Neutrino physics: An update

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We update our recent didactic survey of neutrino physics, including new results from the Sudbury Neutrino Observatory and Kamioka Liquid Scintillator Anti-Neutrino Detector experiments, and recent constraints from the Wilkinson Microwave Anisotropy Probe and other cosmological probes.
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I. INTRODUCTION

Several years ago, we authored a paper in this journal, hereafter called I,[1] to encourage inclusion of material involving neutrinos into the introductory curriculum. We noted at the time that neutrinos, with new experiments about to provide initial data, might continue to be a popular topic for students (and faculty). This prediction has proven true:

- (i) Ray Davis, the founder of the field of experimental solar neutrino physics, shared the 2002 Nobel Prize in physics with Mastoshi Koshiba, who led the Kamioka solar neutrino experiment, and Riccardo Giacconi.[2]
- (ii) Results from the Sudbury Neutrino Observatory (SNO) resolved the solar neutrino puzzle, showing that approximately two-thirds of these neutrinos oscillate into other flavors before reaching earth.[3,4]
- (iii) The KamLAND experiment, in which antineutrinos from Japanese power reactors were detected, confirmed the Sudbury Neutrino Observatory results and further narrowed the allowed range of neutrino mass differences.[5]
- (iv) The Wilkinson Microwave Anisotropy Probe (WMAP) measured subtle temperature differences within the oldest light in the universe, from the epoch when atoms first formed 380 000 years after the Big Bang.[6] When combined with the results of large scale structure studies,[7] a new bound on the sums of the neutrino masses has been obtained.

In addition, evidence has been published (and disputed) for the existence of neutrinoless double beta decay which, if confirmed, would show that one of the standard model's most important symmetries, the conservation of lepton number, is violated.[8] Thus we decided to bring our earlier paper up to date by explaining the importance and implications of the new results.

In Sec. II we present a much abbreviated summary of the material presented in I. In Sec. III we discuss the Sudbury Neutrino Observatory results and how they resolved the puzzling discrepancies Davis first uncovered 30 years ago. In Sec. IV we discuss KamLAND, the first terrestrial experiment to achieve the sensitivity to the small neutrino mass differences relevant to solar neutrino experiments. In Sec. V we describe marvelous new cosmological probes of large scale structure and of the time when atoms were first formed, and discuss why the new data may soon challenge recent double beta decay claims. We summarize where we stand in neutrino physics, including the new discoveries that may soon be within reach, in Sec. VI.

II. THE TWO-MINUTE REVIEW

In I we summarized the basics of neutrino physics, including neutrino history, properties, and implications for contemporary physics. For the purposes of this paper, we note that in the standard model of particle/nuclear physics,[9] which is consistent with nearly all present experimental information, there exist three massless neutrino types, ν_s, ν_μ, ν_τ, which are produced with purely left-handed helicity in weak interaction processes. If the neutrino were shown to have a nonvanishing mass, it would be the first clear failure of the 30-year-old standard model and the first proof of the existence of the particle dark matter that appears necessary to explain the structure and expansion of our universe. Nonzero neutrino masses were suggested by the results of experiments that measure the flux of solar neutrinos, which are produced as a by-product of the thermonuclear reactions occurring in the high temperature core of our sun.[10] Additional strong evidence comes from the study of atmospheric neutrinos, which are produced when high energy cosmic rays collide with the upper atmosphere, producing pions and other particles that then decay into neutrinos.[11] The largest of the various atmospheric neutrino experiments is SuperKamiokande, a detector in a mine in the Japanese alps that contains 50 000 tons of ultra-pure water. SuperKamiokande's precise data show that the flux of muon-type atmospheric neutrinos arriving from the opposite side of the earth, which have traveled a long distance to reach the detector, is depleted.

Both the solar and atmospheric neutrino results can be explained quantitatively if neutrinos are massive and if the mass eigenstates are not coincident with the weak interaction eigenstates, ν_s, ν_μ, ν_τ, that is, if the neutrinos produced in weak interactions are combinations of the various mass eigenstates. This situation is exactly what is known to occur in the analogous case of the quarks.[9] The relation between the neutrino mass and weak-interaction eigenstates is described by a unitary matrix: for three neutrinos, the mass and weak-interaction eigenstates can be viewed as two distinct three-dimensional coordinate systems. The unitary matrix specifies the three rotations describing the orientation of one coordinate system relative to the other.

