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Neutrino Physics

1.1 Introduction – 3 pages

Introduction. Pertinent questions in theory and experiment. Theory of neutrino masses and lepton mixing. Where we are and where we expect to be by approximately 2020.

Neutrinos are the most elusive of the known fundamental particles. They are color and charge neutral spin one-half fermions, and, to the best of our knowledge, only interact with charged-fermions and massive gauge bosons, through the weak interactions. Their existence was postulated in the early 1930s, but they were only first observed in the 1950s. The third neutrino flavor eigenstate, the tau-type neutrino ν_τ was the last of the fundamental particles to be observed, eluding direct discovery six years longer than the top quark. More relevant to this document, in the late 1990s, the discovery of nonzero neutrino masses moved the study of neutrino properties to the forefront of experimental and theoretical particle physics.

Experiments with solar, atmospheric, reactor and accelerator neutrinos have established, beyond reasonable doubt, that neutrinos produced in a well-defined flavor state (say, a muon-type neutrino ν_μ) have a non-zero probability of being detected in a distinct flavor state (say, an electron-type neutrino ν_e). This flavor-changing probability depends on the neutrino energy and the distance traversed between the source and the detector. The simplest and only consistent explanation of almost all experimental data collected over the last two decades is that neutrinos have mass and neutrino mass eigenstates are different from neutrino weak eigenstates, *i.e.*, leptons mix.

Massive neutrinos imply that a neutrino produced as a coherent superposition of mass-eigenstates, such as a neutrino ν_α with a well-defined flavor, has a non-zero probability to be measured as a neutrino ν_β of a different flavor ($\alpha, \beta = e, \mu, \tau$). This oscillation probability $P_{\alpha\beta}$ depends on the neutrino energy E, the propagation distance L, the neutrino mass-squared differences, $\Delta m^2_{ij} \equiv m^2_j - m^2_i$, $i, j = 1, 2, 3, \ldots$, and the elements of the leptonic mixing matrix,[1] U, which relates neutrinos with a well-defined flavor (ν_e, ν_μ, ν_τ) and neutrinos with a well-defined mass ($\nu_1, \nu_2, \nu_3, \ldots$). For three neutrino flavors, the elements of U are defined by:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{e\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}. \tag{1.1}$$

Almost all neutrino data to date can be explained assuming that neutrinos interact as prescribed by the standard model, there are only three neutrino mass eigenstates, and U is unitary. Under these circumstances, it is customary to parameterize U in Eq. (1.1) with three mixing angles $\theta_{12}, \theta_{13}, \theta_{23}$ and three complex phases, δ, ξ, ζ, defined by:

$$\frac{|U_{e2}|^2}{|U_{e1}|^2} \equiv \tan^2\theta_{12}; \qquad \frac{|U_{\mu 3}|^2}{|U_{\tau 3}|^2} \equiv \tan^2\theta_{23}; \qquad U_{e3} \equiv \sin\theta_{13} e^{-i\delta}, \tag{1.2}$$

with the exception of ξ and ζ, the so-called Majorana CP-odd phases. These are only physical if the neutrinos are Majorana fermions, and have virtually no effect in flavor-changing phenomena.

In order to relate the mixing elements to experimental observables, it is necessary to define the neutrino mass eigenstates, *i.e.*, to "order" the neutrino masses. This will be done in the following way: $m^2_2 > m^2_1$ and $\Delta m^2_{12} < |\Delta m^2_{13}|$. In this case, there are three mass-related observables: Δm^2_{12} (positive-definite), $|\Delta m^2_{13}|$, and the sign of Δm^2_{13}. A positive (negative) sign for Δm^2_{13} implies $m^2_3 > m^2_2$ ($m^2_3 < m^2_1$) and characterizes a so-called normal (inverted) neutrino mass hierarchy. Our knowledge of neutrino oscillation parameters can

[1] Often referred to as the Maki-Nakagawa-Sakata (MNS) Matrix, or the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix.

be summarized as [21]:

$$\Delta m^2_{12} = 7.65^{+0.23}_{-0.20}\,\text{eV}^2\,; \qquad |\Delta m^2_{13}| = 2.40^{+0.12}_{-0.11}\,\text{eV}^2\;;$$
$$\sin^2\theta_{12} = 0.304^{+0.022}_{-0.016}\,; \qquad \sin^2\theta_{23} = 0.50^{+0.07}_{-0.07}\,; \tag{1.3}$$

where current hints point toward a central value of 0.09 [4, 5, 20] for $\sin^2 2\theta_{13}$, which will be disussed in more detail later. We have virtually no information concerning δ (and, for that matter, ξ and ζ) or the sign of Δm^2_{13}.

