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Recent developments in neutrino physics

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I. INTRODUCTION

I shall attempt to summarize recent developments in the experimental situation in neutrino physics. The paper will deal with recent results, drawing on either published work or research that has been presented in preprint form, as there is an adequate supply of interesting and controversial data restricting oneself to these generally more reliable sources. The discussion of the theoretical implication of these experimental results will be presented in the following paper by Boris Kayser.

The topics to be covered in this presentation are:

- (1) direct measurements of $\bar{\nu}_e$ mass via beta endpoint studies;
- (2) status of solar neutrino observations;
- (3) status of "17-keV neutrino" reports; and
- (4) the use of νp elastic scattering to determine the "strange quark" content of the proton.

Before launching into these topics, attention should be called to the new result from LEP. Dydak [1] reported earlier this week that the number of standard model type neutrinos that couple to the Z_0 is now known to be 2.95 ± 0.05 . Thus, with ever increasing precision the LEP program verifies the status of minimum standard model (MSM); on the other hand, there is strong suggestion in the research presented below that extensions to the minimal standard model are required, to allow for both neutrino mass and mixing.

2. DIRECT $\bar{\nu}_e$ MEASUREMENTS

To begin, let us consider the direct measurement of the $\bar{\nu}_e$ mass via examination of the endpoint of ^3H decay,

$$^3\text{H} \rightarrow ^3\text{He} + \bar{\nu}_e + e^- + 18.6 \text{ keV} \quad (1)$$

The normal beta spectrum ($m_{\bar{\nu}_e} = 0$)

$$N(E_e) = CF(Z, R, E_e)p_e E_e (E_0 - E)^2 \quad (2)$$

is modified if the $\bar{\nu}_e$ has a mass

$$N(E_e) = CF(Z, R, E_e)p_e E_e (E_0 - E)^2 \left(1 - \frac{m_\nu^2}{(E - E_0)^2}\right)^{\frac{1}{2}} \quad (3)$$

where C is a normalization constant and $F(Z, R, E_e)$ is the Coulomb Fermi function. Once $E - E_0 \gg m_\nu$, the spectrum is, for all intents and purposes, identical with Eq. (2). The modification to the spectrum occurs in the vicinity of a few times m_ν below the endpoint. The situation in the real case is even more complicated because the undetected electron is not necessarily in its ground state around ${}^3\text{He}$ so that a more proper characterization of the beta spectrum due to the final-state spectrum (FSS) of the ${}^3\text{He}^+$ ion is

$$N(E_e) = CF(Z, R, E_0)p_e E_e \sum_i w_i (E_0 - E_i - E_e)(E_0 - E_i - E_e - m_\nu^2)^{1/2} \quad (4)$$

where E_0 is the endpoint energy with the valence electron in the ${}^3\text{He}^+$ ground state. E_i is the excitation energy of the electron, and w_i the probability of the excitation. As E_i for the $1s$ - $2p$ excitation is some 25 eV, it is essential to know the final-state spectrum accurately to extract a proper value of $m_{\bar{\nu}_e}$. Figure 1 shows how large these effects are. In the case of ${}^3\text{H}_2$, only 60% of the time is the unobserved electron in the ground state.

These measurements came to prominence when in 1980 the ITEP group announced [2] that they had measured an electron antineutrino mass of some 30 eV. They have persisted [3] in claiming a finite ($17 < m_{\bar{\nu}_e} c^2 < 40$ eV) neutrino mass.

As experiments sensitive to this small a value of the neutrino mass are very difficult to set up, deal with the specific backgrounds, and investigate systematic errors, results from the first round of experiments following the ITEP measurements did not occur until 1986–87. These results are listed in Table 1. While no experiment found a positive result for neutrino mass, the limits obtained did not rule out the lowest range reported by ITEP.

The next generation of these experiments is now being completed. The published result from the INS-Tokyo group [4] is

$$m_{\bar{\nu}_e} c^2 < 13 \text{ eV} \quad 95\% \text{ C.L.}$$

They have carried out a high-statistics experiment (150K events ($E_0 - E_e$) < 100 eV) using arachiatic acid as a source which, while complicated, allows them to place ${}^{109}\text{Cd}$ in the compound. ${}^{109}\text{Cd}$ has a conversion line at $18.511.7 \pm 1.3$ eV, which is excellent for calibration purposes and allows them to obtain a precise knowledge of their response function. They attribute a 65-eV^2 systematic uncertainty to their knowledge of the FSS for an arachiatic acid source, but with our present state of understanding, it is difficult to assess if this is adequate.

Figure 1. Probability for excitation of the unobserved electron for the decay of molecular ^3H .

Table 1

List of the results from the first generation experiments following the ITEP [2] positive results

Group	Source	Result (eV/c ²) 95% C.L.
Zürich ^(a)	^3H in graphite	<18
LANL ^(b)	$^3\text{H}_2$ gas	<27
INS-Tokyo ^(c)	arachiatic acid	<32

^(a) M. Fritschiset et al., Phys. Lett. B173 (1986) 485.

^(b) J. Wilkerson et al., Phys. Rev. Lett. 58 (1987) 2023.

^(c) H. Kawakami et al., Phys. Lett. B187 (1987) 198.

A preprint [5] from the Los Alamos group reporting on somewhat lower statistics (20K events, $(E_0 - E_e) < 100$ eV), an experiment which employs a $^3\text{H}_2$ gaseous source finds a limit of

$$m_{\bar{\nu}_e} c^2 < 9.3 \text{ eV} \quad 95\% \text{ C.L.}$$

Their reported energy resolution is 16.2 eV with the calibration and response measured via a ^{83}Kr (17820.1 ± 18 eV) decay. The ^{83}Kr is easily incorporated into their $^3\text{H}_2$ source. It is interesting and impressive that 93.5% of the ^{83}Kr conversion electrons escape without any energy loss. A major strength of this experiment, however, is that for $^3\text{H}_2$ the FSS can be calculated. There are three calculations [6–8] of $w_i(E_0 - E_i)$ that agree to within 10 eV^2 on their effect on the extracted value of $m_{\bar{\nu}_e} c^2$. The physics approximations used in the calculations (Bohn-Oppenheimer and sudden approximation) are reckoned to have much smaller uncertainty (0.04 eV^2 and 2 eV^2 , respectively).