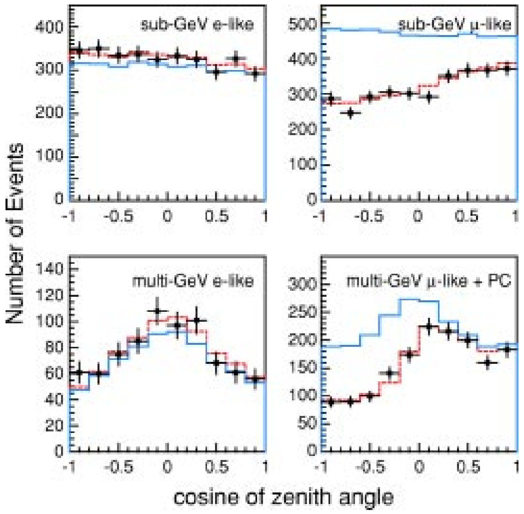

Fig. 1. The SuperKamiokande atmospheric neutrino results showing excellent agreement between the predicted and observed electron-like events, but a sharp depletion in the muon-like events for neutrinos coming from below, through the earth. The results are fit very well by the assumption of $\nu_\mu \rightarrow \nu_\tau$ oscillations with maximal mixing.

The reduced flux of atmospheric muon neutrinos (see Fig. 1) is quantitatively explained by $\nu_\mu \rightarrow \nu_\tau$ oscillations governed by maximal mixing, $\theta_{23} \sim \pi/4$: the relationship between the mass eigenstates ν_2 and ν_3 and the flavor eigenstates ν_μ and ν_τ involves a rotation of 45°. The magnitude of the mass (squared) difference $\delta m_{23} = m_3^2 - m_2^2$ between the two equal components making up the flavor eigenstates is $\sim 2 \times 10^{-3}$ eV^2. When I was written, the favored solution to the solar neutrino problem was also neutrino mixing, but was described by a much smaller mixing angle θ_{12} specifying the relationship between mass eigenstates ν_1 and ν_2 and the flavor eigenstates ν_e and ν_μ. The effects of this small mixing are magnified by interaction with matter in the sun. This is the Mikheyev–Smirnov–Wolfenstein effect and is described in I. But the results of the Sudbury Neutrino Observatory provided a bit of a surprise.

III. THE SUDBURY NEUTRINO OBSERVATORY EXPERIMENT

Because both charged and neutral currents contribute to the reaction important to SuperKamiokande,

$$\nu_x + e^- \rightarrow \nu_x + e^-, \tag{1}$$

experimentalists cannot easily distinguish ν_e's from the ν_μ's and ν_τ's: the detector records both fluxes, though with a reduced sensitivity (0.15) for the heavy-flavor (ν_μ and ν_τ) types. The reaction produces energetic recoil electrons that generate Cerenkov radiation which is recorded in an array of phototubes surrounding the detector. Because the cross section is sharply forward peaked, the correlation with the position of the sun can be used to remove the background contributions associated with cosmic rays and radioactivity in the rock walls surrounding the detector. Because the threshold for electron detection is ~ 6 MeV, only the high energy portion of the ^{8}B solar neutrino flux is measured. These are the same neutrinos that dominate the radiochemical measurements of Ray Davis: Superkamiokande confirmed that this flux was substantially below that predicted by the standard solar model (SSM)[12]

$$\phi_{\rm SSM}(\nu_x) = 5.44 \times 10^6 \ {\rm cm}^{-2}\,{\rm s}^{-1}. \tag{2}$$

When the Davis and SuperKamiokande results were combined with those from the gallium experiments, SAGE and GALLEX, the resulting three constraints on the three principal solar neutrino sources (^{8}B, ^{7}Be, and the low-energy pp fluxes) produced a surprising result. No combination of these fluxes could reproduce the combined data well. Although circumstantial, this evidence indicated that the solution to the solar neutrino problem would not be found in the standard solar model, but instead would require new particle physics.

The favored explanation became neutrino oscillations which, as we have just summarized, occur for massive neutrinos when the weak and mass eigenstates do not coincide. The SuperKamiokande discrepancy, a solar neutrino rate less than half that expected from the standard solar model, would require that approximately two-thirds of the high energy electron neutrinos generated in the solar interior oscillate into ν_μ and ν_τ before reaching earth. Low-energy ν_μ's and ν_τ's are invisible to the Davis and SAGE/GALLEX detectors and scatter electrons in the SuperKamiokande detector with a reduced cross section, as we noted previously.

