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NEUTRINO PROPERTIES AND PUZZLES

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Sixty years after the existence of the neutrino was first postulated, we are still lacking in information on the fundamental properties of neutrinos. Measurements have consistently pushed the limits on the mass, magnetic moment, and possible mixing down. Solar neutrino experiments are now shedding more light on the "solar neutrino problem" and are starting to give a hint that perhaps these quantities are nonzero. The present status of our knowledge of neutrino properties, the newest experimental data on the "solar neutrino problem," and future plans will be presented.

INTRODUCTION

The neutrino was first postulated by Wolfgang Pauli in 1930 in order to conserve momentum and energy in nuclear beta decay. The properties assigned to the neutrino at that time were that it was neutral, that it interacted by the weak force but not by the strong force, and that it had spin one half. In addition, only one type of neutrino was postulated to exist. It was assumed that the mass was zero and that it did not possess any electromagnetic moments.

In the last 60 years we have only learned a bit more about its properties. In this paper I will first discuss the parameters that can be used to define the properties of neutrinos. The reasons for the strong interest in determining these properties will be presented. The bulk of the paper will focus on experiments that have searched for a finite neutrino mass.

NEUTRINO PROPERTIES

The neutrino is a fermion with a spin of one half. The helicity of the neutrino defines whether its spin is parallel (i.e., right-handed) or antiparallel (i.e., left-handed) to its momentum. Experiments have shown that the neutrino has negative helicity (i.e., is left-handed), with high accuracy. However, this definite helicity is absolute only if the mass of the neutrino is exactly zero and assuming a purely V-A weak interaction.

If one relaxes these assumptions, the neutrino can then be classified as a Dirac or Majorana type. This classification has to do with the symmetry properties of the neutrino and its associated antineutrino. For a Dirac neutrino, the neutrino and its antineutrino are distinct, so that there can be two components with different helicity for both the neutrino and the antineutrino, giving a total of four distinct components. For a Majorana neutrino, the neutrino and its antineutrino are identical; thus there can only be left- and right-handed neutrinos.

The symmetry properties of Dirac and Majorana neutrinos dictate the possible electromagnetic couplings that they can have. Using the CPT theorem, one can demonstrate that the Majorana neutrino cannot have

static electric or magnetic moments. Dirac neutrinos may have a magnetic moment, but electric moments are suppressed since they require CP violation.

From the famous experiments of Lederman et al.¹ it was determined that there are two types of neutrinos (called the electron type and muon type). Subsequent measurements have shown that there are in fact three types of neutrinos: electron, muon, and tau (plus their corresponding antiparticles). Recent measurements of the width of the Z_0 indicate that there are only three types of neutrinos (at least for neutrinos with a mass less than about 40 GeV). It is theoretically possible for the three different types of neutrinos to mix; i.e., the physical states of the neutrinos are not true eigenstates, but rather they represent a mixture of different mass eigenstates. For simplicity, consider only two types of neutrinos—the electron and muon neutrinos. The physical states of these two neutrinos can then be written in terms of the neutrino eigenstates 1 and 2 as:

$$|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

$$|\nu_\mu\rangle = -\sin\theta|\nu_1\rangle + \cos\theta|\nu_2\rangle$$

Thus, we see that if the mixing angle theta is nonzero, lepton number will not be conserved. We also note that in order for neutrino species to mix, the mass of at least one of the species must be nonzero.

SCIENTIFIC MOTIVATION

The property of neutrinos that is of the greatest interest is the mass. Remember that in the Standard Weinberg-Salam-Glashow Model the mass is naturally zero. This does not preclude a finite value, but it must be put into the theory by hand. The advent of Grand Unified Field Theories (GUTs) provided a natural way in which the neutrino can acquire a nonzero mass. Unfortunately, GUTs do not provide much guidance as to the magnitude of the values of these properties. For example, various GUT predictions for the neutrino mass span more than 18 orders of magnitude. Nonetheless, experimental demonstration of a nonzero neutrino mass would be a positive indication of physics beyond the Standard Model.

While a nonzero mass is certainly of great interest in particle physics, it also is of great interest in astrophysics and cosmology. In the Standard Big Bang Model, the density of relic neutrinos is $110/\text{cm}^3$ per neutrino species, which is nine orders of magnitude higher than the density of baryons. If the neutrino has even a small mass, on the order of a few tens of eV, the mass density of neutrinos would dominate the universe and could provide the solution to the dark matter problem.