Figures 2(a) and 2(b) show the residual errors after subtraction of the theoretical spectrum shape from the LANL measurement, assuming $m_{\bar{\nu}_e} c^2 = 30 \text{ eV}$ and 0 eV , respectively.

Figure 2. (a) Residuals (experiment-calculation), assuming $m_{\nu} c^2 = 0$; (b) residuals (experiment-calculation), assuming $m_{\nu} c^2 = 30 \text{ eV}$.

As Eq. (4) shows, the quantity directly extracted from the experiment is $m_{\bar{\nu}_e}^2$. The values from the two experiments are

$$\begin{array}{ll} m_{\nu}^2 c^4 = -65 \pm 85 \pm 65 \text{ eV}^2 & \text{INS-Tokyo} \\ m_{\nu}^2 c^4 = -147 \pm 68 \pm 41 \text{ eV}^2 & \text{LANL} \end{array} \quad \text{and}$$

Note both have a negative result for the most likely value of $m_{\nu}^2 c^4$, which, of course, is not physically plausible. If this is not a statistical fluke, it may reflect a common undetected systematic error in these experiments. In both cases, the value for the limit

on $m_{\bar{\nu}}c^2$ is fixed by renormalizing the fraction of reduced uncertainty for $m_{\bar{\nu}}^2 c^4 \geq 0$ to unity.

It is clear that these experiments find no evidence for a neutrino mass well below the values claimed in [2] and [3]. Thus, positive evidence of a detectable mass for the electron neutrino has disappeared, with limit having been dropped by nearly an order of magnitude from where it was previous to the ITEP experiments.

There are third-generation experiments in this field that will be pressing into the regime of $m_{\nu} < 3$ eV. There are three different institutions involved in this round of experiments—LLNL in the US, INR-Moscow, and the University of Mainz in Germany. These are very large undertakings and they have many features in common. Figure 3 shows a schematic diagram of the Mainz setup. In common with the other three experiments, it has large acceptance achieved via magnetic transport, and extremely good energy resolution (2–3 eV) achieved via electrostatic means. The major problem in all these setups is background, as the signal rapidly diminishes in the vicinity of the end-point. The last 10 eV contains only 3×10^{-10} of the total decay rate, so a sensitivity below 1 eV will be likely impossible. Each group feels that the background problems are under control and that counting and analysis will soon begin. The LLNL group is using gaseous $^3\text{H}_2$, the Mainz group frozen $^3\text{H}_2$, and I don't know what the INR plans to use as their ^3H source. Results can be expected over the next few years from these groups, but the experiments are getting harder and harder. It is also evident that work is needed on the issue of FSS for whatever source is used for the tritium. The $^3\text{H}_2$ source used by the LANL group has a claimed systematic error of 10 eV^2 on the value

Figure 3. Schematic of the University of Mainz spectrometer for studying the ^3H end-point.

of $m_{\nu_e}^2$ and so we will need improved calculations, or else atomic ^3H sources will have to be used. There is a possibility that the energy resolution will be so good in these third-generation experiments and the statistics so high that one need only use the last 25 eV below the endpoint, which should be free of FSS effects.

3. SOLAR NEUTRINO EXPERIMENTS

The solar ν situation has not changed a great deal during the past six months. The SAGE group has come forth with a result in preprint form, which will be referred to after some background is provided. The sun produces the vast majority of its neutrinos in the process of converting H to ^4He [9]. Table 2 shows the principal reactions, and Table 3 lists the properties of the neutrino emitted in various stages of this process. Figure 4 shows the expected solar ν flux at the earth, based on the standard solar model. From Fig. 4 it is clear that the preponderance of high energy ($E_{\nu_e} > 2 \text{ MeV}$) neutrinos comes from the decay of ^8B . This is a small branch (0.02%) in the overall process of $4p \rightarrow \alpha + 2e^+ + 2\nu_e + 26.7 \text{ MeV}$. As the Coulomb barriers for ^7Be and ^8B formation are the highest in this process, the amount of ^8B actually formed is extremely sensitive (T^{18}) to the temperature at the center of the sun. There can be legitimate question about how well that temperature is known; a few percent reduction in its value leads to a factor of 2 reduction in the rate of ^8B formation. This is not at all the case for the process $p + p \rightarrow d + e^+ + \nu_e$, which is the principal energy source in the sun. Thus, if equilibrium is assumed between nuclear energy generation and the solar luminosity, the ν flux from the $p + p$ reaction is fixed to within 2%.

As a neutrino source, the sun is unique because it is much farther away than any earth-based sources and insofar as the standard solar model is correct, we know what fluxes to expect. The great distance to the sun is important with regard to the possible phenomena of neutrino oscillations [10].