The main goal of next-generation neutrino oscillation experiments is to test whether the scenario outlined above, the standard three-massive-neutrinos paradigm, is correct and complete. This is to be achieved by not simply determining all of the parameters above, but "over-constraining" the parameter space in order to identify potential inconsistencies. This is not a simple task, and the data collect thus far, albeit invaluable, allow for only the simplest consistency checks. In the future, precision measurements, as will be discussed in Sec. 1.2, will be required.

Large, qualitative modifications to the standard paradigm are currently allowed. Furthermore, there are several, none too significant yet, hints in the world neutrino data that point to a neutrino sector that is more complex than what was outlined above. Possible surprises include new, gauge singlet fermion states that only manifest themselves by mixing with the known neutrinos, and new, weaker-than-weak interactions.

In the standard model, neutrinos are predicted to be exactly massless. The discovery of neutrino masses, hence, qualifies as the first concrete instance where the standard model fails. This is true even if the three-massive-neutrino paradigm described above turns out to be the whole story. More important is the fact that all modifications to the standard model that lead to massive neutrinos change it qualitatively. For a more detailed discussion of this point see, for example, [12].

Neutrino masses, while non-zero, are tiny when compared to all other known mass scales in the standard model[2]. Neutrino masses are at least six orders of magnitude less than the electron mass. The electron mass itself is already over 100 times smaller than the muon mass and tiny compared to the weak scale, around 100 GeV. Furthermore, to the best of our knowledge, there is a "gap" between the largest allowed neutrino mass and the electron mass, in contrast with the fact that, in the charged-fermion part of the mass-space, one encounters a new mass every order of magnitude or so. We don't know why neutrino masses are so small or why there is such a large gap between the neutrino and the charged fermion masses. We suspect, however, that this may be Nature's way of telling us that neutrino masses are "different."

This suspicion is only magnified by the fact that massive neutrinos, unlike all other fermions in the standard model, may be Majorana fermions. The reason is simple: neutrinos are the only electrically neutral fundamental fermions and hence need not be distinct from their antiparticles. Determining the nature of the neutrino – Majorana or Dirac – would not only help guide theoretical work related to uncovering the origin of neutrino masses, but would also reveal that the conservation of lepton number is not a fundamental law of nature. The most promising avenue for learning the faith of lepton number is to look for neutrinoless double-beta decay, a lepton-number violating nuclear process. The observation of a non-zero rate for this hypothetical process would easily rival the first observations of parity violation and CP-invariance violation in the mid twentieth century as far as its implications for our understanding of nature is concerned.

It is natural to ask what augmented, "new" standard model (νSM) leads to non-zero neutrino masses. The answer is that we are not sure. There are many different ways to modify the standard model in order to accommodate neutrino masses. While most differ greatly from one another, all succeed – by design – in explaining small neutrino masses and are all allowed by the current particle physics experimental data. The

[2]Except, perhaps, for the mysterious cosmological constant.

most appropriate question, therefore, is not what are the candidate νSM's, but how can one identify the "correct" νSM? The answer lies in next-generation experiments, which will be described throughout this Chapter.

Modifications to the standard model that allow neutrinos to acquire neutrino masses include augmenting the Higgs sector with, say, $SU(2)_L$ Higgs triplets, augmenting the fermion sector with either $SU(2)_L$ singlets (right-handed neutrinos) or triplets, or adding several new fields and interactions that explicitly violate $U(1)_{B-L}$. In order to explain why neutrino masses are so small, other additions are often employed including large extra dimensions, new spontaneously broken gauge symmetries, etc. For detailed examples see, for example, [17]. The key point is that different models lead to different phenomenology in the neutrino sector and elsewhere.

Neutrino data also provide another perceived puzzle: the pattern of neutrino mixing. The absolute value of the entries of the CKM quark mixing matrix are, qualitatively, given by:

$$|V_{\rm CKM}| \sim \begin{pmatrix} 1 & 0.2 & 0.001 \\ 0.2 & 1 & 0.01 \\ 0.001 & 0.01 & 1 \end{pmatrix}, \tag{1.4}$$

while those of the entries of the PMNS matrix are given by

$$|U_{\rm PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & < 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}. \tag{1.5}$$

It is clear that the two matrices "look" very different. While the CKM matrix is almost proportional to the identity matrix plus hierarchically ordered off-diagonal elements, the PMNS matrix is far from diagonal and, with the possible exception of the U_{e3} element, all elements are $\mathcal{O}(10^\circ)$. Significant research efforts are concentrated on understanding what, if any, is the relationship between the quark and lepton mixing matrices and what, if any, is the "organizing principle" responsible for the observed pattern of neutrino masses and lepton mixing. There are several different theoretical ideas on the market (for summaries, overviews and references see, for example, [7]). Typical results, which are very relevant for next-generation experiments, include predictions for the currently unknown neutrino mass and mixing parameters ($\sin^2\theta_{13}$, $\cos 2\theta_{23}$, the mass hierarchy, etc) and the establishment of "sum rules" involving different parameters.