The key idea behind the Sudbury Neutrino Observatory experiment was the construction of a detector that would have multiple detection channels, recording the ν_e's by one reaction and the total flux of all neutrinos ($\nu_e + \nu_\mu + \nu_\tau$) by another. This was accomplished by replacing the ordinary water in a water Cerenkov detector with heavy water, D_2O instead of H_2O. The charged-current channel that records the ν_e's is analogous to the reaction used in the Davis detector,

$$\nu_e + d \rightarrow p + p + e^-. \tag{3}$$

Because the electron produced in this reaction carries off most of the neutrino energy, its detection in the Sudbury Neutrino Observatory detector (by the Cerenkov light it generates) allows experimentalists to determine the spectrum of solar ν_e's, not just the flux. A second reaction, the neutral current breakup of deuterium, gives the total flux, independent of flavor (the ν_e, ν_μ, and ν_τ cross sections are identical),

$$\nu_x + d \rightarrow n + p + \nu_x. \tag{4}$$

The only signal for this reaction in a water Cerenkov detector is a neutron, which can be observed as it is captured via the (n,γ) reaction. The Sudbury Neutrino Observatory is currently operating with salt added to the water, because Cl in the salt is an excellent target for neutrons, producing about 8 MeV γ's.

Although this strategy may sound straightforward, developing such a detector was an enormous undertaking. The needed heavy water—worth about $300M (Canadian)—was available through the Canadian government because of its CANDU reactor program. The single-neutron detection required for the neutral current reaction is possible only if backgrounds are extremely low. For this reason the detector had to be placed very deep underground, beneath approximately 2 km of rock, so that cosmic-ray muon backgrounds would be reduced to less than 1% of that found in the SuperKamiokande detector. The desired site was chosen to be in an active nickel mine, the Sudbury mine in Ontario, Canada, where experimentalists worked with the miners to carve out a 10-story-high cavity on the mine's 6800 ft level. Trace quantities of radioactivity were another background concern: if a thimblefull of dust were introduced into the massive cavity during construction, the resulting neutrons from uranium and thorium could cause the experiment to fail. Thus, despite the mining activities that continued around them, the detector was constructed to the strictest cleanroom standards. The detector also provided a third detection channel, neutrino elastic scattering (ES) off electrons [Eq. (1)], which we have noted is sensitive to ν_e's and, with reduced sensitivity, ν_μ's and ν_τ's.

The elastic scattering reaction, of course, provides the Sudbury Neutrino Observatory a direct cross check against SuperKamiokande. Sudbury Neutrino Observatory's threshold for measuring these electrons is about 5 MeV. Assuming no oscillations, the Sudbury Neutrino Observatory's detection rate is equivalent to a ν_e flux of

$$\phi_{\rm SNO}^{\rm ES} = 2.39 \pm 0.34({\rm stat}) \pm 0.15({\rm syst}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}, \tag{5}$$

a result in excellent accord with that from SuperKamiokande,

$$\phi_{\rm SK}^{\rm ES} = 2.32 \pm 0.03({\rm stat}) \pm 0.06({\rm syst}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}. \tag{6}$$

The greater accuracy of the SuperKamiokande result reflects the larger mass (50 ktons) and longer running time of the Japanese experiment. (The Sudbury Neutrino Observatory detector contains, in addition to the 1 kton of heavy water in its central acrylic vessel, an additional 7 ktons of ordinary water which surrounds the central vessel, helping to shield it.)

The crucial new information provided by Sudbury Neutrino Observatory detector comes from the two reactions which take place in deuterium. The charged-current channel is only sensitive to ν_e's. Given the assumption of an undistorted ^{8}B neutrino flux, the Sudbury Neutrino Observatory experimentalists deduced that

$$\phi_{\rm SNO}^{\rm CC}(\nu_e) = 1.75 \pm 0.07({\rm stat}) \pm 0.12({\rm sys}) \pm 0.05({\rm theory}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}. \tag{7}$$

The charged-current flux is less than that deduced from the elastic scattering rate, indicating that ν_μ's and ν_τ's must be contributing to the latter. From the difference between the SuperKamiokande elastic scattering and the Sudbury Neutrino Observatory charged-current results,

$$\delta\phi = 0.57 \pm 0.17 \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}, \tag{8}$$

and recalling that the ν_μ/ν_τ elastic scattering cross section is only 0.15 of the ν_e, we can deduce the heavy-flavor contribution to the solar neutrino flux to be

$$\phi(\nu_\mu/\nu_\tau) = 3.69 \pm 1.13 \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}. \tag{9}$$

That is, approximately two-thirds of the solar neutrino flux is in these flavors.

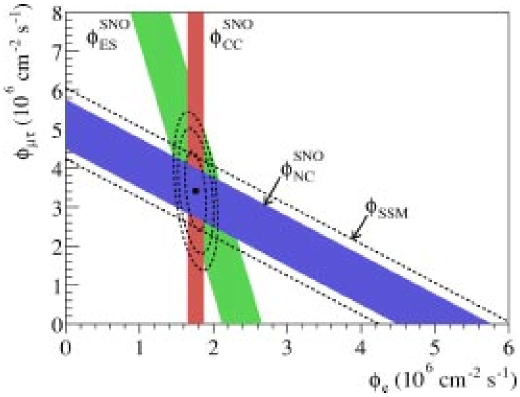

Fig. 2. The flux of ^{8}B solar neutrinos is divided into ν_μ/ν_τ and ν_e flavors by the Sudbury Neutrino Observatory analysis. The diagonal bands show the total ^{8}B flux as predicted by the standard solar model (dashed lines) and that measured with the neutral current reaction in the Sudbury Neutrino Observatory (solid band). The widths of these bands represent the $\pm 1\sigma$ errors. The bands intersect in a single region for $\phi(\nu_e)$ and $\phi(\nu_\mu/\nu_\tau)$, indicating that the combined flux results are consistent with neutrino flavor transformation assuming no distortion in the ^{8}B neutrino energy spectrum.