If we assume that the neutrinos ν_e and ν_μ emitted in weak processes are actually a superposition of mass eigenstates (2 are assumed for simplicity)

$$\begin{aligned} |\nu_e\rangle &= \cos \theta_v |\nu_1\rangle + \sin \theta_v |\nu_2\rangle \\ |\nu_\mu\rangle &= -\sin \theta_v |\nu_1\rangle + \cos \theta_v |\nu_2\rangle \quad , \end{aligned} \tag{5}$$

where ν_1 and ν_2 have masses m_1 and m_2 and $\cos \theta_v$ is the amplitude of ν_1 in the electron neutrino when it decays in the absence of other matter (i.e., in vacuum). As these neutrinos propagate in free space, their amplitudes change as

$$|\nu_e(t)\rangle = \cos \theta_v e^{i(E_1 t - \mathbf{p} \cdot \mathbf{r})} |\nu_1\rangle + \sin \theta_v e^{i(E_2 t - \mathbf{p} \cdot \mathbf{r})} |\nu_2\rangle \tag{6}$$

$$= \cos \theta_v e^{i(m_1/2p)^2 t} |\nu_1\rangle + \sin \theta_v e^{i(m_2/2p)^2 t} |\nu_2\rangle \quad ; \tag{7}$$

hence, after a time t , the original ν_e has altered its state so that

$$|\langle \nu_e | \nu_e(t) \rangle|^2 = 1 - \sin^2 2\theta_v \sin^2 \frac{\pi r}{L_v} \quad , \tag{8}$$

Table 2

The reactions in the sun leading to the conversion of four protons into an alpha particle plus two positrons and electron neutrinos

	<i>pp</i> I	<i>pp</i> II	<i>pp</i> III
	99.6%		
	$p + p \rightarrow d + e^+ + \nu_e$		
	0.4%		
-or-	$p + e^- + p \rightarrow d + \nu_e$		
	100%		
	$d + p \rightarrow {}^3\text{He} + \gamma$		
	25%	15%	
	${}^3\text{He} + {}^3\text{He} \rightarrow {}^4\text{He} + p + p$ -or-	${}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma$	0.02%
		${}^7\text{Be} + e^- \rightarrow {}^7\text{Li} + \nu_e$	-or- ${}^7\text{Be} + p \rightarrow {}^8\text{B} + \gamma$
		${}^7\text{Li} + p \rightarrow {}^4\text{He} + {}^4\text{He}$	${}^8\text{B} \rightarrow {}^8\text{Be}^* + e^+ + \nu_e$
			${}^8\text{Be}^* \rightarrow {}^4\text{He} + {}^4\text{He}$

Table 3

The neutrino energy and flux from the principal weak interaction processes in the sun

Solar Reaction	Maximum Neutrino Energy (MeV)	Predicted Total Flux ($\text{cm}^{-2}\text{sec}^{-1}$)
$p + p \rightarrow d + e^+ + \nu_e$	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

where L_ν is termed the vacuum oscillation length and is equal to

$$L_\nu \equiv \frac{2\pi 2p}{|m_2^2 - m_1^2|} = \frac{2.48}{\delta m^2} \frac{E_\nu \text{ MeV}}{\text{eV}^2} \text{ meters} .$$

Thus, the sun allows investigation of δm^2 10^8 times smaller than can be investigated via terrestrial-based sources. However, due to our imperfect knowledge of the sun, one might properly infer from the above discussion that to observe neutrino oscillations from the sun, the mixing angle would have to be large, say $\sin^2 2\theta_\nu > 0.1$. However, for small

Figure 4. Plot of the solar neutrino flux at earth.

values of $\Delta m^2/2p$, the high density of matter (electrons) in the sun can greatly amplify the mixing via the so-called Mikhael-Smirnov-Wolfenstein [11] effect.

At the time of this talk, three solar neutrino detectors have taken data. They are listed in Table 4, with their neutrino energy thresholds and the period over which they have been accumulating data.

The physical characteristics of the ^{37}Cl detector are listed in Table 5. Standard solar model calculations of the neutrino flux, ϕ , along with knowledge of the nuclear transition rates for $^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e$ predict [9]

$$\langle \phi, \sigma_{^{37}\text{Cl}} \rangle = 7.9 \pm 3.3 \text{ SNU} .$$

A SNU is a rate of 10^{-36} per sec per target atom. The error in the expression above is estimated to be 3σ . Figure 5 is a graph of the measured ratio of the measured ^{37}Ar production rate over an 18-year period [9]. It should be noted that this is based on a total of 774 detected events, of which somewhat more than half (435) are background. The observed production rate of ^{37}Ar corresponds to 2.2 ± 0.3 (1σ) SNU, well below the predicted rate, as is shown in Fig. 5. The ratio of the observed to predicted rate is

$$\frac{\langle \phi, \sigma_{^{37}\text{Cl}} \rangle_{\text{obs}}}{\langle \phi, \sigma_{^{37}\text{Cl}} \rangle_{\text{SSM}}} = 0.28 \pm 0.05 , \quad (^{37}\text{Cl})$$

Table 4
Three ongoing solar neutrino experiments

	Threshold (MeV)	Status
(1) $\nu_e + {}^{37}\text{Cl} \rightarrow e + {}^{37}\text{Ar}$	0.814 (5.8)	20 y
(2) $\nu + e \rightarrow \nu' + e$	7.5	4 y
(3) $\nu_e + {}^{71}\text{Ga} \rightarrow e + {}^{71}\text{Ge}$	0.236	6 mo

Table 5
Characteristics of the ${}^{37}\text{Cl}$ detector

Location	Homestake Mine, Lead, South Dakota
Depth	4850 ft
Tank	20 ft diameter $\times$ 48 ft long
Detector fluid	C_2Cl_4
Total weight of fluid	615 tons
Volume	3.8×10^5 liters
Threshold	0.814 MeV
${}^{37}\text{Cl}$ atoms	2.16×10^{30}
Half-life ${}^{37}\text{Ar}$	35.0 days
Neutrino sensitivity	${}^8\text{B}$, ${}^7\text{Be}$

Figure 5. Diagram of the measure ${}^{37}\text{Ar}$ production rate in the ${}^{37}\text{Cl}$ experiment as a function of time. The solid line at 7.9 SNU is the standard solar model prediction.

where only a 1σ error has been taken for the SSM prediction. The strongest transition between ^{37}Cl and ^{37}Ar occurs between the ^{37}Cl ground state and its analog states in ^{37}Ar . These levels are separated by 5.8 MeV. So, although the threshold for a ^{37}Cl detector is 870 keV, it is most sensitive to neutrinos above 5.8 MeV. Keeping that in mind, we give the ratio for the SSM predictor to the observed ^{37}Ar production rate for ^8B neutrinos only.

