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THE NEUTRINOS

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Recent, irrefutable evidence establishes that the ubiquitous neutrinos have tiny masses. Neutrino mass is physics beyond the Standard Model and is arguably the most important discovery in particle physics in the last quarter century. The mass of the neutrino is most likely of a very special character, such that the neutrino is its own antiparticle. The tiny sizes of the neutrino masses point to a mechanism that not only gives neutrinos mass but allows for the possibility of explaining the matter-antimatter asymmetry of the universe. Exploring the spectrum of the neutrinos and their properties under the CP symmetry will allow us to test our understanding of the neutrinos and their role in the universe.

What are neutrinos?

The neutrinos are the least understood constituents of matter. Yet, they are also by far the most abundant. The universe contains about a billion neutrinos for every quark or electron. These ubiquitous neutrinos were produced in the Big Bang, and more than ten million of them are inside every person on earth.

Like the other constituents of matter – the quarks and the charged leptons – the neutrinos are spin-1/2 fermions. Unlike the other constituents, they are electrically neutral, and interact with other particles only through the weak interaction and gravity.

How significant is the discovery of neutrino mass?

The quarks (u, d, c, s, t, and b) and the charged leptons (e, μ, and τ) are known to have nonzero masses. Until recently, there was no hard evidence that the neutrinos have nonzero masses as well. However, in the last decade, irrefutable evidence has been found that the neutrinos do have nonzero masses, although these masses are extremely tiny. The neutrinos are at least a million times lighter than the next lightest particle – the electron. However, the neutrinos contribution to the energy/mass fraction of the universe is comparable to that of stars.

Steve Weinberg, one of the three Nobel-Prize-winning creators of the Standard Model of the elementary particles, has stated that the discovery of neutrino mass is the most important discovery in elementary particle physics in the last quarter century. He has in mind the fact that neutrino mass is the first phenomenon to be seen in laboratory experiments that cannot be understood within the original Standard Model, and that calls for new physics at a very high energy scale beyond the scope of the Standard Model. Unlike the mass of a quark or charged lepton, that of a neutrino is very unlikely to be due simply to a linear coupling between the particle and the Higgs boson field. Rather, a neutrino mass is very likely to include a “Majorana mass,” which is of a different character. Regardless of the details, neutrino masses have a different origin than the masses of the other constituents of matter. In our quest to understand the physics behind mass, we would like to know what that origin is.

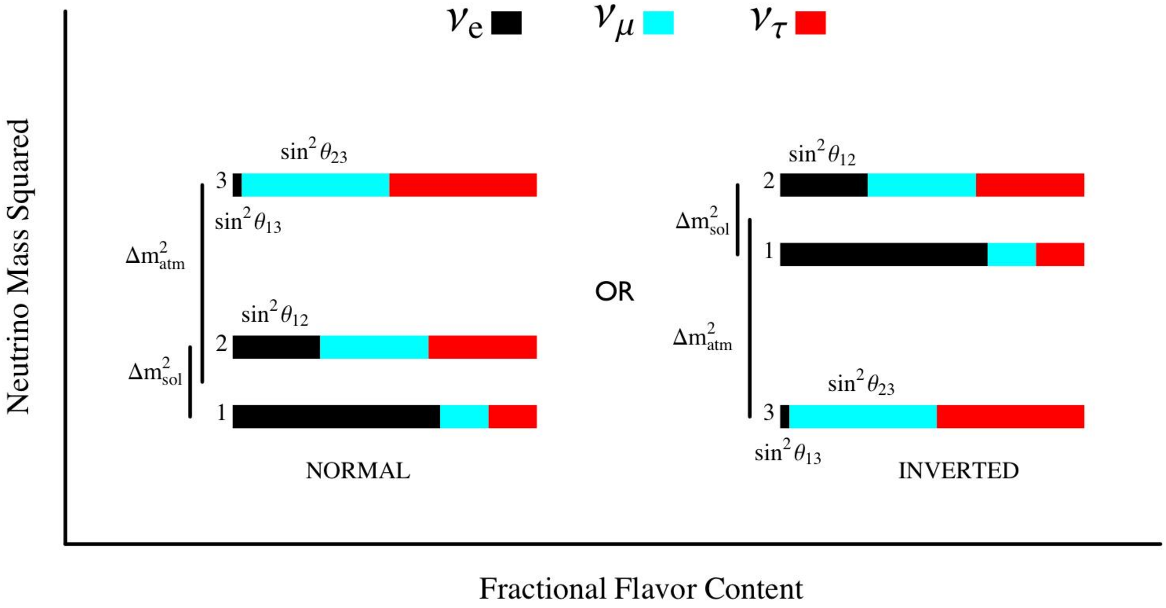
What are the neutrino flavors?

