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REVIEW OF SOLAR NEUTRINOS AND THE MSW EFFECT

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REVIEW OF SOLAR NEUTRINOS AND THE MSW EFFECT

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ABSTRACT
I review the MSW solution to the solar neutrino problem in light of the existing data from the $^{37}Cl$ and Kamiokande II experiments. Taken together, they disfavor the adiabatic solution and tend to support either the large angle solution or the nonadiabatic one. In both cases the $^{71}Ga$ experiment will yield a much smaller signal than that predicted by the standard solar model; the suppression factor in the former case will be about the same as for $^{37}Cl$, and in the latter it could be as large as 10 or more. I await the outcome of this experiment with great anticipation.
INTRODUCTION

I am going to review the solar neutrino problem and the MSW effect under the following set of assumptions:

(1) There really is a deficit of solar neutrinos as compared with solar models. I am thus declaring myself to be a faithful disciple of John Bahcall; and to ward off the evil eye, I carry with me a copy of his book of revelations.

(2) There is no strong evidence for a time-dependent signal. The statistical power of existing experiments is not sufficient to establish this behavior, but the issue of time dependence should be the top priority for the next generation of experiments, for example SNO and BOREX.

(3) Neutrino oscillations combined with the elegance of the MSW effect are the true cause of the deficit. The important point is that in time, a sufficient set of experiments will prove, or disprove my contention.

Let us recall that the solar neutrino spectrum consists of three principal chains: the pp chain with energies up to 430 keV; the mono-energetic $^7$Be neutrinos at 820 keV; and the high energy $^8$B neutrinos with energies up to 14 MeV. In terms of flux, the pp neutrinos are the most copious and the least dependent on solar models, being about 90% in number; the $^7$Be make up about 10% and are moderately dependent on the temperature of the solar core. According to the standard solar model, only about one neutrino in ten thousand is a $^8$B neutrino and this minute fraction is very sensitive to the core temperature; however, because of their relatively high energies, these solar neutrinos are the 'easiest' ones to see.

After a brief review of the MSW effect, I shall discuss its application to the $^{37}$Cl and KamioKande II experiments. I then discuss the implications for the $^{71}$Ga experiments, and review the potential roles of the next generation of experiments that are being planned.

BRIEF REVIEW OF MSW

As a matter of historical record, I think it is fair to say that the MSW effect received its name at the January 1986 Moriond Workshop and began to attract widespread attention after that meeting. By now it is well-known that the basis of the effect is the existence of the charged-current diagram for the scattering of electron-type neutrinos by electrons. The forward scattering amplitude from this diagram contributes an effective mass term for the electron-neutrino which is different from those of the other types of neutrino. When the famous condition

$$\sqrt{2} G_F N_e = \frac{\Delta m^2}{2\rho} \cos 2\theta. \quad (1)$$

is met, the electron-neutrino mixes maximally with another type, say the muon-neutrino, no matter how small the 'in vacuo' mixing angle $\theta$ may be, and the probability for an oscillation from electron- to muon-neutrino becomes very large.

There are several solutions of the $^{37}$Cl suppression within the context of MSW which depend on the size of the mixing angle and the way in which the spectrum of $^8$B neutrinos from the sun overlaps the probability curve for an electron-neutrino to remain an electron-neutrino at Earth as a function of its oscillation length. For small mixing angles, the spectrum can overlap the curve in such a way that low-energy neutrinos remain as electron-neutrinos and high energy ones are converted to muon-type (the Bethe, or adiabatic solution), or in such a way that low energy neutrinos are converted to muon-type.
Rosen-Gelb, or nonadiabatic solution). For large angles there is the additional possibility that the entire spectrum can fall within the asymptotic region of the adiabatic part of the probability curve (the Parke and Walker solution); in this case the survival probability for electron-neutrinos is essentially independent of energy and equal to $\sin^2 \theta$. Appropriate values of $\theta$ will then give the observed reduction in $^{37}Cl$ experiment.

The modified shape of the spectrum of electron-neutrinos from $^8B$ for both the adiabatic and nonadiabatic solutions is a key feature of the MSW effect and observation of either form of modification would establish neutrino oscillations in general and MSW in particular as the solution of the solar neutrino problem. Another important property of the nonadiabatic solution is that it can, for a certain range of parameters, yield a very small signal in the $^{71}Ga$ experiment because of the large conversion probability for low energy neutrinos; observation of such a suppression would also be a key signal for oscillations and MSW.