$$\frac{\langle \phi_s \sigma^{37}\text{Cl} \rangle_{\text{obs}}}{\langle \phi_s \sigma^{37}\text{Cl} \rangle_{\text{SSM, } ^8\text{B only}}} = 0.36 \pm 0.06 \quad . \quad ({}^{37}\text{Cl})$$

The characteristics of the Kamiokande II detector are listed⁹ in Table 6. Though designed as a detector for proton decay, it has, by dint of ingenuity and high photocathode coverage (20%), become an excellent solar neutrino detector. The neutrinos are detected via the Čerenkov radiation from the struck electron in the process

$$\nu + e \rightarrow \nu + e \quad , \quad (10)$$

where $E_e > 7.5$ MeV. The cross section for ν_e interaction with an electron is about six times larger than for ν_μ or ν_τ because ν_e can exchange $W^\pm$ in addition to Z^0 vector bosons. The struck electron retains a sense of the direction of the incident neutrino so that one can investigate if the neutrino signal comes from the direction of the sun. The energy of the recoil electron is also a function of incident neutrino energy. The Kamioka group has published [12] results from three years of observation. Figure 6(a) shows the direction of recoiling electrons with $E_e > 9.3$ as a function of $\cos\theta$, where θ is the angle between the electron direction and the direction to the sun. Figure 6(b) shows the spectrum of electrons with $\cos\theta_s > 0.8$, and one can see that it gratifyingly looks like what one would expect for the decay of ^8B , though suppressed in magnitude compared to what one expects in the SSM.

Table 6
Characteristics of the Kamiokande II detector

Location	Kamioka (Japanese Alps)
Depth	1 km (2700 m.w.e.)
Detector fluid	H_2O
Fiducial mass	680 tons
Electron threshold	7.5 MeV
Number of electrons	2.27×10^{32}
Neutrino sensitivity	^8B
Detectors	20-in. diameter PMT Čerenkov light

Figure 6. (a) The angular distribution of detected electrons above 9.3 MeV with respect to the direction of the sun. (b) The energy distribution of electrons with large $\cos \theta$. The solid line is the prediction of the standard solar model, while the dashed histogram is that prediction reduced by 0.46.

Figure 7 shows Kamioka's data rate relative to the SSM prediction as a function of time. The rate is consistent with being constant in time and the ratio of observed to expected from the SSM calculation for ^8B is

$$\frac{\langle \phi \sigma_{\nu_e} \rangle_{\text{obs}}}{\langle \phi \sigma_{\nu_e t} \rangle_{\text{SSM}}} = 0.46 \pm 0.05 \pm 0.06 \quad . \quad (\text{Kamioka})$$

The errors are 1σ , the first statistical, the second systematic. Thus, the deficit observed in ^{37}Cl is confirmed and the two experiments can be readily made consistent with one another. One should bear in mind that the ^{37}Cl is only sensitive to ν_e , while Kamiokande is sensitive to both ν_e and ν_μ . I will beg the question of the correlation of ϕ_s with the sunspot cycle, as it is by no means conclusive that there is any time variation.

Figure 7. Ratio of the observed ν_e solar ν rate to that predicted by the standard solar model as a function of time.

Taking these experiments at face value, the ν_e content of the solar flux from ^8B decay is somewhere between $1/3$ and $1/2$ of the SSM prediction. A change of the central temperature of the sun by 3–4% would explain this, as would the more exotic explanation that the neutrinos are altered on their way out of the sun or on their way in transit to the earth. A way to examine this dilemma is to measure the flux of neutrinos from the solar $p + p \rightarrow d + e^+ + \nu_e$ process. This flux depends on the sun's central

temperature only as the 1.2 power; thus, one is certain of the number created to within a few percent by virtue of the observed ^8B ν_e fluxes. Any large reduction in this low energy flux must involve neutrino physics.

To observe the low-energy neutrino flux, gallium is employed as the detector material via the $^{71}\text{Ga} + \nu \rightarrow ^{71}\text{Ge} + e$ reaction, which has a threshold of 233 keV. In this case, the ground state to ground state transition is both well known and strong, $\log ft = 4.1$, so that the physical threshold is also a good representation of the detector sensitivity. Thus, gallium is fully capable of detecting the pp -generated neutrino flux. Two collaborations have been assembled to measure the solar neutrino flux using Ga. One is called the Soviet-American Gallium Experiment [13] (SAGE) and the other is a largely European collaboration called GALLEX [14]. SAGE had an appreciable head start, as 60 tons of Ga were available in the Soviet Union to carry out the experiment, while GALLEX had to procure the gallium required for their project. The SAGE group has some six months worth of data on the solar neutrino flux. Fortunately for the purposes of this talk, the SAGE collaboration has produced a preprint [15] submitted for publication, which is used as the basis of reporting their results to this meeting.

Table 7 lists the characteristics of the SAGE detector as it has operated in its initial stages. Table 8 lists the SSM prediction [9] for the rates expected in a Ga detector. Somewhat more than half the predicted yield comes from $p + p$ neutrinos. The reason that other processes contribute to ^{71}Ge production more strongly than their relative flux would suggest is the energy dependence of the production cross section.

$$\sigma(\nu^{71}\text{Ga} \rightarrow e^{71}\text{Ge}) = \text{const} \times p_e(E_\nu - 0.233 \text{ MeV}) \quad . \quad (11)$$

As natural Ga contains 39.9% ^{71}Ga , one expects 1.17 ^{71}Ga atoms to be formed per day in 30 tons of Ga if the SSM flux is correct. In the SAGE experiment, the metallic Ga is in the liquid state and the ^{71}Ge is chemically extracted by adding a weak HCl solution in the presence of hydrogen peroxide. This results in the extraction of Ge into the aqueous phase. This solution is then distilled, additional HCl is added, and an Ar purge is carried out, which sweeps the Ge out of the acid solution in the form of