There are three "flavors" of neutrinos: ν_e, ν_μ, and ν_τ. Each of these is coupled via the weak interaction to the charged lepton of the same flavor: ν_e to e, ν_μ to μ, and ν_τ to τ. When the W boson, the carrier of the weak force, decays into a charged lepton plus a neutrino, the neutrino is always the one with the same flavor as the charged lepton. Thus, we have $W \to e + \nu_e$, or $W \to \mu + \nu_\mu$, but not $W \to \mu + \nu_e$. Similarly, when a neutrino of a certain flavor interacts with a target in a detector and creates a charged lepton, this charged lepton is always of the same flavor as the neutrino. This correlation between neutrino and charged lepton flavors makes it possible for us to identify the flavor of a neutrino by observing the flavor of the charged lepton that the neutrino has produced in a detector.

The discovery of neutrino mass is based on the experimental observation that a neutrino can change from one flavor to another. This spontaneous changing of flavor is the phenomenon referred to as neutrino oscillation. Oscillation implies not only neutrino mass, but also neutrino mixing. That is, the neutrinos of definite flavor, ν_e, ν_μ, and ν_τ, are not particles of definite mass (mass eigenstates), but coherent quantum-mechanical superpositions of such particles. The neutrinos of definite mass are called ν_1, ν_2, and ν_3, and the coefficients that express ν_e, ν_μ, and ν_τ in terms of ν_1, ν_2, and ν_3 form a 3×3 matrix known as the leptonic mixing matrix, U, see figure.

What is the neutrino mass hierarchy?

Two of the three neutrinos of definite mass, ν_1 and ν_2, have squared masses differing by $\Delta m^2_{sol} \cong +7.6\times10^{-5}\,\mathrm{eV}^2$. The third, ν_3, is separated from the $\nu_1 - \nu_2$ pair by a splitting that is thirty times larger: $\left|\Delta m^2_{atm}\right| \cong 2.4\times10^{-3}\,\mathrm{eV}^2$. These $\Delta \mathrm{m}^2$ were first determined by solar and atmospheric neutrino experiments, respectively. We do not know whether the closely-spaced $\nu_1 - \nu_2$ pair is at the bottom of the spectrum, as on the left of the figure below, or at the top, as on the right. If the closely-spaced pair is at the bottom, then the neutrino spectrum resembles the charged lepton and quark spectra, and for this reason would be called a normal hierarchy. If this pair is at the top, the spectrum would be referred to as an inverted hierarchy.



Just as each neutrino of definite flavor, such as ν_e, is a superposition of the neutrinos of definite mass, so each of the latter is a superposition of the neutrinos of definite flavor. In the figure, we indicate what is known experimentally about the flavor content of each neutrino of definite mass by color coding, showing the ν_e fraction in black, the ν_μ fraction in cyan, and the ν_τ fraction in red. The indicated small ν_e fraction of the isolated member of the spectrum, ν_3, is just an illustration; at present we know only that this fraction is no larger than 3% of this neutrino. We see from the figure that no neutrino of definite mass is anywhere near being just a neutrino of a single flavor. That is, neutrino mixing is large, in striking contrast to quark mixing, which is present, to be sure, but is quite small.