More on where we expect to be by approximately 2020.

1.2 Testing the Standard Oscillation Paradigm – 4 pages

Three flavor oscillations, phenomenology. Discussion of the different sources and detector types.

The overarching goal of flavor physics in general, is to obtain a decisive clue towards unlocking the flavor mystery and to understand where the observed pattern of fermion masses and mixing comes from. Neutrino physics can contribute to this effort by either discovering new flavor effects which go beyond the mixing of three generations of quarks and leptons or by providing information within the three flavor framework, which points towards an underlying structure, *e.g.* if the atmospheric mixing angle is found to be maximal within very small error bars, this would unequivocally point towards a symmetry between the second and third families. While the second argument stresses precision, the first argument is also best served by precision measurements. In this context, it is worthwhile to point out that in neutrino physics the track record of theory in terms of predicting neutrino properties is abysmal and therefore, this field has been entirely data driven – neutrinos have surprised us at every turn in the past and there is no reason to expect that this will change in the future. With this caveat in mind, the goals of precision neutrino oscillation physics can be broken down into the following questions, which are listed in no particular order

- Is the atmospheric mixing angle maximal?
- Is there leptonic CP violation?
- Are SM singlets involved in oscillations?
- What is the ordering of mass eigenstates?
- What is the value of the "reactor" angle, θ_{13}?

The last question has seen a flurry of activity in 2011, with a number of hints by T2K [4], MINOS [5] and Double Chooz [20] which point towards $\sin^2\theta_{13} \simeq 0.09$ and in combination, these results exclude $\sin^2 2\theta_{13} = 0$ at more than $3\,\sigma$ without direct reference to solar or atmospheric data, as was required prior to the result from Double Chooz [13]. The combined significance of this result is comparable to the one for the Higgs at 125 GeV [18, 19] and thus, it seems premature to declare this question solved; we will have to wait for more data. Fortunately, reactor neutrino experiments [9, 15, 6] will soon provide better results and also T2K will resume data taking, therefore we can expect a definitive answer to whether the current indications are correct or not sometime in 2012. In the longer term, Daya Bay and NOνA are expected to provide precise measurements of θ_{13}, which will be significant in the context of precision tests of three flavor oscillation framework.

The initial discoveries in neutrino physics have largely been made using neutrino sources which already were available, either natural ones like the atmosphere or artificial ones like nuclear power reactors. The obvious advantage of these sources is their easy availability and associated low cost. The drawback is, that the experimenter has no control over these sources and systematic uncertainties can be substantial. To make further progress, purpose-made neutrino sources will be necessary and this implies a transition to intense accelerator-driven systems with a concomitant increase in complexity and cost, while at the same time very large detectors are still needed to obtain sufficient statistics. These large detectors, if located deep underground, are also ideal tools to study low energy phenomena like supernova neutrinos, proton decay *asf.*. While this presents a true synergy, one cannot fail to notice that none of these non beam-related physics topics would warrant an investment at the required level and it is the beam-related precision oscillation physics which is the physics driver for this program.