Table 7
Characteristics of the SAGE detector

Location	Mt. Andyrchi, North Caucasus, Russia
Depth	4700 m.w.e.
Detector fluid	Natural Ga (39.9% ^{71}Ga)
Fluid mass	30 tons
Threshold	0.233 MeV
^{71}Ga atoms	10^{29}
Half-life ^{71}Ga	11.43 days

Table 8

Capture rates predicted by the standard model for a ^{71}Ga detector

Neutrino Source	Capture Rate (SNU)
<i>pp</i>	70.8
<i>pep</i>	3.0
<i>hep</i>	0.06
^7Be	34.3
^8B	14.0
^{13}N	3.8
^{15}O	6.1
^{17}F	0.06
Total	132 SNU

GeCl_4 and into 1.2 liters of H_2O . This is then converted to GeH_4 (germane) from the extracted GeCl_4 . This gas sample is then mixed with xenon and injected into a low-background proportional counter with a volume of about 1 cm^3 . The efficiency of all the chemical processes is monitored by initially adding about $160\text{ }\mu\text{g}$ of natural Ge to each of four reactors that contain the 30 tons of Ga. The amount of carrier extracted can be measured both by atomic adsorption analysis and in the last stages by the volume of synthesized GeH_4 that is produced. The overall extraction efficiency is typically 80% with an uncertainty of $\pm 6\%$.

^{71}Ge decays via electron capture with a half life of 11.4 days. The capture is accompanied by emission of a 10.4-keV *K-x* ray 40% of the time and by the emission of a 1.2-keV *L-x* ray also 40% of the time. Unfortunately, the background in the region of the *L* peak was too large for it to be used for determining the ^{71}Ge production rate. The typical background rate in the region of the *K* peak is 0.1 events per day. Taking all efficiencies into account, the SSM would predict that SAGE should detect four ^{71}Ge in an extraction after the Ga has been exposed for, say, 30 days since it was last extracted. When the Ga was above ground, a relatively large amount of ^{68}Ge was produced via the hadronic component of cosmic radiation. ^{68}Ge has a half life of 271 days and also decays via electron capture, so its decay signal (apart from half-life) is identical with ^{71}Ge ; hence, it must be very thoroughly removed before ^{71}Ge production measurements can proceed. When initially brought underground, the rate of ^{68}Ge decay was more than 10^4 higher than what is expected for the rate from solar neutrino production of ^{71}Ge . The chemical extraction of ^{68}Ge began in the summer of 1988 and by January 1990 the experiment was ready to start.

Figure 8 shows a time histogram of the integrated number of events in the ^{71}Ge K peak windows from each of the extractions. There is no clear indication of a signal with a 11.4-day half life, which is perhaps not too surprising in that each run is expected to have only approximately four events due to ^{71}Ge decay. A statistical analysis of the data yields the statistical upper limit shown in Table 8. As a further check on the extraction

Figure 8. The integrated number of events satisfying the ^{71}Ge pulse height and rise time cuts for the K x -ray signal. The individual plots represent the observation for the month in 1990 for which the extraction was made.

and counting efficiency, a known amount of ^{71}Ge was put into a Ga reactor, extracted, and counted. Table 9 shows the results from that test, and one sees very good agreement between the efficiency determined by chemical analysis of the carrier ^{71}Ge and the actual counting of the much smaller amount of radioactive ^{71}Ge introduced into the Ga. In addition to statistical uncertainties, there are systematic uncertainties in the lengthy procedure involved in this experiment. The largest of the systematic uncertainties has to do with the time dependence of the background. The statistical analysis fits the data with two components—one has an 11.4-day half life and the other is the background rate taken to be constant in time. A radioactive decay chain such as, for example, Ra can introduce episodic background. Though none of the events in that particular decay are well suited to produce background in the region of the Ge K peak. In order to investigate this possibility, the time dependence of a wide body of data with energies and rise times outside the 10.4-keV x -ray window were investigated. All observations are consistent with a background that is constant in time. However, in order to be conservative about possible time variation in the background, it was fitted to a polynomial expression for the time dependence of the background. This analysis led to a maximal change in the limits set on the ^{71}Ge production rate of 30 SNU (68% C.L.) and 35 SNU (90% C.L.).

Table 9
Extraction efficiency test—Ge carrier versus ^{71}Ge counting

Extraction #	Ge Carrier (μg)	^{71}Ge (atoms)	Efficiency (%)	
			Carrier	^{71}Ge
1	410 ± 10	5188 ± 195	78 ± 4	79 ± 5
2	97 ± 2	1131 ± 107	84 ± 20	84 ± 26
3	21 ± 2	<200		
Σ	528 ± 10	6519 ± 222	101 ± 5	99 ± 6
Amount added	525 ± 26	6555 ± 359		-8

$$\tau(^{71}\text{Ge})_{\text{meas}} = 11.0 \pm 2.4 \text{ days (11.4 days)}.$$

The result of combining the statistical and systematic errors leads to a value

$$\langle \phi, \sigma_{^{71}\text{Ga}} \rangle = 20 + 15 / -20 \pm 32 \text{ SNU}.$$

In terms of limits on the solar ν flux, this corresponds to

$$\begin{aligned} \langle \phi, \sigma_{^{71}\text{Ga}} \rangle &< 55 \text{ SNU} \quad 68\% \text{ C.L.} \\ &< 79 \text{ SNU} \quad 90\% \text{ C.L.} \end{aligned}$$

Taken at face value, this result demonstrates that the ν flux from the sun must undergo modification. There is one possible experimental escape. It could be the case that ^{71}Ge formed via (ν, e) production undergoes some unknown "hot atom" chemistry and forms a complex that cannot be extracted as efficiently as the Ge carrier used to determine the extraction efficiency. The most effective way to test this is to irradiate a sizable Ga sample (~ 10 tons) with an intense (~ 1 Megacurie) ^{51}Cr source. ^{51}Cr decays by electron capture, emitting a 746-keV neutrino 90% of the time and a 426-keV neutrino the other 10%. An engineering run was carried out at SAGE with a fraction of a Megacurie source in the fall of 1990 but produced insufficient data to permit a measurement of the extraction efficiency. A calibration run will be carried out in late 1992 or 1993.