Why is the mass hierarchy important?

The Grand Unified Theories (GUTs) that unify the weak, electromagnetic, and strong interactions lead us to expect – at first – that the neutrino spectrum will resemble the charged lepton and quark spectra. The reason is simply that in a GUT the neutrinos, charged leptons, and quarks are all related; they belong to common multiplets of the theory. On the other hand, the neutrinos can have Majorana masses, but the charged leptons and quarks cannot. A Majorana mass mixes a particle with its antiparticle, and such mixing violates electric charge conservation if the particle is charged. Thus, the possibility of Majorana masses distinguishes the neutrinos from the other constituents of matter, and Majorana masses can readily turn a normal, quark-like neutrino spectrum into an inverted one. In addition, some classes of string theories lead one to expect an inverted neutrino spectrum. Clearly, in working toward an understanding of the origin of neutrino mass, we would like to know whether the mass spectrum is normal or inverted.

Is the neutrino its own antiparticle?

If, as is widely expected, neutrinos do have Majorana masses, then they are their own antiparticles. Like the Majorana masses, this property would distinguish them from the other constituents of matter. The knowledge of whether the spectrum is normal or inverted could help us to determine whether the neutrinos do indeed have Majorana masses and consequently are their own antiparticles. The only known practical approach to confirming this expectation is to show that neutrino-less double beta decay occurs. Neutrino-less double beta decay is the reaction $\mathrm{Nucl} \rightarrow \mathrm{Nucl}' + e^- + e^-$, in which one nucleus decays to another with the emission of two electrons. The rate for this process is proportional to the square of an effective Majorana neutrino mass, $\langle m_{\beta\beta} \rangle$. If neutrinos are identical to their antiparticles, and the mass spectrum is inverted, then, aside from a rather exotic possibility, $\langle m_{\beta\beta} \rangle$ *must* be larger than (10 – 15) milli-electron Volts (meV). Thus, if the spectrum should be found to be inverted, and a search for neutrino-less double beta decay can establish that the rate for this process is less than the rate that would correspond to $\langle m_{\beta\beta} \rangle = 10$ meV, then we will have learned that, contrary to prejudice, neutrinos are distinct from their antiparticles. Looking at the matter in another way, if the spectrum should be found to be inverted, and neutrinos are their own antiparticles, then an experimental search for neutrino-less double beta decay is guaranteed to see a signal if its reach extends to $\langle m_{\beta\beta} \rangle = 10$ meV. It should be noted that a reach extending to this point is the target of the next generation of neutrino-less double beta decay experiments.

Can neutrinos explain the matter antimatter asymmetry of the universe?

One of the most striking features of today's universe is the fact that it contains matter but virtually no antimatter. Since antimatter and matter annihilate each other when they meet, living creatures made of matter can exist in today's universe only because of this almost total absence of antimatter. Yet, arguments based on cosmology and particle physics lead to the conclusion that very shortly after the Big Bang, the universe contained *equal* amounts of matter and antimatter. How did that early, matter-antimatter *symmetric*, universe, evolve into today's matter-antimatter *asymmetric* one? This question is one of the leading puzzles of elementary particle physics and cosmology.

Sakharov pointed out long ago that a universe with equal amounts of matter and antimatter cannot become one with unequal amounts of the two unless matter and antimatter behave differently. This difference in behavior would be a violation of CP (Charge conjugation × Parity) invariance. Laboratory experiments with K and B mesons have revealed that there is indeed a violation of CP invariance coming from a complex phase factor in the quark mixing matrix. However, this observed CP violation in quark mixing would have been very highly suppressed when the universe was hot, as it was just after the Big Bang, and would have led to a matter-antimatter asymmetry orders of magnitude smaller than the one we see. Consequently, there must be *another* source of CP violation that is behind the cosmic matter-antimatter asymmetry. The last decade's experimental and theoretical discoveries concerning the neutrinos very strongly suggest that this crucial, so far missing, CP violation involves the neutrinos.