In addition, even if the neutrino has a very tiny mass (of order 10^{-3} – 10^{-6} eV) and mixing occurs, then the solar neutrino problem could be explained by neutrino oscillations. And if the neutrino has a magnetic moment of order 10^{-10} Bohr magnetons, then the interaction of the magnetic moment with the magnetic fields in the sun might also explain the solar neutrino problem and might also account for the postulated anticorrelation of the solar neutrino flux with sunspot number.

NEUTRINO MASS: KINEMATIC TESTS

The only method that allows one to directly search for a finite neutrino mass without requiring any other conditions is kinematic tests. The first class of such tests involves studying the beta decay of particles

or nuclei and examining the spectrum shape for the effect of a finite neutrino mass. The second class of tests has involved time-of-flight measurements of the neutrinos arriving from SN1987a.

The best limits at present on neutrino mass are given in Table I. In the searches for a finite mass of the tau and muon neutrinos, the technique used has been to study the beta decay of taus and muons, determine the endpoint energy of the beta spectrum, and compare this measured endpoint with the measured mass difference between the parent and daughter particles. Any difference between the measured endpoint and the mass difference provides evidence for a finite neutrino mass. For the tau neutrino, the decay of taus into five charged pions and a neutrino provides the most sensitive test, as the phase space left after producing five pions is small and quite sensitive to neutrino mass. The measurement of the tau mass is predominately limited by statistics, and it is expected that as accelerators with higher luminosities come on line that this limit will be improved. For the muon mass, there are two measurements that measure the momentum of the muon emitted in pion beta decay. The measurements differ in that in one the pion is at rest when it decays, while in the other experiment the pion decays in flight. Both experiments have comparable accuracy and are both limited by systematic effects. The dominant limitation is the ability to measure the muon momentum spectrum with sufficient accuracy (currently done to a part in 10^5 in these experiments). New experiments with stopped pions will likely improve the present limits by a factor of a few, but in order to improve the limits on the muon neutrino mass substantially, new experimental techniques must be developed.

Table I. Limits on Neutrino Mass.

Flavor	Group	Limit	CL
Tau	ARGUS ²	<35 MeV	95%
Muon	Abela et al. ³	<250 keV	95%
Electron	Bennett et al. ⁴	<225 eV	95%
Electron Antineutrino	LANL ⁷	<9.4 eV	95%

The mass of the neutrino should be the same as the mass of the antineutrino by the CPT theorem. The only case to date in which a comparison can be made is in the case of the electron neutrino, where a finite mass has been searched for in electron capture, and for the electron antineutrino, which has been measured in tritium beta decay. Electron capture held the promise of high sensitivity by studying the internal bremsstrahlung accompanying electron capture. The atomic physics effects that usually limit neutrino mass searches in heavy nuclei were believed to be small. Unfortunately, it was found that, in fact, atomic effects did limit the ultimate sensitivity to 225 eV.⁴ This is not of sufficient accuracy to really allow an interesting comparison to be made with tritium beta decay.

The highest sensitivity for neutrino mass of any laboratory measurement has been made studying the beta decay of tritium.

TRITIUM BETA DECAY

In 1980 the ITEP group⁵ claimed evidence for a finite neutrino mass of about 35 eV in tritium beta decay. A mass this large would be sufficient to close the universe, as well as being the first indication of new physics beyond the Standard Model. Thus, numerous groups have initiated experiments to check this claim. While many concerns about the ITEP experiment have been raised, the group still claims to observe a finite mass between 17 and 40 eV,⁷ and other experiments have not completely ruled out this claim. The largest systematic uncertainties in this experiment have to do with distortions of the beta spectrum caused by finite spectrometer energy resolution (including energy loss and backscattering in the source) and excitations of atomic final states during the beta decay of one of the tritium atoms. Such excitations produce a distortion of the beta spectrum in the opposite direction as that due to neutrino mass, and the spectrum must be corrected for these effects. An overestimate of the distortion results in a spurious finite neutrino mass.