While the first Sudbury Neutrino Observatory analysis was done in the manner described, a second publication gave the long awaited neutral current results. The measurement of the neutral current event rate allowed a direct and very accurate determination of the flavor content of solar neutrinos, without the need for combining results from two experiments. The published neutral current results were obtained without the addition of salt to the detector: the neutron was identified by the 6.25 MeV γ ray it produces when captured by deuterium. The resulting total flux, independent of flavor, is

$$\phi_{\rm SNO}^{\rm NC}(\nu_x) = 5.09 \pm 0.44({\rm stat}) \pm 0.45({\rm syst}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}. \tag{10}$$

If we combine the net total flux with the charged-current signal, we obtain

$$\phi_{\rm SNO}(\nu_e) = 1.76 \pm 0.05({\rm stat}) \pm 0.09({\rm syst}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}, \tag{11a}$$

$$\phi_{\rm SNO}(\nu_\mu/\nu_\tau) = 3.41 \pm 0.45({\rm stat}) \pm 0.46({\rm syst}) \times 10^6\ {\rm cm}^{-2}\ {\rm s}^{-1}. \tag{11b}$$

The presence of heavy-flavor solar neutrinos and thus neutrino oscillations is confirmed at the 5.3σ level! Furthermore, the total flux is in excellent agreement with the predictions of the standard solar model, Eq. (2), an important vindication of stellar evolution theory.

The Sudbury Neutrino Observatory analysis is summarized in Fig. 2, which shows the three bands corresponding to the charged-current, neutral current, and elastic scattering measurements coinciding in a single region. These results can now be combined with other solar neutrino measurements to determine the mixing angle and mass-squared difference parameters governing the oscillations. At the time I was written, there were several contending solutions, though the data favored one characterized by a small mixing angle (thus called the SMA solution). Figure 3 shows that the Sudbury Neutrino Observatory result has determined an oscillation solution that, at the 99% confidence level, is unique, and as in the atmospheric neutrino case, has a large mixing angle, $\theta_{12} \sim 30°$. This large mixing angle oscillation is clearly distinct from that observed with atmospheric neutrinos, with $\delta m_{12}^2 = m_2^2 - m_1^2$ centered on a region $\sim 8 \times 10^{-5}$ eV^2.

The discovery that the atmospheric and solar neutrino problems are both due to neutrino oscillations has provided the first evidence for physics beyond the standard model. That neutrinos provided this evidence is perhaps not unex-

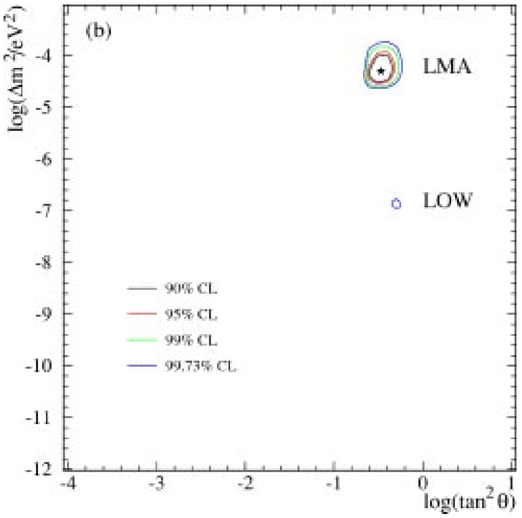

Fig. 3. For two-flavor mixing, the values of the mass difference and mixing angle consistent with the world's data on solar neutrinos, post Sudbury Neutrino Observatory. At 99% confidence level, the addition of the Sudbury Neutrino Observatory data isolates a unique, large mixing angle solution.

pected: if the standard model is viewed as an effective theory, one largely valid in our low-energy world but missing physics relevant to very high energies beyond the reach of current accelerators, then a neutrino mass term is the lowest-order correction that can be added to that theory. But a surprise is the large mixing angles characterizing the neutrino oscillations, which contradicts the simple prejudice that neutrino mixing angles might be similar to the small angles familiar from quark mixing. Perhaps this result simply reinforces something that should have been apparent at the outset: with their small masses and distinctive mixings, neutrinos likely have an underlying mechanism for mass generation that differs from that of the other standard model fermions.