Neutrino oscillations are a quantum interference effect and this is the reason that they are sensitive to extremely small differences in phase velocity. In the ultra-relativistic approximation, which is true for basically all neutrinos with the possible exception of the cosmic relic neutrinos, the phase velocity is proportional to $E + \frac{m^2}{2E}$, *e.g.* for MeV neutrinos and $m \sim 1\,\mathrm{eV}$, the second term is suppressed by 12 orders of magnitude. Only the interference of two or more mass eigenstates allows sensitivity to the $m^2/2E$ term. To observe CP violation, it is necessary to use a flavor transition, *i.e.* the initial and final flavor have to be different. Given the fact that we have no practical method to produce or to detect ν_τ efficiently, this implies that we have to study either the conversion of ν_e into ν_μ or *vice versa*. In order to identify the final state flavor we have to use charged current reactions and thus, in the case the final state is ν_μ, we need sufficient energy to overcome the m_μ threshold. On the other hand, if the final state is ν_e, the initial state has to be a ν_μ and therefore, there is a lower limit to the energy of about 100 MeV also in this case. Thus, there is an absolute lower limit on the energy, which combined with the size of the atmospheric mass splitting of about $2.5 \times 10^{-3}\mathrm{eV}^2$ requires an arm length for the interferometer, or baseline L, of $L \gtrsim 100\,\mathrm{km}$ to obtain a phase difference $\frac{m_1^2 - m_2^2}{2E} L \simeq 1$. Long baselines can only be obtained by sending the neutrino beam through the Earth and thus, matter effects can not be neglected, in general. Matter effects are due to the coherent forward scattering of neutrinos from the electrons present in matter and create an additional contribution to the phase difference. Notably, this additional contribution distinguishes between neutrinos and antineutrinos, since there are no positrons present in the Earth. This leads to a significant background contribution from matter effects for CP violation searches. Secondly, the matter contribution also depends on whether the electron neutrino predominantly is made out of the heaviest or lightest mass eigenstate, thus allowing a determination of the ordering of mass eigenstates, also called the mass hierarchy.

Discussion of basic concepts behind experimental approaches: beams and detectors. Atmospheric, solar neutrinos as well as different beam approaches.

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1.3 The Nature of the Neutrino – Majorana versus Dirac – 3 pages

Theory and phenomenology. Double-beta decay and other channels.

With the realization that neutrinos are massive, there is an increased interest in investigating their intrinsic properties. Understanding the neutrino mass generation mechanism, the absolute neutrino mass scale, and the neutrino mass spectrum are some of the main focuses of future neutrino experiments. Whether neutrinos are Dirac (*i.e.* exist as separate massive neutrino and antineutrino states) or Majorana (have identical neutrino and antineutirno states) is a key experimental question, the answer to which will guide the theoretical description of neutrinos.

All observations involving leptons are consistent with their appearance and disappearance in particle anti-particle pairs. This property is expressed in the form of lepton number, L, being conserved by all fundamental forces. We know of no symmetry relating to this empirical conservation law. Neutrinoless double beta decay violates lepton number conservation and thus, if observed, requires a revision of our current understanding of particle physics. In terms of field theories, such as the Standard Model, neutrinos are assumed to be massless and there is no chirally right-handed neutrino field. The guiding principles for extending the Standard Model are the conservation of electroweak isospin and renormalizability, which do not preclude each neutrino mass eigenstate ν_i to be identical to its anti-particle $\overline{\nu}_i$, or a "Majorana" particle. However, L is no longer conserved if $\nu = \overline{\nu}$. Theoretical models, such as the see-saw mechanism that can explain the smallness of neutrino mass, favor this scenario. Therefore, the discovery of Majorana neutrinos would have profound theoretical implications in the formulation of a new Standard Model while yielding insights into the origin of mass itself. If neutrinos are Majorana particles, they may fit into the leptogenesis scenario for creating the baryon asymmetry, and hence ordinary matter, of the universe.

As of yet, there is no firm experimental evidence to confirm or refute this theoretical prejudice. Experimental evidence of neutrinoless double-beta ($0\nu\beta\beta$) decay would establish the Majorana nature of neutrinos. Several high level studies such as the 2004 APS Multi-Divisional Neutrino Study, the 2005 NuSAG report, the 2006 EPP 2010 study, conducted by the National Academy of Sciences, and the 2007 Nuclear Physics Long Range Plan identified the investigation of neutrinoless double beta decay as one of the core areas of interest of the nuclear and particle physics communities. It is clear that $0\nu\beta\beta$ experiments sensitive at least to the mass scale indicated by the atmospheric neutrino oscillation results are needed.

For $0\nu\beta\beta$ decay the sum energy of the emitted electrons is mono-energetic. Observation of a sharp peak at the $\beta\beta$ endpoint would thus quantify the $0\nu\beta\beta$ decay rate, demonstrate that neutrinos are Majorana particles, indicate that lepton number is not conserved, and, paired with nuclear structure calculations, provide a measure of the effective (average) Majorana mass, $\langle m_{\beta\beta}\rangle$, of the electron neutrino. There is consensus within the neutrino physics community that such a decay peak would have to be observed for at least two different decaying isotopes at two different energies to make a credible claim for $0\nu\beta\beta$ decay. Neutrino oscillation experiments indicate that at least one neutrino has a mass of ~ 45 meV or more. As a result and as shown in Fig. 1-1, in the inverted hierarchy mass spectrum with $m_3 = 0$ meV, $\langle m_{\beta\beta}\rangle$ is between 10 and 55 meV depending on the values of the Majorana phases. This is sometimes referred to as the atmospheric mass scale. Exploring this region requires a sensitivity to half-life exceeding 10^{27} years. This is a challenging goal requiring several tonne-years of exposure and very low backgrounds. To accomplish this goal requires a detector at the tonne scale of enriched material and a background level below 1 count/(tonne y) in the spectral region of interest (ROI). Good energy resolution is also required.