The effects of spectrometer resolution can be dealt with by careful measurements of the system response. However, the final state effects due to atomic excitations can only be modeled theoretically. For solid sources (in particular, valine, with 19 atoms and 64 electrons in the molecule), calculations must be carried out using approximations and truncated basis spaces. Thus, there is a large (of order 15 or more eV) intrinsic uncertainty in the deduced neutrino mass in experiments using solid sources. In order to eliminate this uncertainty, the Los Alamos group has designed and built a system using free molecular tritium as the source. Atomic and molecular tritium are the only systems in which the atomic excitations can be calculated with an uncertainty in the deduced neutrino mass of less than a few eV.

Table II summarizes the results of the experiments that have reported results. In addition to these experiments, there are several others that are now coming into operation with expected sensitivities of better than 10 eV (assuming zero neutrino mass). At present, the ITEP claims are completely ruled out by the recently announced results from both the Zurich and Los Alamos groups. It is also now clear that the mass of the electron antineutrino is by itself insufficient to close the universe.

Table II. Tritium Beta Decay Results.

Group	Source	m_ν^2 (eV ²)	Stat (eV ²)	Syst (eV ²)	Limit (eV)	CL
ITEP ⁶	Valine				$17 < m_{\bar{\nu}_e} < 40$	95
LANL ⁷	Free T ₂ Gas	-147	55	58	9.4	95
Zurich ⁸	Monolayer Polymer	-158	150	103	15.4	95
Tokyo ⁹	L-M Monolayer	-82	87	?	29	95

SUPERNOVAE

The only neutrino mass measurements with sensitivity comparing with tritium beta decay are measurements that were made of the temporal distribution of neutrinos arriving from SN1987a. If the neutrinos are emitted simultaneously (within a small fraction of a second), it is easy to show that the dispersion in arrival

times of the neutrinos as a function of their energy depends on the neutrino mass according to the formula:

$$\Delta t = 0.026(d/50 \text{ Kpc})(m_\nu/1 \text{ eV})^2(10 \text{ MeV } E_\nu)^2$$

Several detectors claimed to have observed neutrinos from SN1987a, but the only two detectors with sufficient statistics to be really interesting are the IMB and Kamiokande water Čerenkov detectors. These detectors were built to search for proton decay, but fortunately both were upgraded just shortly before SN1987a, giving them sufficient sensitivity to observe the supernova neutrinos. IMB¹⁰ observed nine events above a threshold of 20 MeV and Kamiokande¹¹ observed 11 events above a threshold of 7.5 MeV. The time duration of the neutrino pulse was observed to be 12 seconds. The primary question in analyzing these data is whether the dispersion is due to the intrinsic time scale of the supernova or is associated with the dispersion of massive neutrinos. There have been a tremendous number of papers published analyzing the data. Claims of limits on neutrino mass ranging from 40 eV to 0.2 eV, along with claims for observation of a finite mass between 5 and 40 eV have been published. It seems clear to this author that the analysis of the meager data is quite model dependent. A complete analysis, including model dependence,¹² gives a believable limit on the neutrino mass of about 20 eV. It is remarkable that this limit from the supernova falls so close in sensitivity to the terrestrial measurements of tritium beta decay. It is certainly expected that as larger and better instrumented solar neutrino detectors come into operation, this limit will come down significantly, assuming Mother Nature is kind enough to set off a supernova within our galaxy sometime in the not-too-distant future.

NEUTRINO MASS: NONKINEMATIC TESTS

Searches for a finite neutrino mass, which are not kinematic tests, all require lepton number violation, in addition to a finite neutrino mass. These tests fall into two categories: double beta decay and neutrino oscillations.

Double beta decay involves the simultaneous emission of two electrons from a parent nucleus (Z,A) to a daughter nucleus (Z-2,A). The allowed second-order process of double beta decay has been observed,¹³ but involves the emission of two neutrinos, along with the two electrons, and does not require a finite neutrino mass or lepton number violation. Neutrinoless double beta decay that does require a finite neutrino mass and lepton number violation, as well as requiring the neutrino to be a Majorana neutrino, has been actively searched for in a variety of nuclei, but so far no confirmed observation has been reported. The searches with the highest sensitivity have all been carried out in ⁷⁶Ge, and limits of 1.2×10^{24} years at 90% CL have been reported.¹⁴ Depending on which set of nuclear structure calculations are used, this corresponds to a limit on the neutrino mass for Majorana neutrinos of 0.7 to 2.0 eV. Future experiments are centered around using enriched ⁷⁶Ge detectors (natural germanium contains only 7.8% ⁷⁶Ge) and these experiments expect to reach 10^{26} years, corresponding to a sensitivity for neutrino mass down to 0.01 eV.

