Solutions to the Solar Neutrino Problem

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Several well known neutrino physics solutions to the solar neutrino problem are briefly reviewed and their status in the light of the latest experimental data is presented.

1. The Solar Neutrino Problem

All solar neutrino detectors measure rates which are about a half to a third below the predicted rates from the Standard Solar Model [1]. Moreover, the rates from all solar neutrino experiments are poorly fitted with even free solar neutrino fluxes, completely independent of any solar model predictions. For an arbitrary pair of experiments the minimum χ^2 obtained with free fluxes is discomfortingly large, although the number of free parameters is larger than the number of data points [2]. Therefore attempts to solve the solar neutrino problem by modifying the solar model to obtain lower fluxes and to fit the rates from all experiments (and even just any pair of experiments) are doomed to fail. There are already limits on the solar neutrino fluxes from helioseismology which constrain this type of solutions, e.g. putting a lower limit on the ^{7}Be flux [3]. On the other hand we do have solutions to the puzzle which involve non-standard neutrino properties. The most plausible one is the MSW solution[4] which only involves small neutrino masses. There are many examples of theories beyond the standard electroweak theory in which the predicted neutrino masses are very close to the ones necessary to fit the experimental data [5]. This remains true even if one includes the atmospheric neutrino data which strongly suggests oscillations with maximal mixing. The other solutions reviewed at this meeting involve more radical departures from either the standard electroweak theory or general relativity. Nevertheless, since these solutions are not in conflict with any known data and since they provide very good fits to the latest solar neutrino data, one should keep an open mind and continue to explore their implications for future experiments which will put them to further tests.

2. MSW and Vacuum Oscillations Solutions

The MSW solution has received a lot of attention since the time it was proposed. [4] The most significant theoretical development in the past year has been the realization [6] that even for mixing angles larger than $\pi/4$, which were previously neglected because of expected poor fit to the data and because of some mental inertia favoring small mixing, there are solutions allowed by the data at C.L. higher than about 95%. It has become a standard to present the results as a function of $\tan^2\theta$ rather than $\sin^2 2\theta$. At the Neutrino 2000 conference the SuperKamiokande collaboration presented their results on the recoil-electron spectrum from boron neutrinos [7]. Both the day-time and the night-time spectra turned out to be very flat (undistorted). This result rules out almost all of the vacuum oscillation region and restricts the small-mixing angle solution to $\tan^2\theta < 10^{-2}$, but allows a new region with close to maximal mixing and extending from the LOW solution ($\approx 10^{-7}\mathrm{eV}^2$) down to about $10^{-9}\mathrm{eV}^2$. The new region has been dubbed "quasi-vacuum oscillations" [8]. Plots showing this regions, as well as detailed explanations of the calculational procedures can be found in Ref.[9]. There has been a lot of work in recent months in which predictions for future experiments have been obtained and ways to distinguish between the different solutions have been investigated. In Ref.[10] predictions for various observable in the Sudbury Neutrino Observatory (SNO) have been made assuming either MSW or vacuum oscillations. At this meeting a new and promising way to utilize the energy dependence of the day-night asymmetry was presented [11]. The expected results from SNO, Borexino and Kamland will significantly constrain the number of viable solutions and might even solve the solar neutrino problem.

3. Flavor Changing Neutral Currents

A solution involving Flavor Changing Neutral Currents (FCNC) was proposed in Ref.[12] and quickly improved [13] to include also Flavor Diagonal Neutral Currents (FDNC) contributions so that a resonantly enhanced transition becomes possible. An appealing feature of this solution is the fact that it could provide an alternative solution to the MSW or vacuum oscillations without neutrinos being massive. The neutrino conversion here is due to new interactions, some of which are flavor changing and others are flavor conserving but non-universal. In principle the electron neutrinos could be converted into either mu or tau neutrinos. However stringent limits exist on the $\nu_e \leftrightarrow \nu_\mu$ channel from accelerator experiments and from semi-hadronic decays (see Ref.[15] for details). Therefore only $\nu_e \leftrightarrow \nu_\tau$ transitions are relevant to the solar neutrino problem. This solutions predicts a small day-night effect, no spectral distortion of the recoil-electron spectrum in SuperKamiokande or SNO and a NC/CC double ratio different from one. It also in general predicts an event rate in Borexino that is less suppressed than the boron neutrino rate. There should be no seasonal variations related to change of the oscillation length in vacuum.

For the sake of completeness let us mention that there is a theoretical fine tuning problem with this solution. The large Yukawa couplings that make possible for the transitions to be sufficiently strong to be relevant for solar neutrinos contribute to the neutrino mass through loop diagrams. The only detailed example of a theory that can provide the necessary flavor changing and flavor diagonal interaction is the one developed in [13] where in a well motivated theory, the minimal standard supersymmetric model without R-parity, it was shown that the couplings can be large enough for a solution to exist. However naturally the neutrino masses in this model are quite large ($\approx$ KeV) and fine tuning is needed to keep them small.