The results of the three solar neutrino experiments just discussed can be accounted for by taking account of matter-induced neutrino oscillation in the sun. Boris Kayser will discuss that in his presentation. I want only to list the conclusion [16] of that analysis,

$$\Delta m^2 \sin^2 2\theta_\nu = 4 \times 10^{-8 \pm 1} \text{ eV}^2 .$$

A not unreasonable and consistent interpretation of these results would be

$$m_\mu \sim 10^{-3} \text{ eV}$$

$$m_e \ll 10^{-3} \text{ eV}$$

$$\theta_\nu \simeq 0.1 .$$

Thus, these experiments show $m_\nu \neq 0$ and that lepton flavor is not conserved. If correct, this is the *first observed breakdown* of the *minimal standard model* and hence is an extremely important result.

The task of future research would then lie in measuring the neutrino masses and mixing angles in a manner similar to the K.M.C. mass matrix for the quark sector. However, the first order of business must be to generate more robust results from the Ga experiments. The SAGE experiment is now back in operation employing the full complement of 60 tons of Ga as a detector. The GALLEX experiment received final shipment on its 30 tons of Ga in March of 1990 and has reduced the ^{68}Ge background to a sufficiently low level that it is now sensitive to ^{71}Ge production via solar neutrinos. The counting systems in the GALLEX experiment have sufficiently low noise and low background that they can count the L -x ray, as well as the K -x ray. Hence, both experiments are of comparable sensitivity and within a year a good value for $\langle \phi, \sigma_{71\text{Ga}} \rangle$ will be to hand. Then with a good calibration of each experiment, the issue should be settled.

4. THE 17-keV NEUTRINO

The 17-keV neutrino rides again! While the solar neutrino results can be incorporated into the MSM via a straightforward extension, the 17-keV neutrino is a real outsider. It first appeared on the scene some six years ago when Simpson reported [17] on an anomaly in the spectrum of ^3H decay. The ^3H was implanted in a Si(Li) detector. Subsequent experiments did not substantiate Simpson's claims of a 2–4% admixed component of a 17-keV neutrino into normal beta decays. Needless to say, a 17-keV neutrino is a very difficult object to accommodate at this stage, as there are a variety of constraints on neutrino masses and mixing angles. Boris Kayser will discuss these constraints in his presentation, and I will deal with the experimental situation in the following.

One is compelled to point out what a tricky business beta decay experiments are, especially those that depend on measurement of the spectrum shape. Erroneous inferences have been drawn in the past regarding the electron antineutrino mass, the existence of second-class currents, and the present set of $\bar{\nu}_e$ mass measurements seems to be finding $m_{\bar{\nu}_e}^2 < 0$ as yet a further example of how hard it is to control systematic errors in these low-energy spectral measurements.

A paper [18] by Hime and Jelley earlier this year contains what appears to be very convincing data for a 17.0 ± 0.4 -keV neutrino with a mixing angle of $\sin^2 \theta = 0.0084 \pm 0.0006 \pm 0.0005$. The measurement was carried out on the decay of ^{35}S ($E_0 = 167$ keV), which is a better choice than ^3H as a source of 17-keV neutrinos, as ^3H decay forces one to study electrons below 2 keV. In [17], the source was external to the detector, which was again a Si(Li) detector. The detector had a 200-mm² active area and a thickness of 5 mm. Very considerable attention was paid to chamber vacuum, beta collimation, source preparation, detector response, pile-up, etc. Figure 9 shows the results of spectra obtained in two different runs and a composite of the two runs relative to data less than 17 keV below the endpoint. To understand these figures, first let us consider Fig. 10, which shows the local effect of a heavy neutrino on the beta spectrum. It has all the properties evidenced by Eq. (4) and is added with a weight of $\sin^2 \theta$ on top of the normal beta spectrum with $m_{\nu_e} \cong 0$. Thus, a best fit to the overall spectrum produces a local notch at the heavy neutrino threshold and then undershoots the spectrum where $(E_0 - E_e) > (E_0 - m_\nu)$. The shape of the notch is nontrivial and is a function of neutrino mass. Figures 9(a) and 9(b) show the ratio of the measured spectrum to the best fit obtained, assuming no heavy neutrino emission. There is a local notch some 17 keV below the endpoint and data between this notch and the beta endpoint are well above the best fit.

Similar effects have been seen by an LBL group who measured the spectrum of ^{14}C dissolved into a Ge(Li) crystal that is used as the detector and source. Their statistics are not as impressive as those of [18], but they also obtain [19] a notch at 17.1 keV with a value of $\sin^2 \theta \sim 1.3\%$.

Figure 9. (a) Ratio minus one of the observed spectra to a calculated spectrum assuming that $\sin^2 \theta = 0$ (Run 1). (b) Ratio minus one of the observed spectra to a calculated spectrum assuming that $\sin^2 \theta = 0$ (Run 2). (c) Ratio minus one of observed spectra fitted to a calculated spectrum using the data at $E_e > 150$ keV to determine the fit. The solid line through the data points is for $\sin^2 \theta = 0.009$ (Runs 1 and 2).

Figure 10. Schematic figure showing the effects of a heavy neutrino on the beta spectrum.