NEUTRINO OSCILLATIONS

Oscillations between two different types of neutrinos can occur if at least one of the neutrino families has a nonzero mass and if lepton number is not conserved, so that there is mixing between neutrino

families. The probability for a neutrino ν_1 to oscillate to a neutrino ν_2 is given by

$$P_{\nu_1 \rightarrow \nu_2} = \sin^2 2\theta \sin^2 \frac{1.27 \Delta m^2 L}{E_\nu} ,$$

where L is the distance in meters that ν_1 has traveled, E_ν is the neutrino energy in MeV, and $\Delta m^2 = m_1^2 - m_2^2$ in eV^2 . Searches for the appearance of ν_2 measure the probability $P_{\nu_1 \rightarrow \nu_2}$ that a neutrino beam, which initially had no neutrinos of type ν_1 , will be observed to contain some amount of ν_2 after a distance L . The probability that a neutrino has oscillated from ν_1 into any other neutrino, ν_x , is given by

$$P_{\nu_1 \rightarrow \nu_x} = 1 - P_{\nu_1 \rightarrow \nu_2} .$$

Thus, searches for neutrino disappearance measure the probability $P_{\nu_1 \rightarrow \nu_x}$ that the flux of neutrinos of type ν_1 disappear at a rate faster than $1/L^2$ at a distance L away from the source.

The above formulas are valid for neutrinos propagating in free space. It was observed in 1984 by Mikheyev and Smirnov,¹⁵ using the earlier results of Wolfenstein, that the oscillation parameters are modified when neutrinos pass through matter. This is due to the fact that electron neutrinos can scatter from electrons by both the charged and neutral currents, while other neutrinos species can scatter from electrons only by the neutral current. This leads to the possibility of a resonance for the mixing between electron-type neutrinos and other neutrino types at densities of electrons that occur in the sun. The modified parameters are given by

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta}{[1 + (\ell/\ell_0)^2 + 2 \cos 2\theta(\ell/\ell_0)]} , \quad \ell_m = \frac{\ell}{[1 + \ell/\ell_0 - 2 \cos 2\theta(\ell/\ell_0)]^{1/2}} ,$$

where

$$\ell_0 = \frac{2\pi}{\sqrt{2}G_F N_e} \approx \frac{1.7 \times 10^7}{\rho(\text{gm/cm}^3) \frac{Z}{A}} \text{ m} .$$

Neutrino oscillations have been searched for using reactor antineutrinos, neutrinos and antineutrinos from accelerators, neutrinos and antineutrinos originating from cosmic ray interactions in the atmosphere, and neutrinos originating from the sun. At present, there is no confirmed evidence for neutrino oscillations. There are, however, three unconfirmed reports of neutrino oscillations. The first comes from an analysis of old data from neutrinos produced in beam dump experiments at CERN, which results in a claim¹⁶ for neutrino oscillations with a $\Delta m^2 = 400 \text{ eV}$ and a mixing probability $\sin^2 2\theta = 0.5$. However, this claim comes from comparing different experiments and may be subject to systematic errors that are not properly accounted for. The second unconfirmed report comes from the Kamiokande observation of atmospheric neutrinos, in which the ratio of observed number of events due to electron neutrinos compared to muon neutrinos divided by this ratio calculated by Monte Carlo is¹⁷ $0.64 + 0.10/-0.08 \pm 0.05$. The analysis of the Kamiokande data is currently being checked by the Kamiokande collaboration and should be regarded as preliminary. Data from the Frejus and IMB detectors do not entirely rule out the Kamiokande claims, but it appears that it is difficult to reconcile the Kamiokande results with the Frejus and IMB detectors. The

third claim comes from the beta decay of tritium and ^{35}S , in which evidence for a 16.7-keV neutrino with a mixing probability of 0.8% has been reported.¹⁸ However, a number of other experiments claim to rule this out.¹⁹

The present limits from accelerator, reactor, and atmospheric neutrinos, which come from a combination of several experiments, are shown in Fig. 1. Also shown in Fig. 1 is the sensitive region that can be probed using solar neutrinos. A number of terrestrial experiments are planned, which will provide increased sensitivity to both $\sin^2 2\theta$ and Δm^2 by an order of magnitude or more. These planned experiments will allow one to bridge the gap in Δm^2 between the current terrestrial experiments and the solar neutrino experiments. It is obvious from the figure that solar neutrinos offer unparalleled sensitivity to small Δm^2 . The sensitivity of the different solar neutrino experiments will be discussed later in this paper.