4. Magnetic Moment

This solution [16] was proposed in the late eighties when an exciting apparent anti-correlation between the 11-year solar activity cycle and the event rate in the Homestake detector received a lot of publicity. The magnetic moment solution assumes that neutrinos, in addition to being massive, have large transition magnetic moments ($\mu \sim 10^{-12}$ Bohr magnetons), by far larger than the flavor diagonal magnetic moments obtained in the minimally modified to include right-handed neutrinos standard electroweak theory. Models that could give such large magnetic moments have been constructed but they usually involve ad hoc assumptions, like extra particles or extra flavor symmetries, specifically designed so as to keep the masses of the neutrinos small but the magnetic moments large enough to solve the solar neutrino problem. In addition to that the magnetic field in the sun is essentially unknown. A rather strong magnetic field, of the order of 10^5 gauss, which spans a large region inside the sun (about $0.1\mathrm{R}_\odot$) is needed for this solution to work. Although such magnetic field at the base of the convective zone is not ruled out[1], opposite polarity of the magnetic field in the northern and southern hemispheres of the sun imposes a constrain on this solution, namely there should be a modulation of the solar neutrino signal with a period of 1/2 year. No such modulation has been observed in any of the detectors although a thor-

[1]A recent helioseismological analysis [18] concludes that a magnetic field as a large as 3×10^5 Gauss might exist at the base of the convection zone but only confined to a region which extends 0.02 $\mathrm{R}_\odot$.

ough analysis remains to be done. Similarly no anti-correlation has been observed between solar activity and event rates in any of the detectors. The average rates from all experiments are fitted very well with a minimum χ^2 of $\approx$ 0.05. The spectrum in SuperKamiokande can be fitted also for a wide range of parameters (magnetic field and mixing). Allowed regions exist for plausible profiles. The solution predicts bi-annual modulation of solar neutrino signals, no day-night effect, energy dependent NC/CC ratio and in principle measurable spectral distortions of recoil electrons in SNO (see Ref.[17] for details).

5. Violation of the Equivalence Principle

This is undoubtedly the most exotic solution of all. It involves violation of the equivalence principle (VEP) by introducing neutrino eigenstates in a gravitational field which mix with the flavor eigenstates [19]. The parameter characterizing the violation of the equivalence principle, $\phi\Delta\gamma$, is of order 10^{-24}, where ϕ is the gravitational field (e.g. $\phi \sim 3 \times 10^{-5}$ for the local supercluster) and $\Delta\gamma$ is the difference between the "couplings" of the neutrinos to the gravitational field. The neutrino eigenstates in the gravitational field propagate differently and acquire a phase difference along the way which accounts for the oscillations. If the standard electroweak interactions of the neutrinos with matter are included in the evolution equations describing the neutrino propagation in matter one gets neutrino transitions in the Sun which look much like MSW transitions with flipped energy dependence. The oscillation length for the VEP oscillations is inversely proportional to the neutrino energy whereas for oscillations in vacuum it is proportional to the neutrino energy. Most of the allowed region obtained in this MSW-like VEP solution is ruled out: the small mixing angle region is disfavored by the flat spectrum in SuperKamiokande and the large mixing angle is ruled out by old accelerator data.[20]. However it was recently realized [21] that a "just-so" VEP solution is also possible. This solution is still viable and can account for all the solar neutrino data (rates and spectrum from SuperKamiokande). No day-night variations are expected and the spectrum of recoil electrons from boron neutrinos should be only mildly distorted. Predictions for future experiments have been made. For SNO the NC/CC ratio is expected to be slightly energy dependent, the spectrum of electrons should be nearly undistorted, there should be no anomalously large seasonal variations and day-night asymmetry. Similarly there should be no zenith angle distortions.

6. Conclusions

If all solutions had to be compared on purely theoretical grounds a clear winner would emerge, namely the MSW solution. It only requires neutrinos to have masses and to mix, which comes out naturally in almost any extension of the standard electroweak theory. If one had to chose without a prejudice using only the available data from the rates and the SuperKamiokande spectrum data there there would be hardly any difference between the solutions. All of them provide a reasonably good, in fact in most cases excellent, description of the present data. This situation might change soon as (fortunately!) the different solutions predict different values for a variety of observables, like day-night asymmetries, seasonal variations, NC/CC ratio in SNO, etc. which are soon going to be measured. Long baseline experiments can provide in many cases additional constraints on these solutions. There is no doubt the next few years will be very exciting time for researchers in the field of solar neutrinos.

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