In a recent publication, a Yugoslavian group reported [20] observation of a spectral modification of the inner bremsstrahlung following electron capture. Again, the statistics are not as large as those in [18], but the analysis yields a 18-keV neutrino with a mixing angle $\sin^2 \theta = 0.0160 \pm 0.0053$ (1σ). In this case, they measured the internal bremsstrahlung following capture in ^{71}Ge (endpoint ~ 230 keV). The photons were detected in a 4.7-cm-diameter, 3.65-cm-thick Ge detector.

All of the experiments mentioned above are difficult; the significant data are within 30 keV of the endpoint where the signal is usually small. There is, in each of their fits, some small linear or quadratic correction term to account for imperfect detector response. There is no apparent reason why or how these corrections would introduce anomalies into the spectrum of the kind reported. The one common feature of all these experiments is that the spectra have been measured with semiconducting crystalline detectors. Again, no known mechanism can explain the occurrence of a common anomaly in these three experiments. However, it should be borne in mind that no experiment using a magnetic spectrometer has observed any positive evidence for a heavy neutrino.

The most recent data from a magnetic spectrometer is contained in a preprint [21] from the Caltech group, who have examined $^{35}\text{S} \rightarrow ^{35}\text{Cl} + e + \nu$, the same decay as Hime and Jelley. They use a $\pi\sqrt{2}$ iron-free double focusing spectrometer to measure the ^{35}S beta spectrum. Their setup has a momentum resolution of 0.27% (FWHM), or an energy resolution of approximately 0.9 keV at the threshold energy for 17-keV neutrino emission. The data have high statistics, approximately 10^6 counts per every 1.4 keV in the 17-keV neutrino threshold region. The measured spectrum is fit using both a linear (K_1) and a quadratic (K_2) function of p_e to account for smooth variation in the spectrometer response, as well as different admixtures of a 17-keV neutrino. These small detector response constants change value depending on what is assumed for the magnitude of the mixing angle for the 17-keV neutrino. Thus, for $\sin^2 \theta = 0$, $K_1 = 9.9 \times 10^{-4}$ keV/c and $K_2 = -3.8 \times 10^{-6}$ (keV/c) 2 , while for $\sin^2 \theta = 0.0085$, $K_1 = 6.3 \times 10^{-3}$ and $K_2 = -1.7 \times 10^{-6}$. The χ^2 for the fits are not impressive in either case— $\chi^2 = 303$ for $\sin^2 \theta = 0$ and 458 for $\sin^2 \theta = 0.0085$ for 81 degrees of freedom for both cases. The χ^2 fit would appear to strongly favor $\sin^2 \theta = 0$ relative to $\sin^2 \theta = 0.0085$, but the overall large value for χ^2 is disturbing. Figure 11 shows their data and the fit expected for a 17-keV neutrino present with a mixing angle of 0.0085. They claim that at 90% C.L., $\sin^2 \theta \leq 0.0060$, well below the value claimed by [17].

For me, the most compelling evidence against the need for a heavy neutrino component in nuclear beta decay is the earlier work [22] of a Chalk River group. They also employed a $\pi\sqrt{2}$ iron-free beta spectrometer, shown in Fig. 12, to study the decay of ^{63}Ni ($E_0 = 67$ keV). The energy resolution is the order of 100 eV and 900 data points were taken between 25 and 70 keV (60 eV/step at 50 keV). Some 10^8 total events were measured. The Kurie plots of the data are shown in Fig. 13. Figure 14 shows the fits to the data from their article, and it is obvious that a mixing as large as the value being claimed at that time ($\sin^2 \theta = 0.03$) is incompatible with the data. Figure 15 shows a best fit value for $\sin^2 \theta$ as a function of the mass of a possible heavy neutrino. At

Figure 11. Residuals in percent from the observed spectra of beta particles from ^{35}S , assuming no heavy neutrino components. The curve represents how the deviation would occur for a 17-keV neutrino with $\sin^2 \theta = 0.0085$.

Figure 12. Plan section of the Chalk River iron-free $\pi\sqrt{2}$ beta spectrometer.

Figure 13. (a) Kurie plot of the measurements for ^{63}Ni beta decay. (b) Detail of the Kurie plot in the region of $E_\beta = 50$ keV, where the effects of a 17-keV neutrino would be expected to be manifest.

Figure 14. (a) Ratio of the observed data to a calculated spectrum, assuming no heavy neutrino ($\sin^2 \theta = 0$). (b) Ratio of the observed data to a calculated spectrum, assuming a 17-keV neutrino with $\sin^2 \theta = 0.03$.

Figure 15. Residuals of fits to the observed ^{63}Ni beta decay spectrum, assuming different values of heavy neutrino masses and mixing angles. The solid line shows the 90% confidence level on the upper limit of the possible $\sin^2 \theta$ for a value of the heavy neutrino mass.

17 keV, the 90% confidence limit on $\sin^2 \theta$ would appear to be 0.3%, again well below the value claimed in [18].

There have been other measurements reporting limits on a 17-keV component to nuclear beta decay. It can be said that every report of a positive effect occurs when a crystalline semiconducting detector has been used. No magnetic spectrometer measurement has confirmed the existence of a heavy-neutrino component. It is also fair to say, even though the subject has been given a great deal of thought, that no one has come forth with a definite idea of what mechanism in Si and Ge detectors can simulate the effect of a 17-keV neutrino.

This is an exciting and interesting issue which, if true, would upset the standard model in a rather serious way. As you will learn from Boris Kayser, this 17-keV neutrino does not easily fit into our prejudices or what we already know about neutrino properties.

5. νp ELASTIC SCATTERING

As this conference is entitled "Hadronic Structure and Electroweak Interactions," I think it appropriate to point out the use of the neutrino to reveal a very important aspect of the structure of the nucleon. Neutrino elastic scattering can be used to obtain the strange quark contribution to the proton spin or more generally the $SU(3)_F$ singlet axial vector form factor.