SOLAR NEUTRINOS

Solar neutrinos provide an unparalleled opportunity to study the properties of neutrinos, due to the low energy of the neutrinos, the large distance from the source (the sun) to the earth, and the high electron densities in the sun necessary for the MSW effect to come into play. The calculated fluxes are shown in Table III, and the spectrum of neutrinos produced is shown in Fig. 2.

The first measurements of the solar neutrino flux began 20 years ago in the chlorine experiment of Davis et al.²⁰ This radiochemical experiment uses the inverse beta decay reaction on ^{37}Cl to produce ^{37}Ar with a threshold of 814 keV. The experiment is located at the Homestake gold mine in South Dakota and consists of a tank of 615 tons of perchlorethylene, which is swept every two to three months with He gas to remove the ^{37}Ar . The flux of high-energy solar neutrinos observed in the Homestake experiment is shown in Fig. 3. The average of all of the runs is 2.3 ± 0.3 SNU, while the flux calculated by Bahcall in the Standard Solar Model (SSM) is 7.9 ± 2.6 SNU.²¹ (The error quoted by Bahcall is 3 sigma, while the experimental error is 1 sigma.) There is some uncertainty in the SSM, as other calculations²² predict

Fig. 1. Limits from terrestrial experiments are shown, along with the sensitive region for solar neutrino experiments.

Table III. Main Neutrino Producing Reactions in the Sun, Maximum Neutrino Energy, and the Integrated Flux Predicted by the Standard Model.

Solar Reaction	Maximum Neutrino Energy (MeV)	Predicted Total Flux (cm ⁻² sec ⁻¹)
$p + p \rightarrow d + e^+ + \nu_e$	0.42	6.1×10^{10}
$p + e^- + p \rightarrow d + \nu_e$	1.44	1.5×10^8
$e^- + {}^7\text{Be} \rightarrow {}^7\text{Li} + \nu_e$	0.86	4.0×10^9
${}^8\text{B} \rightarrow {}^8\text{Be} + e^+ + \nu_e$	14.10	5.6×10^6
${}^{13}\text{N} \rightarrow {}^{13}\text{C} + e^+ + \nu_e$	1.15	5×10^8
${}^{15}\text{O} \rightarrow {}^{15}\text{N} + e^+ + \nu_e$	1.73	4×10^8

fluxes as low as 5.9 SNU. However, it is clear that there is strong disagreement between the SSM and experiment by a factor of about three.

There has been a large variety of possible explanations offered for the observed deficit of solar neutrinos. Since the flux of ${}^8\text{B}$ neutrinos, which is the dominant flux to which the chlorine experiment is sensitive, depends on the core temperature as T^{18} , astrophysical explanations, such as turbulent mixing, different mix of heavy metals, etc., have been offered as a means of reducing the core temperature by the 5–7% required to agree with the measured flux. However, all of these Non-standard Solar Models are in conflict with some other measured property of the sun. The other class of proffered explanations involves new particle physics, such as neutrino oscillations, neutrino decay, WIMPs, etc.

Recently, a great deal of interest in the results of the chlorine experiment has been generated by the claim that there is an observed time variation of the flux, which is anticorrelated with sunspot number, as shown in Fig. 3. The origin of this claimed anticorrelation has been postulated to arise from a neutrino magnetic moment, which interacts with the magnetic fields in the convective zone of the sun.²³ The magnetic fields at the surface of the sun are known to vary by an order of magnitude during the solar

Fig. 2. Solar neutrino spectrum. Thresholds for different solar neutrino experiments are indicated.

Fig. 3. Time variation of ^{37}Cl data (solid line) compared to sunspot numbers (dotted line).

cycle, but essentially no data exist about the strength of the magnetic fields deep in the convective zone. In addition, one runs into some difficulty in generating a neutrino magnetic moment of 10^{-10} – 10^{-11} .