IV. THE KAMLAND EXPERIMENT

One remarkable aspect of the solar and atmospheric neutrino discoveries is that the derived oscillation parameters are within the reach of terrestrial experiments. This fortunate circumstance did not have to be the case—solar neutrinos are sensitive to neutrino mass-squared differences as small as 10^{-12} eV^2, for which terrestrial experiments would be unthinkable.

Very recently, KamLAND (the Kamioka Liquid Scintillator Anti-Neutrino Detector), the first terrestrial experiment to probe solar neutrino oscillation parameters, reported their initial results. The inner detector consists of 1 kton of liquid scintillator contained in a spherical balloon, 13 m in diameter. The balloon is suspended in the old Kamioka cavity (where SuperKamiokande's predecessor was housed) by Kevlar ropes, with the region between the balloon and the 18-m-diam stainless steel containment vessel filled with additional scintillator (to shield the target from external radiation). Several Japanese power reactors are about 180 km from the Kamioka site, and the electron antineutrinos emitted by nuclear reactions in the cores of these reactors can be detected in KamLAND via the inverse beta decay reaction,

$$\overline{\nu}_e + p \rightarrow e^+ + n, \tag{12}$$

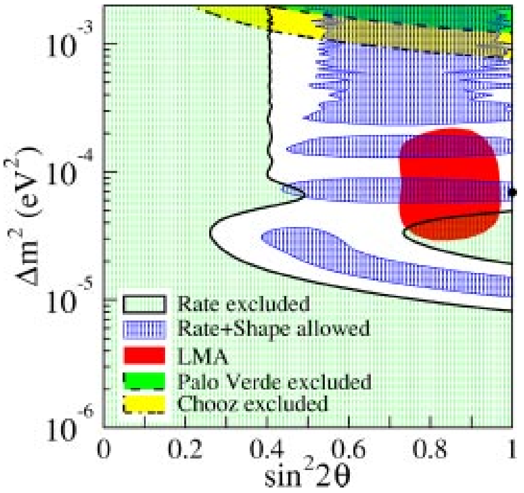

Fig. 4. The 95% confidence level. The large mixing angle allowed region of the Sudbury Neutrino Observatory and other solar neutrino experiments is shown. The regions marked "Rate and Shape allowed" show the 95% c.l. KamLAND allowed solutions. The thick dot indicates the best fit to the KamLAND data, corresponding to $\sin^2 2\theta_{12} \sim 1.0$ and $\delta m^2_{12} \sim 6.9 \times 10^{-5}$ eV^2.

where the e^+ is seen in coincidence with the delayed 2.2 MeV γ ray produced by the capture of the accompanying neutron by a proton. This coincidence allows the experimentalists to distinguish $\overline{\nu}_e$ reactions from the background.

From the reactor operation records the KamLAND experimentalists can calculate the resulting flux at Kamiokande to a precision of $\sim 2\%$, in the absence of oscillations. Thus, if a significant fraction of the reactor $\overline{\nu}_e$'s oscillate into $\overline{\nu}_\mu$'s or $\overline{\nu}_\tau$'s before reaching the detector, a low rate of e^+ capture-γ-ray coincidences will be evident [see Eq. (12)]. This type of experiment is an example of the "disappearance" oscillation technique we described in I. For the 162 ton/yr exposure so far reported by the KamLAND collaboration, the number of events expected in the absence of oscillations is 86.8 ± 5.6. But the number measured is 54, just 61% of the no-oscillation expectation. From the two-neutrino-flavor oscillation survival probability [see Eq. (66) in I],

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \simeq 1 - \sin^2 2\theta_{12} \sin^2 \frac{\delta m^2_{12} L}{4E_\nu}, \tag{13}$$

we obtain the oscillation parameters of Fig. 4. KamLAND confirms the large mixing angle solution and significantly narrows the Sudbury Neutrino Observatory's allowed region (the dark area in Fig. 4). KamLAND has excellent sensitivity to δm^2_{12}, but less sensitivity to $\sin^2 2\theta_{12}$ (due to uncertainties in the shape of the reactor $\overline{\nu}_e$ spectrum). The result is the separation of the Sudbury Neutrino Observatory large mixing angle allowed region into two parts, with the best-fit $\delta m^2_{12} \sim 7 \times 10^{-5}$ eV^2, but with a larger mass difference $\sim 1.5 \times 10^{-4}$ eV^2 also a good fit. KamLAND is an excellent example of complementary terrestrial and astrophysical measurements: solar neutrino experiments provide our best constraints on θ_{12}, but KamLAND places the tightest bounds on δm^2_{12}.