The report [23] of the EMC group of the violation of the Ellis-Jaffe [24] sum rule and the immediate corollaries of a sizable strange quark contribution

$$2\langle S_Z \rangle_s \equiv \Delta s = \int_0^1 [\vec{s}(x) + \vec{\bar{s}}(x) - \overleftarrow{s}(x) - \overleftarrow{\bar{s}}(x)] dx = 0.190 \pm 0.032 \pm 0.046 \quad (12)$$

to the proton spin and small value for the sum of all quark spins in the proton

$$\sum \Delta q = \Delta u + \Delta d + \Delta s = +0.12 \pm 0.094 \pm 0.138 \quad (13)$$

has spurred great theoretical and experimental interest in the issue of how the nucleon spin is realized. The experiment reported by the EMC group is very difficult. It consists of measuring the asymmetry (A) in the yield of longitudinally polarized muons from longitudinally polarized protons.

$$A(x) = \frac{d\sigma(x) \uparrow\downarrow - d\sigma(x) \uparrow\uparrow}{d\sigma(x) \uparrow\downarrow + d\sigma(x) \uparrow\uparrow} \quad , \quad (14)$$

where x is the fraction of momentum of the proton carried by the struck quark in the infinite momentum frame. The proton spin structure function $g_1(x)$ is measured by

$$g_1(x) \simeq A(x)F_1(x) \quad . \quad (15)$$

Kaplan and Manohar [25] have pointed out that neutrino elastic scattering can determine the strange quark contribution to the proton axial vector form factor. Actually, a very similar point had been made much earlier [26], but the context was lacking to motivate any meaningful experiments. Neutrino-proton elastic scattering has been measured [25] but at a Q^2 that is too high, so that a variety of uncertainties enter the problem and render impossible interpreting the result in terms of a strange quark axial vector form factor. The expressions developed below follow a scheme similar to that used by Beise and McKeown [27].

In terms of quark currents, the neutral weak current (NWC) of a nucleon may be written as

$$j_N^{Z_0} \simeq \left\langle N' \left| \sum_{i=u,d,s} \bar{q}_i \gamma^\mu (1 - \gamma_5) t_{3i} q_i - 2 \sin^2 \theta_W Q_i \bar{q}_i \gamma^\mu q_i \right| N \right\rangle \quad , \quad (16)$$

where Q_i is the quark charge and t_3 is the weak isospin ($t_3(u) = \frac{1}{2}u$, $t_3(d) = -\frac{1}{2}d$, $t_3(s) = -\frac{1}{2}s$). The first product in the sum is pure V - A , while the second is just $-2\sin^2 \theta_W$ times the electromagnetic current. Thus, we can readily write the NWC in terms of known form factors and unknown strange quark contributions

$$j_N^{Z_0} \simeq \left\langle N' \left| \frac{-G_A(Q^2)}{2} \gamma^\mu \gamma_5 \tau_3 + \frac{\bar{s} \gamma_\mu \gamma_5 s}{2} + (1 - 2\sin^2 \theta_W) F_v^{\text{EM}}(Q^2) \tau_3 \right. \right. \\ \left. \left. + (-2\sin^2 \theta_W) F_s^{\text{EM}}(Q^2) - \frac{\bar{s} \gamma^\mu s}{2} \right| N \right\rangle . \quad (17)$$

where $F_v^{\text{EM}}(q^2)$ and $F_s^{\text{EM}}(q^2)$ are the isovector and isoscalar electromagnetic form factors, respectively—a $\tau_3 = +1$ for proton, -1 for neutron. Hence, $F_v^{\text{EM}}(q^2) = F_{1,v}(q^2)\nu^\mu + F_{2,v}(q^2)(\sigma_{\mu\nu}q_\nu/2m_p)$ and so forth. $G_A(Q^2)$ is the axial vector form factor of the nucleon and $(\bar{s}\gamma_5 s/2)$ and $(\bar{s}\gamma_\mu s/2)$ are strange quark contributions to the axial vector and vector form factors, respectively. The strange quark contributions are isoscalar.

In order to measure, say $(G_s/2)$, the strange quark contribution to the axial current, it is essential to carry out the measurement of the yield of $\nu + p \rightarrow \nu + p$ at low Q^2 , i.e., ($Q^2 < 0.1 \text{ GeV}^2$). This minimizes the following uncertainties in the determining contributions of $G_s(q^2)$, the uncertainty in $G_A(q^2)$ because of the uncertainty in $m_A = 1.03 \pm 0.04 \text{ GeV}$, and $F_1^s(q^2)$ and $F_2^s(q^2)$ are completely unknown. At $|Q| \ll m_p$, magnetic contributions are suppressed so that, using Eq. (17),

$$\sigma(\nu p) \sim \left| \left\langle p' \left| \left(\frac{-1.26}{2} + \frac{G_s}{2} \right) \gamma^\mu \gamma_5 + \frac{1 - 4\sin^2 \theta_W}{2} \gamma^\mu \right| p \right\rangle \right|^2 . \quad (18)$$

Fortuitously, the charge form factor is seen to be much suppressed (0.04). In this representation, the value of $G_s(0)$ inferred from the EMC values [22] of $g_1(x)$ is

$$G_s = 0.19 \pm 0.08 .$$

In a LAMPF experiment (E1173), $G_s(0)$ is expected to be measured to an accuracy of 0.05 via low-energy ($\nu_\mu = 200 \text{ MeV}$) neutrino-proton scattering. Notice that there was no need to use SU_3 symmetry arguments in the case of νp scattering. The strange quark contribution appears as an isoscalar contribution to the nucleon axial weak current.

6. CONCLUSIONS

I hope it has been apparent that neutrino physics, mostly at low energy, has proven to be interesting and revealing of very fundamental issues in the standard model. Further, there are more potentially interesting questions presently being addressed than is the case for most areas of nuclear and particle physics.

In addition to their own intrinsic properties, neutrinos allow investigation of new and unique properties of the structure of the nucleon.

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