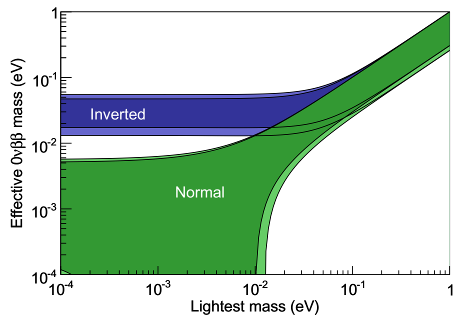

Figure 1-1. *Allowed values of $\langle m_{\beta\beta}\rangle$ as a function of the lightest neutrino mass for the inverted and normal hierarchies. The dark shaded regions correspond to the best-fit neutrino mixing parameters from [8] and account for the degeneracy due to the unknown Majorana phases. The lighter shading corresponds to the maximal allowed regions including mixing parameter uncertainties as evaluated in [8].*

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The observed half-life can be related to an effective mass according to $(T_{1/2,0\nu\beta\beta})^{-1} = G_{0\nu}|M_{0\nu}|^2\langle m_{\beta\beta}\rangle^2$, where the effective mass which has contributions from all mass states, is defined as: $\langle m_{\beta\beta}\rangle^2 = |\sum_i U_{ei}^2 m_i|^2$. $G_{0\nu}$ is a phase space factor, m_i is the mass of mass state i, and $M_{0\nu}$ is the matrix element. The matrix element has significant nuclear theoretical uncertainties, dependent on the nuclide under consideration.

There are a large number of current neutrinoless double beta decay search efforts; a recent review is reference [10].

Here will be material on specific experiments with U.S. participation: Majorana, EXO, Cuore.

1.4 Weighing Neutrinos – 2 pages

Precision measurements of beta-decay. Neutrino masses and cosmology.

The neutrino's rest mass has a small but potentially measureable effect on its kinematics, in particular to the phase space available in low-energy nuclear beta decay. The effect is indifferent to the distinction between Majorana and Dirac masses, and hence its observation would provide information complementary to neutrinoless double-beta decay.

Two nuclides are of major importance to current experiments; tritium (^{3}H or T) and ^{187}Re. The particle physics is the same in both cases, but the experiments differ greatly. Consider the superallowed decay $^3\mathrm{T} \rightarrow {}^3\mathrm{He} + e^- + \bar{\nu}_e$. The electron energy spectrum has the form:

$$dN/dE \propto F(Z,E)p_e(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-m_\nu^2} \tag{1.6}$$

where E, p_e are the electron energy and momentum, E_0 the Q-value, and $F(Z,E)$ the Fermi function. If the neutrino is massless, the spectrum near the endpoint is approximately parabolic around E_0. A finite neutrino mass makes the parabola "steeper", then cuts it off m_ν before the zero-mass endpoint. m_ν can be extracted from the shape without knowing E_0 precisely, and without resolving the cutoff.

The flavor state ν_e is an admixture of three mass states ν_1, ν_2, and ν_3. Beta decay yields a superposition of three spectra, with three different endpoint shapes and cutoffs, whose relative weights depend on the mixing matrix. Unless the three endpoint steps are fully resolved, the spectrum is well-approximated by the single-neutrino spectrum with an effective mass $m_\beta = \Sigma_{i=1,3}\Theta_{ei}m_i$. Past tritium experiments have determined $m_\beta < 2.0$ eV.

In order to measure this spectrum distortion, any experiment must have the following properties:

- high energy resolution—in particular, a resolution function lacking high-energy tails—to isolate the near-endpoint electrons from the more numerous low-energy electrons.
- an extremely well-known spectrometer resolution. The neutrino mass parameter covaries very strongly with the detector resolution.
- ability to observe a very large number of decays, with high-acceptance spectrometers and/or ultra-intense sources, in order to collect adequate statistics in the extreme tail of a rapidly-falling spectrum.