Can the neutrino sector provide the missing CP violation?
The most plausible explanation of the extreme lightness of neutrinos is the see-saw mechanism. This mechanism suggests a scenario, leptogenesis, which would indeed have violated CP in just such a way as to change the matter-antimatter-symmetric early universe into the matter-dominated world we see today. The see-saw picture gives the light neutrinos, ν, very heavy neutrino "see-saw partners", *N*, identical to their antiparticles. The heavier these *N* are, the lighter the ν are. Even if the heavy neutrinos *N* are too massive to be produced at the LHC, they would have been produced in the hot Big Bang. They would then have quickly decayed via the modes $N \to \ell + H$ and $N \to \bar{\ell} + \bar{H}$, where ℓ is one of the familiar leptons, and *H* is the Standard-Model Higgs boson. It is expected that, in violation of CP invariance, these two CP-mirror-image decay modes have different rates, so that *N* decays in the early universe would have produced a world with different numbers of leptons and antileptons. Processes predicted by the Standard Model would then have converted some of this lepton-antilepton asymmetry into a nucleon-antinucleon asymmetry, producing the leptonic and nucleonic matter-antimatter asymmetric universe in which we reside. This scenario, starting with CP violation in *N* decay, is the one referred to as leptogenesis.

If the decays of the heavy neutrinos *N* do violate CP, then very likely so do the oscillations of their see-saw partners, the light neutrinos ν. Indeed, in the see-saw picture, these two CP violations have the same origin. Thus, we expect a CP-violating difference between the oscillation of neutrinos made at an accelerator via the decay $\pi^+ \to \mu^+ + \nu_\mu$, and the oscillation of those made via the CP-mirror-image decay $\pi^- \to \mu^- + \nu_\mu$. Observation of this CP-violating difference would be a centrally important piece of evidence in favor of leptogenesis. Finding that this difference is absent would call leptogenesis into very serious question.

Can the physics of the see-saw lead to CP violation in *N* decays without producing CP violation among the light neutrinos? Yes, in principle it can, but for it to do so requires a very implausible fine tuning. Unless some unknown physics, beyond the see-saw, intervenes to create such a situation, it will not occur. The CP violations in *N* decays, in the oscillations of the light neutrinos, and in neutrino-less double beta decay are all linked by their common origin, and so we expect that all of these CP violations occur, or that none of them do.

The violation of CP in any physical system always arises from the effects of complex phase factors in quantum mechanical amplitudes. In light neutrino physics, these phase factors are found in the leptonic mixing matrix, *U*. In the see-saw picture, all of light neutrino physics, including *U*, is a consequence of the physics of the same see-saw that gives rise to leptogenesis. In particular, the phases in *U*, which hopefully will be measured in future neutrino experiments, contribute directly to the matter-antimatter asymmetry of the universe. To be sure, the phases in *U* do not by themselves permit a determination of the magnitude of the cosmic asymmetry produced by leptogenesis. However, in special versions of the see-saw picture, nonzero values of these phases establish that leptogenesis does make some contribution to this asymmetry.

What determines the size of CP violation in neutrino oscillations?

The size of the CP violation in neutrino oscillation depends not only on the phases in U, but also on the three mixing angles in this matrix. CP violation grows with the amount of mixing. Two of the mixing angles are already known to be very large. The third one, θ_{13}, is unknown, but we do know that it is less than 10^0. Knowledge of this critical angle will help guide the program to observe CP violation. It will also help guide the effort to determine whether the neutrino mass spectrum is normal or inverted — a challenge whose difficulty depends on θ_{13} — and will help to discriminate among theoretical models. Learning the value of θ_{13} is one of the aims of the NOνA experiment, whose primary purpose is to try to determine whether the neutrino mass spectrum is normal or inverted. On the near horizon, NOνA is the only experiment that has a chance of achieving this goal. Learning the value of θ_{13} is the sole aim of the T2K experiment in Japan, and of several reactor neutrino experiments.

