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#### Neutrino masses and solar neutrinos

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It has been pointed out by Bahcall and Bethe and others that all solar-neutrino data can be explained by Mikheyev-Smirnov-Wolfenstein oscillations with  $m(\nu_\mu) \sim 10^{-3}$  eV consistent with ideas of grand unified theories (GUT's). We point out here a second possibility consistent with GUT ideas with  $m(\nu_\tau) \sim 10^{-2}$  eV and  $m(\nu_\mu) \sim 10^{-4}$  eV. The two cases can be distinguished by a measurement of the solar neutrinos from  ${}^7\text{Be}$ .

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There exists some indication that all the solar neutrinos of the  $\nu_e$  variety produced in the deep interior of the Sun do not reach detectors on Earth. A particularly attractive solution to this apparent problem is that some of the  $\nu_e$  are transformed to  $\nu_\mu$  or  $\nu_\tau$  on their way from the center to the surface of the Sun by neutrino oscillations in matter, the Mikheyev-Smirnov-Wolfenstein (MSW) effect.

Several recent papers [1-4] have pointed to a particular choice of neutrino masses and mixings that fits all the experimental data perfectly and also fits into the theoretical ideas of grand unified theories (GUT's) such as SO(10). Here I wish to point out an alternative choice that I feel is equally attractive.

The starting point of the recent papers is the theoretical neutrino flux of Bahcall and Ulrich [5]. The Kamiokande detector finds [6] a flux about 0.5 of the theory and the Davis  ${}^{37}\text{Cl}$  detector [7] a flux about 0.3 of the theory. Furthermore, the first data [8] on a gallium experiment, sensitive to the low-energy  $pp$  neutrinos finds a rate less than half of the theoretical rate. All these data are fitted perfectly [1-4] by the MSW effect with a small mixing angle:

$$\begin{aligned} m(\nu_x) &\approx 2 \times 10^{-3} \text{ eV to } 4 \times 10^{-4} \text{ eV,} \\ \sin^2 2\theta_{ex} &= 10^{-2} \text{ to } 3 \times 10^{-1}, \end{aligned} \quad (1)$$

where  $\nu_x$  is  $\nu_\mu$  or  $\nu_\tau$ ,  $\theta_{ex}$  is the mixing of  $\nu_e$  with  $\nu_x$ , and one assumes  $m(\nu_e) \ll m(\nu_x)$ .

The suggestion from GUT's is the seesaw formula

$$m(\nu_x) \sim 0.1 \frac{m^2(u_x)}{M_x}, \quad (2)$$

where  $m(u_x)$  is the mass of the  $t$  quark ( $c$  quark) for  $\nu_x = \nu_\tau$  ( $\nu_\mu$ ) and  $M_x$  is a large mass scale less than or equal to the GUT scale. In particular, an intermediate mass scale may be needed in theories such as SO(10) in order that the theory will fit the observed low-energy couplings. For the fit of Eq. (1),  $M_x \sim 10^{15}$  GeV for  $\nu_x = \nu_\tau$  and  $M_x \sim 10^{11}$  GeV for  $\nu_x = \nu_\mu$ . Furthermore, GUT's suggest that qualitatively the mixing angles should be like that of the quarks; thus,

$$\begin{aligned} \sin^2 2\theta_{e\mu} &\sim 10^{-1}, \\ \sin^2 2\theta_{e\tau} &\sim 10^{-3} \text{ to } 10^{-4}. \end{aligned} \quad (3)$$

Thus there is some preference for choosing  $\nu_x = \nu_\mu$  in this scenario, as suggested in Ref. [1].

It follows from Eq. (2) that neutrinos follow a mass hierarchy like the quarks. The relation between the  $M_x$  of different generations depends on the details of the theory. We consider two possibilities:

$$(A) M_x = \text{const}, \quad (4a)$$

$$m(\nu_x) \propto m^2(u_x),$$

$$(B) M_x = \text{const} \times m(u_x), \quad (4b)$$

$$m(\nu_x) \propto m(u_x).$$

We do not believe it is possible to choose between these until one has a theory of the generation hierarchy.

To set the stage for our scenario we assume the data compared to the standard solar model (SSM) is given by

$$\text{Kamiokande/SSM} = 0.5 \pm 0.1,$$

$$^{37}\text{Cl/SSM} = 0.3 \pm 0.1,$$

$$\text{gallium/SSM} \leq 0.5.$$

We have enlarged the error in the  $^{37}\text{Cl}$  experiment to allow for systematic errors which may be indicated by the fluctuation in the data. (As in Refs. [1–4] we attach no significance to the time variation in the neutrino flux reaching the detectors.)

Ignoring the gallium and  $^{37}\text{Cl}$  data for the moment, we fit the Kamiokande data with

$$m(\nu_\tau) \approx 10^{-2} \text{ eV}, \quad (5)$$

$$\sin^2 2\theta_{e\tau} \approx 3 \times 10^{-4},$$

consistent with the analysis of Ref. [9]. This is not a good fit to the Davis data because for this value of  $\Delta m^2$  there is no suppression of the lower-energy neutrinos (such as those from  $^7\text{Be}$ ) which provide one-quarter of the theoretically expected  $^{37}\text{Cl}$  signal. Thus this solution by itself predicts less suppression for  $^{37}\text{Cl}$  than for Kamiokande. Furthermore, it provides no suppression of the gallium signal.

However, we now add  $\nu_\mu$  to the story. We expect  $m(\nu_\mu)$  to be much smaller than  $m(\nu_\tau)$  with a much larger mixing angle. Assuming  $\theta_{e\mu}$  is given by the Cabibbo angle and using Eq. (3b) which assumes  $M_x$  scales with the generation we have

$$m(\nu_\mu) \approx 10^{-4} \text{ eV} \times (0.7-1.4), \quad (6)$$

$$\sin^2 2\theta_{e\mu} = 0.2.$$

This leads to a prediction of 30–70 solar-neutrino units (SNU) for the gallium experiment. In this scenario it is the  $\nu_e - \nu_\tau$  transformation that converts  $^8\text{B}$  neutrinos and  $\nu_e - \nu_\mu$  that converts the low-energy  $pp$  and  $^7\text{Be}$  neutrinos [10]. Because of this conversion of the  $^7\text{Be}$  neutrinos there is a further suppression of the  $^{37}\text{Cl}$  signal thus making the Davis and Kamiokande results compatible within our assumed errors, particularly for the upper part of the range of  $m(\nu_\mu)$  in Eq. (6).

There exists an interesting way to distinguish these two choices of MSW solutions. In the case of Eq. (1) the gallium suppression corresponds to the adiabatic solution so that the suppression is increased as the energy increases. Thus for this solution a suppression of the gallium result by a factor of 4 involves an almost total suppression of the  $^7\text{Be}$  neutrinos. In this case the gallium signal is nearly all due to  $pp$  neutrinos. However, for the case of Eqs. (5) and (6) the gallium suppression corresponds to the non-adiabatic solution for which the suppression decreases slowly as the energy increases. Thus the  $^7\text{Be}$  neutrino suppression is always less than that of gallium. Indeed for this case the  $^7\text{Be}$  neutrinos may contribute more than the  $pp$  neutrinos to the gallium signal. An experiment that directly detects the  $^7\text{Be}$  neutrinos, such as the Borexino proposal, could thus distinguish these two solutions.

It should be emphasized that our use of GUT's is for qualitative guidance; specific models allow a large range of mass ratios and mixing angles [11]. We also believe that better quantitative observational data are needed before any definitive conclusions are possible.

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