1.4.1 Upcoming experiments

KATRIN The KATRIN experiment, now under construction, will attempt to extract the neutrino mass from decays of gaseous T_2. KATRIN achieves high energy resolution using a MAC-E (Magnetic Adiabatic Collimation-Electrostatic) filter. In this technique, the T_2 source is held at high magnetic field. Beta-decay electrons within a broad acceptance cone are magnetically guided towards a low-field region; the guiding is adiabatic and forces the electrons nearly parallel to B field lines. In the parallel region, an electrostatic field serves as a sharp energy filter. Only the highest-energy electrons can pass the filter and reach the detector, so MAC-E filters can tolerate huge low-energy decay rates without encountering detector rate problems.

In order to achieve high statistics, KATRIN needs a very strong source, supplying 10^{11} e$^-/s$ to the spectrometer acceptance. This cannot be done by increasing the source thickness, which is limited by self-scattering, so the cross-sectional area of the source and spectrometer must be made very large, 53 cm^2 and 65 m^2 respectively. KATRIN anticipates achieving neutrino mass exclusion limit down to 0.2 eV at 95% confidence, or 0.35 eV for a 3-sigma discovery.

MARE The MARE experiment attempts to extract the neutrino endpoint from the endpoint of ^{187}Re. Rhenium's extremely low endpoint, 2.6 keV, is 7 times lower than tritium's; all else being equal, a ^{187}Re endpoint measurement has 7^3 times as much statistical power as a T measurement. However, because the ^{187}Re half-life is so long, it is impossible to make a strong transparent source; the decay energy is always self-absorbed. MARE attempts to capture this energy in a microcalorimeter with 1–3 eV energy resolution. To amass high statistics without pileup, MARE needs a large number of individual counters.

MARE is made possible by microbolometer-array technology pioneered in the x-ray astronomy community. MARE's arrays might include, on each of thousands of pixels: a rhenium source/absorber/calorimeter, a transition-edge sensor including readout wiring, and a weak thermal link to a cold support, all fabricated using lithographic techniques. A future implementation of MARE might include 10^5–10^6 microcalorimeters and achieve neutrino mass sensitivity comparable to KATRIN; the two experiments may cross-check one another thanks to their entirely independent systematic effects. The MARE technology can also be adapted to ^{163}Ho electron capture decay, which may have a useful neutrino-mass-dependent endpoint on its otherwise Breit-Wigner x-ray spectrum.

Project 8 Project 8 is a new technology for pursuing the tritium endpoint; it is currently running proof-of-concept experiments, but anticipates providing a roadmap towards a large tritium experiment with new neutrino mass sensitivity. In Project 8, a low-pressure gaseous tritium source is stored in a magnetic bottle. Magnetically trapped decay electrons undergo cyclotron motion for $\sim 10^6$ orbits. This motion emits microwave radiation at frequency $\omega = qB/\gamma m$, where γ is the Lorentz factor. A measurement of the frequency can be translated into an energy. A prototype, now operating at the University of Washington, is attempting to detect and characterize single conversion electrons from a ^{83m}Kr conversion electron calibration source. If this is successful, Project 8 offers a tritium measurement strategy with very different scaling laws and systematics than KATRIN.

1.4.2 Cosmology

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One way of addressing the question of absolute neutrino masses is to look on cosmological scales: the field of observational cosmology now has a wealth of data. Non-zero neutrino mass affects galaxy formation, and overall there are a host of other effects on cosmological observables. Global fits to the data– large scale structure, high Z supernovae, cosmic microwave background, and Lyman α forest measurements – yield limits on the sum of the three neutrino masses of less than about 0.3-0.6 eV, although specific results depend on assumptions. Future cosmological measurements will further constrain the absolute mass scale. Reference [3] are recent reviews.