V. WMAP, DOUBLE BETA DECAY, AND NEUTRINO MASS

Despite the wonderful recent discoveries in neutrino physics, there remain quite a number of open questions. Several have to do with the pattern of neutrino masses. All of the experiments described previously probe mass differences, not absolute neutrino masses. Furthermore, the atmospheric neutrino experiments only constrain the magnitude of δm_{23}^2, and not its sign. As a result, there exist several mass patterns fully consistent with all known data. One choice would be to assign m_3 to be the heaviest neutrino, split by the atmospheric mass difference $\delta m_{23}^2 \sim 2\times 10^{-3}$ eV^2 from a lighter, nearly degenerate pair of neutrinos responsible for solar neutrino oscillations. (This pair is split by the solar neutrino mass difference $\delta m_{12}^2 \sim 10^{-5}$ eV^2.) However, because the sign of δm_{23}^2 is not known, it also is possible that m_3 is the lightest neutrino, with heavier, nearly degenerate m_1 and m_2. Finally, the best direct experimental constraint on absolute neutrino masses comes from studies of tritium beta decay, as described in I. Studies of the tritium spectrum near its end point energy places a bound[13] of 2.2 eV on the $\overline{\nu}_e$ mass (or more properly, on the principal mass eigenstate contributing to the $\overline{\nu}_e$). Consequently, we can add an overall scale of up to 2.2 eV to the mass splittings described earlier. That is, no terrestrial measurement rules out three nearly degenerate neutrinos, each with a mass $\sim$2.2 eV, but split by $\delta m_{\mathrm{atmos}}^2$ and $\delta m_{\mathrm{solar}}^2$.

As discussed in I, the absolute neutrino mass is crucial in cosmology, because a sea of neutrinos produced in the Big Bang pervades all of space. If these neutrinos carry a significant mass, they would constitute an important component of particle dark matter, invisibly affecting the structure and expansion of our universe. Light neutrinos, such as those we have been discussing, decoupled from the rest of the matter as relativistic particles, about 1 s after the Big Bang. Their number density and temperature can be calculated at the time of decoupling and at the present. Their contribution to the universe's mass–energy budget is now dominated by their masses,

$$\rho_\nu = 0.022 \rho_{\mathrm{crit}} \sum_i m_\nu(i), \tag{14}$$

where ρ_{crit} is the critical density that will just close the universe and m_ν is in electron volts. A variety of cosmological probes suggest that our universe is very close to the critical density $\rho/\rho_{\mathrm{crit}} = 1.0 \pm 0.04$.

From this discussion, we know that at least one neutrino must have a mass of at least $\sqrt{\delta m_{\mathrm{atmos}}^2}$. Similarly, the tritium beta decay limit places an upper bound on the sum of the masses of 6.6 eV (corresponding to three nearly generate neutrinos of mass 2.2 eV). It follows that the neutrino contribution to dark matter is bounded above and below by

$$0.0012 \lesssim \rho_\nu/\rho_{\mathrm{crit}} \lesssim 0.15. \tag{15}$$

This broad range implies that the amount of mass in neutrinos could easily exceed all the familiar baryon matter—stars, dust, gas clouds, and us!—visible or invisible: big-bang nucleosynthesis and precision measurements of the cosmic microwave background both indicate that $\rho_{\mathrm{baryons}}/\rho_{\mathrm{crit}} \sim 0.042$.

However, in the past few years a series of extraordinarily precise measurements have been made in cosmology. One of these is the recent WMAP full-sky map of the cosmic microwave background and its subtle (few millionths of a degree) temperature anisotropies. This background is the oldest light in the universe, the photons that decoupled from matter at the time atoms formed, about 380 000 years after the Big Bang. The cosmic microwave background temperature anisotropies tell us about the structure of the universe, its clumpiness, at this very early epoch. Measurements of distant type-Ia supernovae, a sort of "standard candle" by which astronomers can measure cosmological distances, have constrained the expansion rate and mass/energy budget of the universe. Large-scale surveys, such as the 2dF Galaxy Redshift Survey, have mapped the distribution of visible matter in the universe today and in recent times.[7] The result from combining these and other cosmological probes is a rather sharp constraint on the amount of hot dark matter, in particular, the mass density in neutrinos, that can be allowed, given that our universe has evolved to its present state. We find

$$\rho_\nu/\rho_{\mathrm{crit}} \lesssim 0.022, \tag{16}$$

that is, an upper bound on the sum of neutrino masses of about 1.0 eV. (Some analyses claim even tighter upper bounds.) This bound is significantly tighter than that of Eq. (14), derived from laboratory data only.