The deficit of high-energy neutrinos observed in the chlorine experiment has been confirmed by the measurements from the Kamiokande II experiment in Japan. The original Kamiokande I experiment, designed to search for proton decay, was upgraded by substantially reducing the low-energy backgrounds to allow observation of ^8B neutrinos from the sun. The detector is a water Čerenkov detector consisting of 3000 tons of water (800 tons fiducial volume) viewed by 20-in. photomultipliers. The ^8B solar neutrinos are observed by the ν - e elastic scattering process, which produces a recoil electron. Using the hit pattern of the photomultipliers to separate signal from background, energy, and directional information, this experiment has observed a flux of ^8B solar neutrinos that is $0.46 \pm 0.05 \pm 0.06$ of the flux predicted by the Standard Solar Model. The experiment has been taking data since 1986 on the solar neutrino flux, so that recently it has been possible to study the data for any time variations associated with the solar cycle. The results indicate that the measured flux is flat to within 30% during the period of 1986–1990.²⁴ The data are also in very good agreement with the chlorine data during this time period. The intensity of sunspots changed by a factor of about eight during this same time period. Therefore, neither the chlorine or Kamiokande experiments saw any significant variation in flux, either correlated or anticorrelated with sunspot number during the last four years. One has to take the entire 20 years of chlorine data in order to find hints of the claimed anticorrelation of neutrino flux with sunspot number.

Thus, while the deficit of high-energy neutrinos is observed by both the chlorine and Kamiokande experiments, but only the chlorine experiment claims to observe a time variation of neutrino flux anticorrelated

with sunspot number. The obvious question is whether or not these two experiments are consistent. The two experiments have different thresholds, so that while Kamiokande can only observe ^8B neutrinos, the chlorine experiment is sensitive not only to ^8B neutrinos, but also to ^7Be , ^{15}O , ^{13}N , and pep neutrinos. The flux measured by Kamiokande corresponds to $2.8 \pm \text{SNU}$, while the chlorine experiment observes $2.3 \pm 0.3 \text{ SNU}$. Thus, these experiments can be consistent only if the low-energy ^7Be , ^{15}O , ^{13}N , and pep neutrinos are missing. This could be consistent with MSW oscillations, but not with a lower core temperature of the sun. So, there may be an indication of new particle physics coming out of these two experiments. In terms of possible time variations, both experiments should see the same variation, so that one really has to wait and see if the purported time variation observed in the chlorine experiment holds up.

The chlorine and Kamiokande experiments are unable to unambiguously distinguish between possible solar physics and particle physics explanations of the solar neutrino problem, due to the very strong temperature dependence of the ^8B production rate. In order to resolve this ambiguity, it is necessary to measure the flux of the low-energy p-p solar neutrinos. The flux of p-p neutrinos is determined in a model independent way to high accuracy from the observed luminosity of the sun. A gallium radiochemical experiment, with a threshold of 233 keV, provides the only means feasible at present to observe the p-p neutrinos.

Two gallium experiments are presently under way: the German-Italian-French-American GALLEX experiment²⁵ at the Gran Sasso Laboratory in Italy, and the Soviet-American SAGE experiment²⁶ at the Baksan Neutrino Observatory in southern Russia. The GALLEX experiment employs 30 tons of gallium in an aqueous HCl solution, while the SAGE experiment employs 30 tons (60 tons ultimately) of metallic gallium. Solar neutrinos produce ^{71}Ge by inverse beta decay on ^{71}Ga , which is then chemically extracted and the subsequent decay of the ^{71}Ge atoms ($\tau_{1/2} = 11$ days) is detected in small proportional counters. The initial stages of the chemical extraction differ in the two experiments, but the final chemistry and counting are very similar. The GALLEX experiment is coming into operation this summer, while the SAGE experiment began operation in 1989, and has recently reported first results.²⁷

The SAGE experiment began operation in the summer of 1988 with the purification of the gallium. Large amounts of ^{68}Ge were present in the gallium due to spallation reactions by cosmic-ray muons when the gallium was stored on the surface. By spring of 1989, after many successive extractions of ^{68}Ge , the background rate from ^{68}Ge in the K peak at 10.4 keV was reduced from almost 800 counts/day to a fraction of a count/day, and measurements of the solar neutrino flux began. By winter of 1989, enough data had been gathered to determine that there was a background component in the K peak with a half-life of 4 days, which is consistent with radon. Careful checks using a recently installed very low-background hyper pure germanium detector confirmed the presence of low levels of radon in the water used in the chemical extraction process. The extraction procedure was modified to include additional purification steps to remove any radon from the water and reagents, and runs were resumed in January of 1990 with this new procedure. Initial analysis of data from runs in January, February, March, and April has been carried out. The data indicate that there is no observable ^{71}Ge decays in the counters. Using the measured extraction efficiencies from these runs (determined by using very small amounts of natural germanium added to the gallium as a carrier), and calculated detector efficiencies and assuming the Standard Solar Model flux of