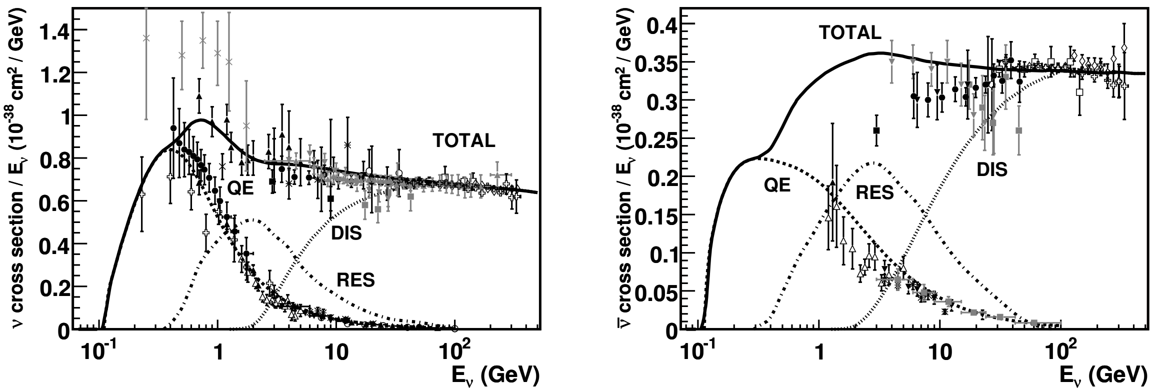

Figure 1-2. *Existing muon neutrino (left) and antineutrino (right) charged current cross section measurements [22] and predictions [11] as a function of neutrino energy. The contributing processes in this energy region include quasi-elastic (QE) scattering, resonance production (RES), and deep inelastic scattering (DIS).*

1.5 Neutrino Scattering – 3 pages

Importance for oscillation searches. Theory and phenomenology, experiments. Neutrino scattering and probes of nucleon and nuclear structure, the Standard Model, and beyond. MINERνA, SciNoVA, coherent scattering, new ideas

The discovery of neutrino oscillations has instigated a world-wide experimental effort to use this phenomenon to measure the fundamental properties of the neutrino. Recent and near-future oscillation experiments in this program such as MiniBooNE, MINOS, T2K, CNGS, NOvA, and LBNE require detailed knowledge of neutrino-nucleus interactions to avoid being limited by uncertainties in the underlying neutrino-nucleus scattering process. Recent data from MiniBooNE and others indicate this knowledge currently eludes us.

1.6 Neutrinos in Cosmology and Astrophysics – 3 pages

Neutrinos in the early universe. Leptogenesis. Neutrinos from supernovae (and "similar" sources). Ultra-high energy neutrinos. Solar neutrinos and geoneutrinos. Synergy with dark matter detectors. Neutrinos as probes of dark matter (annihilation in the center of the Sun et al).

1.7 Neutrinos and the Energy Frontier – 2 pages

Neutrinos and the energy frontier (LHC). From conventional neutrino beams to neutrino factories to muon colliders.

1.8 Neutrinos and the "Other" Intensity Frontier – 2 pages

Synergies with muon experiments (edms, $g-2$, clfv). Other synergies.

1.9 Beyond the Standard Paradigm – Short-Baseline Anomalies – 3 pages

Introduce the short-baseline anomalies. Some theoretical and phenomenological models. Short-baseline experiments and how they match to set-ups to test the standard paradigm. Non-neutrino tests of the anomalies.

Data from a variety of short-baseline experiments as well as astrophysical observations and cosmology favor the existence of additional neutrino mass states beyond the three active species in the Standard Model. The possible implications of additional sterile neutrino states would be profound and change the paradigm of the Standard Model of particle physics. As a result, great interest has developed in testing the hypothesis of sterile neutrinos and providing a definitive resolution to the question: do sterile neutrinos exist [1, 2]?

Recently, a number of tantalizing results (anomalies) have emerged from short-baseline neutrino experiments that cannot be explained by the current 3-neutrino paradigm. These anomalies are not directly ruled out by other experiments and include the excess of electron-antineutrino events (3.8σ) observed by the LSND experiment, the excess of electron-neutrino events (3.0σ) observed by the MiniBooNE experiment in neutrino mode, the excess of electron antineutrino events (2.3σ) observed by the MiniBooNE experiment in antineutrino mode, the deficit of electron-antineutrino events (0.937 ± 0.027) observed by reactor neutrino experiments, and the deficit of electron neutrino events (0.86 ± 0.05) observed by the SAGE and GALLEX gallium calibration experiments.