Cosmology now demands that neutrino dark matter can make up no more than 2%–3% of the universe's mass–energy budget and, in particular, is less important than other forms of matter we know about (for example, nucleons). (We will not go into the disconcerting fact that at least 93% of the universe's mass–energy budget appears to be dark energy and cold dark matter that we have not yet adequately characterized!) It also tells us that neutrino mass at the $\sim$1 eV level now effects cosmological analyses: such analyses would constrain other cosmological parameters more tightly if neutrino masses were measured, rather than being free parameters that one must dial into cosmological models until unacceptable deviations are found. (The 1 eV bound was derived by such cosmological arguments, which underscores how important it is to significantly improve laboratory mass limits.)

One possibility is a new-generation tritium experiment. There is a serious effort under way to improve the current bound on the $\overline{\nu}_e$ mass to about 0.3 eV, which would then place an upper bound on the sum of the masses of about 0.9 eV.[13] Another possibility—less definitive, perhaps, but with even greater reach—is offered by new-generation neutrinoless double beta decay experiments.

The phenomenon of neutrinoless double beta decay, described in I, tests not only mass, but also whether a standard model symmetry called lepton number conservation is violated. In neutrinoless double beta decay a nucleus spontaneously decays by changing its charge by two units while emitting two electrons,

$$(A,Z) \rightarrow (A,Z+1) + e^- + \overline{\nu}_e \rightarrow (A,Z+2) + e^- + e^-, \tag{17}$$

where the intermediate nuclear state $(A,Z+1)$ is virtual. The emitted electrons carry off the entire nuclear energy release, allowing this process to be distinguished from the standard-model-allowed process of two-neutrino double beta decay (where the energy is shared between two electrons and two $\overline{\nu}_e$'s in the final state). The neutrinoless process clearly violates lepton number, as two leptons (the electrons) are spontaneously produced. (By contrast, because the e^- carries l

$=+1$ and the $\overline{\nu_e}$ carries $l=-1$, two-neutrino double beta decay conserves lepton number.)

What conditions will lead to neutrinoless double beta decay? The necessary lepton number violation is present if the neutrino is a Majorana particle, that is, is identical to its antiparticle. Most theoretical models include Majorana neutrinos, because they arise as part of the mechanism that allows us to understand why neutrinos have masses much smaller than those of the other standard-model fermions, such as electrons and quarks. But the existence of a Majorana neutrino alone is not sufficient because of the exact handedness of neutrinos, which we discussed in I. In the neutrinoless double beta decay reaction given in Eq. (17), the $\overline{\nu_e}$ appearing in the intermediate nuclear state was produced in the nucleus by the neutron β decay reaction $n\rightarrow p+e^- + \overline{\nu_e}$. To complete the decay, the antineutrino must be reabsorbed by a second neutron, $\nu_e+n\rightarrow p+e^-$. At first glance, if $\overline{\nu_e}=\nu_e$, that is, if the neutrino is its own antiparticle, this reabsorption looks possible. However, this conclusion overlooks the neutrino handedness. In the first step, the $\overline{\nu_e}$ produced is right-handed, while the second reaction only proceeds if the ν_e is left-handed. Thus it would appear that the neutrinoless process is forbidden, even if $\overline{\nu_e}=\nu_e$.

This argument, however, overlooks the effects of neutrino mass: a small neutrino mass breaks the exact neutrino handedness, allowing neutrinoless $\beta\beta$ decay to proceed, although the amplitude is suppressed by the factor m_ν/E_ν, where $E_\nu\sim 30$ MeV is the typical energy of the exchanged neutrino. It follows that neutrinoless double beta decay measures the neutrino mass—at least the Majorana portion of that mass. (Making this statement more precise, unfortunately, takes us beyond the limits of this paper.)

In the simplest case—a single Majorana mass eigenstate dominating the $\beta\beta$ decay—the neutrinoless amplitude is proportional to $U_{ei}^2 m_i$, where U_{ei}^2 is the mixing probability of the ith mass eigenstate in the ν_e and m_i is the mass. Currently the best neutrinoless $\beta\beta$ decay limits are those obtained by the Heidelberg-Moscow and IGEX enriched (86%) ^{76}Ge experiments, which both probe lifetimes beyond 10^{25} yr—corresponding to roughly one decay per kg yr![14,15] These experiments employ Ge crystals—the Ge is both source and detector—containing about 10 kg of active material. Next-generation experiments, using a variety of double beta decay sources (^{76}Ge, ^{136}Xe, ^{100}Mo), have been proposed at the 1 ton scale. These have as their goals sensitivities to neutrino masses of 10–50 meV, corresponding to lifetimes well in excess of 10^{27} yr. One important motivation for these heroic proposals is the number $\sqrt{\delta m^2_{\mathrm{atmos}}} \sim 55$ meV: in several scenarios accommodating the solar and atmospheric oscillation results, this scale plays a role in determining the level at which neutrinoless $\beta\beta$ decay might be observed.

