hence won't help answer whether neutrinos are Majorana or Dirac.

Q23: What did you mean by a particle (or neutrino) being "almost dirac?" This is maybe related to a previous question you addressed with 1-2 of the mass eigenstates being majorana and the other states are not.

There is the concept of a pseudo-Dirac fermion. In a nutshell, the story is as follows. We can visualize a Dirac fermions as a pair of Majorana fermions with equal and opposite masses. Imagine that I have a pair of Majorana fermions with masses that are almost equal and opposite. In this case, I have two Majorana fermions but, it turns out, they behave, experimentally, almost like a Dirac fermion! I have a paper on this https://arxiv.org/pdf/0906.1611.pdf which has references on pseudo-Dirac neutrinos and may be useful.

Q24: If neutrinos are Dirac neutrinos, but the lightest mass is zero, there would be 1 neutrino with 2 degrees of freedom and 2 with 4 degrees of freedom. Could this be possible and how would this affect the mixing?

A24: the answer is yes and nothing would change. One way of making peace with this issue is to think about the Dirac massless neutrons as having four degrees of freedom but that two of these degrees of freedom can never be excited (i.e. they don't interact in any way). See also A13.