How can we explain these anomalies? Although there are several possibilities (e.g., Lorentz violation), one of the simplest explanations is the $3+N$ sterile neutrino model, where there are 3 light, mostly active neutrinos and N heavy, mostly sterile neutrinos. For $N > 1$, these models allow for CP violation in short-baseline experiments. These $3+N$ models fit the world's neutrino and antineutrino data fairly well [14, 16]. A key test of these $3+N$ models is the existence of muon-neutrino disappearance ($\sin^2 2\theta > 10\%$) at a $\Delta m^2 \sim 1$ eV^2. For the future, there is a diverse set of experiments, spanning vastly different energy scales, that have been proposed or are being built to test the $3+N$ models and resolve the present anomalies. These include accelerator neutrino experiments, reactor neutrino experiments, radioactive neutrino source experiments, and atmospheric neutrino experiments. The MicroBooNE experiment is building a liquid-argon (LAr) TPC just upstream of the MiniBooNE detector that will be able to determine whether the event excesses observed by MiniBooNE are due to electron events, as expected from $3+N$ models, or are simply due to unmodeled photon backgrounds. Another LAr TPC proposal is to move the ICARUS detector, now taking data in the Gran Sasso Laboratory, to the PS neutrino beamline at CERN and to build a second, smaller LAr TPC. With two detectors at different distances, many of the associated systematic errors cancel, which will allow a definitive test of the LSND neutrino oscillation signal. Other accelerator neutrino experiments at Fermilab include the MINOS+ experiment, which will search with high sensitivity for muon neutrino disappearance, and the BooNE experiment, which proposes the construction of a second MiniBooNE-like detector at a different distance (200 m) than the original MiniBooNE detector (541 m). BooNE would have the potential to measure electron neutrino and electron antineutrino appearance, muon neutrino and muon antineutrino disappearance, and CP violation in the lepton sector, as well as proving that sterile neutrinos exist from the comparison of neutral current π^0 scattering at different distances. Fermilab already has world-class neutrino beams (the Booster neutrino beamline and NuMI); however, future facilities could significantly enhance these capabilities. These future facilities include Project-X, which would increase present proton intensities by an order of magnitude or more, and a muon storage ring, which would enable an extremely precise search for electron neutrino and electron antineutrino disappearance.

Besides Fermilab and CERN, there are also several other opportunities for pursuing short-baseline neutrino physics. The SNS facility at ORNL produces an intense and well-understood flux of neutrinos from π^+ and μ^+ decay at rest. An idea has been put forward, OscSNS, for building a MiniBooNE-like detector approximately 60m from the SNS beam dump. OscSNS would be capable of making precision measurements of electron antineutrino appearance and muon neutrino disappearance. Also, the SCRAAM reactor neutrino experiment could be built at the San Onofre reactor or at the Advanced Test Reactor. SCRAAM would have less baseline spread than previous reactor neutrino experiments and would be able to measure oscillations by looking for a spectral distortion in the reactor neutrino energy spectrum. In addition, neutrino radioactive source experiments could be mounted inside either the BOREXINO or Daya Bay reactor neutrino detectors. The advantage of radioactive source experiments is that, due to the low neutrino energies, oscillations could be observed in a single detector. A final opportunity for measuring short-baseline oscillations is to search for atmospheric muon antineutrino disappearance with the IceCube experiment at the South Pole. With a typical atmospheric neutrino energy of a few TeV and a typical distance of a few thousand km, IceCube is very sensitive to oscillations at the roughly 1 eV mass scale, especially because these oscillations would be matter-enhanced via the MSW mechanism.

In summary, there are anomalies in short-baseline neutrino experiments that cannot be explained by the 3-neutrino paradigm and suggest the possible existence of sterile neutrinos. The world neutrino and antineutrino data can be fit fairly well to a $3{+}N$ oscillation model with $\Delta m^2 \sim 1$ eV^2. This model predicts observable muon neutrino disappearance. Future short-baseline neutrino experiments (accelerator, reactor, radioactive source, and atmospheric) could measure neutrino oscillations with high significance ($> 5\sigma$) and prove that sterile neutrinos exist. Short-baseline oscillations will affect and are complementary to long-baseline neutrino experiments and the measurement of θ_{13} and the CP phase, δ_{CP}.

1.10 Neutrino Probes of New New Physics – 2 pages

Looking for new physics in oscillations. Theoretical and phenomenological models one could test. Non-standard-interactions Faster than light neutrinos?

1.11 Facilities and Instrumentation Challenges – 3 pages

1.11.1 Experimental Approaches

Overview with more details than in the intro on specific experimental approaches: concepts of different kinds of beams and other sources, pros and cons of different kinds of large detectors, issues related to underground laboratories.

1.11.2 Experimental Programs

1.11.2.1 Global context

Brief description of existing and proposed programs in Canada, Europe, Asia.

1.11.2.2 Facilities in the U.S.

Existing and near future facilities and programs: NuMI, LAR program, Nova, Minerva, Argoneut, Microboone, etc. Mention also Daya Bay– not in U.S. but substantial U.S. participation

Some discussion about future exploitation of existing facilities

LBNE status and sensitivity in some detail.

Homestake

Project X

New ideas, and farther future ideas: VLENF, nu factory, Daedalus, etc.

1.12 Conclusions – 1 page

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