A few members of the Heidelberg-Moscow collaboration have claimed that their present results are not a limit, but rather a detection of neutrinoless $\beta\beta$ decay, with a best value for the Majorana neutrino mass of ~ 0.4 eV.[8] This claim has been strongly criticized by a group that argues that the claimed peak, shown in Fig. 5, is not statistically significant. Regardless, this claim will clearly be tested soon in other $\beta\beta$ decay experiments and in future cosmological tests, which promise to soon be probing masses ~ 0.3 eV.

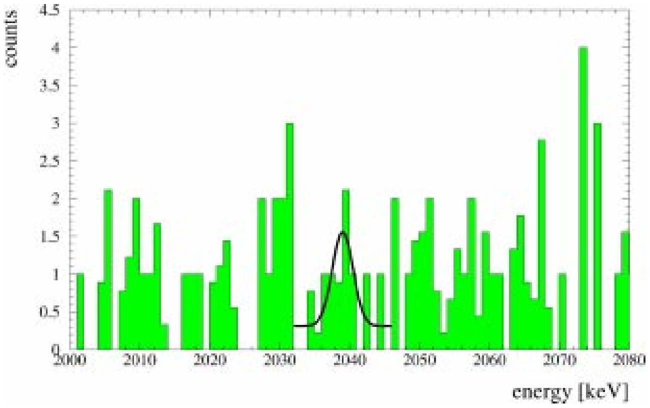

Fig. 5. The spectrum found in Ref. 8. The claimed signal is as shown.

VI. CONCLUSION

In the three years since the publication of I, several very significant neutrino discoveries have been made.

(i) The Sudbury Neutrino Observatory detector has shown that approximately two-thirds of the ^{8}B neutrinos that arrive on earth have oscillated into ν_μ's or ν_τ's, thus demonstrating that new neutrino physics is responsible for the solar neutrino puzzle first uncovered by Davis. Together with the atmospheric neutrino discoveries of SuperKamiokande, this discovery of an effect requiring massive neutrinos and neutrino mixing is the first evidence for physics beyond the standard model. The Sudbury Neutrino Observatory results for the total solar neutrino flux, independent of flavor, are in excellent agreement with the predictions of the standard model—despite the challenge of calculating a flux that varies as ${T_c}^{22}$, where T_c is the solar core temperature. The Sudbury Neutrino Observatory results, when added to other solar neutrino data, isolate a single oscillation scenario, the large mixing angle solution.

(ii) The first terrestrial experiment to probe solar neutrino oscillation parameters, KamLAND, has confirmed the Sudbury Neutrino Observatory results and further narrowed the large mixing angle range of allowed δm^2_{12}.

(iii) Both the absolute scale of neutrino masses and the detailed pattern of the masses remain unknown, as the present results measure only mass differences (and leave the sign of δm^2_{23} undetermined). The most stringent current bound on the absolute scale of neutrino mass comes from recent precision tests of cosmology (notably WMAP and the 2dF Galaxy Redshift Survey). This limit, a bound of about 1 eV for the sum of neutrino masses, is likely to improve as new surveys are done. In addition, much improved tritium β decay and neutrinoless $\beta\beta$ decay experiments are being planned. There is one controversial claim of an observation of neutrinoless $\beta\beta$ decay that must be checked soon.[8]

We stress, as we did in I, that this field is producing many new results that promise to impact physics broadly. The most common mechanisms for explaining neutrino mass suggest that current experiments are connected with phenomena far outside the standard model, residing near the grand unified energy scale of 10^{16} GeV. Thus there is hope that, by fully determining the properties of neutrinos—a few of the unresolved problems have been mentioned here—we may equip theorists to begin constructing the next standard model. Neutrino physics is also crucial to astrophysics—not just the standard solar model, but also in supernovae and in high energy astrophysical environments—and to cosmology. We now have identified the first component of particle dark matter, although the significance of the neutrino mass is still unclear due to our ignorance of the overall scale. Neutrinos could prove central to one of cosmology's deepest questions, why our universe is matter dominated, rather than matter–antimatter symmetric. But this is a story for another paper and another time.

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STYLE

My first course was on Plato's dialogue *Theatetus*. I went through the dialogue line by line with frequent asides on ancient and modern problems. For example, I connected Plato's theory of perception with quantum mechanics, and I dealt at length with his reason for choosing the dialogue over the epic, the drama, the public speech, and the scientific essay as a means of communication. "Plato thought about his style," I said; "today the style of a scientific paper is decided by editors."

Paul K. Feyerabend, *Killing Time: The Autobiography of Paul Feyerabend* (The University of Chicago Press, Chicago, 1995), p. 159.

Submitted by Alan DeWeerd.