How is muon-to-electron conversion related to neutrino physics?

Strong arguments support the hypothesis that there is new physics waiting to be discovered just around the corner in the energy range that will be made accessible by the LHC. However, it is striking that the indirect virtual effects of this new physics that should have been visible at present-day energies have never shown up. In particular, so-called flavor changing neutral current effects, such as non-Standard-Model $K \leftrightarrow \overline{K}$ and $B \leftrightarrow \overline{B}$ mixing, have never appeared. This suggests that, if the new physics is indeed around the corner, it does not change flavor at all except by inheriting the flavor-changing mechanism of the Standard Model in the quark sector, and that of the see-saw picture in the lepton sector, where there is no Standard Model mechanism for changing flavor. Thus, the same see-saw physics that leads to the masses and mixing of the light neutrinos also leads to muon-to-electron conversion in a nuclear field. In addition to mounting a world-leading neutrino physics program, Fermilab hopes to use its future intensity-frontier facilities to seek this charged-lepton flavor-changing process at a very sensitive level. As we see, this process may shed light on the same physics as that probed by neutrino oscillation.

How can the see-saw picture be tested?

That depends on how heavy the neutrinos N actually are. In some versions of the see-saw picture, these particles have masses above 10^9 GeV, which puts them far beyond the reach of the LHC. However, evidence concerning the see-saw will come from the searches for neutrino-less double beta decay. In the see-saw picture, neutrinos have Majorana masses, and both the light neutrinos ν and the heavy ones N are their own antiparticles. Thus, the observation of neutrino-less double beta decay, which implies the presence of Majorana neutrino masses, would be evidence in favor of the see-saw, although not a proof of it. In addition, there are phenomena that could be seen at the LHC whose discovery would falsify the hypothesis of leptogenesis. If a new W boson that couples to right-handed quarks and leptons, rather than the left-handed ones to which the Standard Model W couples, is discovered at the LHC, leptogenesis (but not the see-saw from which it could have arisen) will have been disproved. Finally, even if the heavy neutrinos N are far beyond the range of the LHC, the see-saw mechanism may eventually become part of a more general theory that encompasses many phenomena besides neutrino physics. Evidence for that theory would then be evidence for the see-saw.

Can the heavy neutrinos be observed at the LHC?

There are also versions of the see-saw picture in which the heavy neutrinos N are at the TeV scale, putting them within reach of the LHC. If the heavy neutrinos are at the TeV scale, then there is a good chance that there is also at this scale a new neutral boson, Z', which is like the Z boson of the Standard Model, but which, unlike the latter, couples to the heavy neutrinos. A Z', having been produced at the LHC, can then decay into an NN pair. If both members of this pair subsequently decay into $\ell^- W^+$, or both decay into $\ell^+ W^-$, we will be left with a pair of like-sign leptons, a very unusual signature. Moreover, if there is CP violation in N decay, as required for leptogenesis, then the rate for decay into $\ell^- W^+$ will differ from that for decay into $\ell^+ W^-$, so that we will observe unequal numbers of $\ell^- \ell^-$ and $\ell^+ \ell^+$ pairs. Indeed, the difference between the rates for these two charge combinations will determine the CP violation in N decay in the early universe. This could provide direct evidence for both leptogenesis and the see-saw picture from which it springs.

What is the role of the proposed future Fermilab experiments?

The most important questions in neutrino physics are:

- Do neutrino oscillations violate CP?
- Is the neutrino mass hierarchy normal or inverted?
- What is the size of mixing angle θ_{13}?
- Is the neutrino its own antiparticle?

The future Fermilab experiments aim to answer the first three of these key questions.

Are there further surprises?

What we have described grows out of current theoretical thinking. But neutrino physics has already violated theoretical expectations, and further surprises may well be in store. The world of neutrinos could prove to be quite different from that of the current hypotheses. There may be new light neutrinos, perhaps of a different character from the three we know, new neutrino interactions not described by the Standard Model, and other surprises.