132 SNU, the group should have observed a total from all four runs of 14 counts in the K-peak in the first 30 days of counting. What the group actually observed only 3 counts, all of which were consistent with background. A maximum likelihood analysis of the data gives a best fit of 0 SNU. The quoted limits are for 68% CL [$<72 \text{ SNU}/(^{71}\text{Ge Eff}/\text{Ge Carrier Eff})$] and 95% [$<138 \text{ SNU}/(^{71}\text{Ge Eff}/\text{Ge Carrier Eff})$]. The results are quoted in SNU divided by the ratio of the extraction efficiencies for ^{71}Ge to the extraction efficiency for the Ge carrier. It is expected that these two extraction efficiencies should be the same, so that the ratio should be unity. However, the group plans to measure this ratio directly by exposing the gallium to an artificially produced ^{51}Cr source, which provides a monochromatic neutrino source at 746 keV.

Thus, the first report from the gallium experiments indicates that the p-p flux is quite low. However, these initial results have quite low statistics and some systematics still remain to be checked. The SAGE collaboration plans to upgrade the experiment this year from 30 tons of gallium to 60 tons. They also plan to try to reduce the backgrounds further in order to also count the decay of ^{71}Ge using the L peak at 1.2 keV. This would result in a total increase in count rate of almost a factor of four. In addition, it is anticipated that the GALLEX collaboration will have first results early next year, so that they will be able to either confirm or reject the first SAGE results.

If the flux measured does indeed turn out to be quite low, what are the implications? If the flux turns out to be significantly lower than 70 SNU, the implication seems to be inescapable that new particle physics has come into play. A result consistent with zero would indicate that quite likely the solution to the solar neutrino problem is due to the nonadiabatic branch of the MSW matter enhanced neutrino oscillations.

FUTURE SOLAR NEUTRINO EXPERIMENTS

The fundamental problem in this field has always been very low count rates. None of the present experiments observes more than one event every few days. In order to search for time variations with high sensitivity, and to really tie down the parameters of possible MSW oscillations, high-count-rate experiments with low energy thresholds and sensitivity to neutral currents are required. There are a variety of efforts underway to build such detectors, including Superkamiokande (a 32,000-ton water Čerenkov detector), SNO (a 1000-ton heavy-water Čerenkov detector), BOREX (a 1000-ton borated scintillator detector), and efforts to develop superconducting detectors and detectors using rotons in liquid helium. While it is likely that several of these experiments will be funded, the only experiment that is fully funded at this time and has begun construction is the SNO project.

SNO (Sudbury Neutrino Observatory) will use 1000 tons of heavy water enclosed within a 12-m diameter acrylic sphere inside a 5-m thick light water shield. The detector will be viewed by 8000–10000 25-cm photomultipliers. The detector is sensitive to charged current reactions on deuterium, neutral current disintegration of the deuterium, and elastic scattering of neutrinos on electrons. Anticipated event rates (with a 5-MeV threshold) are about 8, 3, and 1 events/day, respectively. Since this detector is sensitive to all (nonsterile) flavors of neutrinos, a comparison of the charged and neutral current event rates will provide detailed information about possible MSW oscillations. In addition, the spectral information from the detector will allow one to constrain the parameters of possible MSW oscillations.

SUMMARY

Our experimental knowledge of the neutrino has increased considerably during the last 60 years. However, the fundamental question of whether or not neutrinos have mass has not yet been answered. Experiments with ever greater sensitivity have pushed down the limits on the masses without any direct indication of a finite mass. However, perhaps the solar neutrino experiments are giving the first hints of MSW oscillations, which require mass and mixing. During the coming decade, one can anticipate that the solar neutrino problem will be solved, and the solution may well be the first confirmed evidence for physics beyond the Standard Model. The 90's promise to be a most exciting decade for nuclear and particle physics.

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