THE CHLORINE EXPERIMENT

For more than twenty years now, Ray Davis and his colleagues$^{1}$ have been performing one of the most remarkable experiments in neutrino physics. Except for a couple of periods during which they have repaired or modified their equipment, they have gone down the Homestake Mine every two months to extract a handful of $^{37}Ar$ atoms from a six-hundred-ton tank of perchloroethylene, an inexpensive fluid which is rich in $^{37}Cl$. The average value of the signal they observe has remained at approximately four-tenths of an $^{37}Ar$ atom per day, or 2 SNU (solar neutrino units), although there do appear to be significant variations in anti-coincidence with the solar sunspot cycle. Unfortunately the errors are too large for us to be able to decide whether the time dependence is real or not. Here I take it to be 'not proven' and treat only the twenty-year average signal of $2.1 \pm 0.3$ SNU.

The theoretical predictions of the standard solar model (SSM) have also varied with time as the empirical parameters associated with it have been refined. In recent years, however, its fluctuations have not been as pronounced as those of the experimental signal appear to be. At present the SSM predicts a signal of $7.8 \pm 0.9$ SNU according to Bahcall and Ulrich, and $5.8 \pm 1.3$ according to Turck-Chi
c and colleagues. Thus there is a discrepancy of somewhere between 2 and 4 between experiment and theory.

As pointed out in the introduction, the MSW effect gives rise to three different solutions which can be characterized in the following way. The adiabatic solution satisfies

$$\Delta m^2 \approx 10^{-4} V^2$$

(2)

for all values of $\sin^2 2\theta$; the nonadiabatic solution has the approximate property that

$$\Delta m^2 \times \sin^2 2\theta \approx 3 \times 10^{-6};$$

(3)

and the large angle solution has

$$\sin^2 \theta \approx 1/2 - 1/4.$$ 

(1)

In order to choose between these solutions it is necessary to look at other experiments.

THE KAMIOKANDE EXPERIMENT

The Kamiokande II experiment observes solar neutrino scattering by electrons and, like the MSW effect, it too relies upon the charged-current diagram for its signal. The electron-
neutral-current diagrams, whereas the muon-neutrino scatters only through the neutral-current. Since the amplitude for the charged-current diagram is much larger than that of the neutral-current one, the cross-section for electron-neutrino scattering turns out to be about 6 to 7 times larger than that for muon-neutrino scattering. Thus the observation in this experiment of a signal smaller than the prediction of the SSM can be interpreted as meaning that some or all of the $^8B$ neutrinos to which it is sensitive have been converted to muon-type neutrinos.

I understand that at the present time the KII team has collected about 800 days of data with recoil electrons having more than 7.5 MeV of kinetic energy, and that the ratio of the number of events observed to the number expected on the basis of the SSM is:

$$R = \frac{\text{No. of events}}{\text{No. expected}} = 0.39 \pm 0.13.$$  (5)

The errors are too large for us to draw any definitive conclusions, but the central value is suggestive. It is too large for the adiabatic solution, but is consistent with the large angle solution and quite close to the prediction of the nonadiabatic solution. The adiabatic solution appears to be disfavored and one of the other two is more likely to be correct.

If this is so, then we ought to see a significant reduction in the signal for the $^{71}$Ga.

THE GALLIUM EXPERIMENT

In the standard solar model, the signal in the gallium experiment is 132 SNU, of which 71 come from pp neutrinos, 34 from $^7Be$ neutrinos, 14 from $^8B$, and the remainder from minor branches of the solar spectrum. Although this interaction rate is much larger than that of $^{37}Cl$, the target is very much smaller, being 60 tons for SAGE and 30 tons for GALLEX. Thus the actual event rate in these two experiments is of the same order as that in the chlorine experiment.

Now, if the large angle solution is the correct one for $^{37}Cl$ and KII, then the signal in $^{71}Ga$ should be reduced by the same factor between 2 and 4 as in the $^{37}Cl$ experiment. On the other hand, if the nonadiabatic solution is correct, then the reduction factor could be as much as 10, or even greater. It follows that a significantly reduced signal in the gallium experiment will provide strong evidence for the MSW effect, and the amount of reduction will indicate which solution holds.

While the adiabatic solution is disfavored at present, the errors on existing data are large enough that it could eventually come back into favor when more accurate measurements are available. In this eventuality, the $^{71}Ga$ should be close to the predictions of the SSM.

THE NEXT GENERATION OF EXPERIMENTS

Two experiments with much greater statistical power than existing ones are being developed. At the Sudbury Neutrino Observatory (SNO), a kiloton of heavy water will be located about 6800 feet below the surface in a nickel mine and the break-up of the deuteron by both charged- and neutral-currents will be observed. The comparison between these two processes is a crucial test of the oscillation hypothesis in the standard model (i.e. oscillations into non-sterile neutrino species), since the charged-current break-up is caused only by electron neutrinos from the sun, whereas the neutral-current break-up is independent of neutrino type. Thus if oscillations take place, the former process will be
Event rates for the charged- and neutral-current processes are predicted by the SSM to be 30 and 10 events per day, more than an order of magnitude greater than that of existing experiments. These measurements will therefore be able to settle the question of time dependence of the solar signal. In addition, the charged-current process will enable us to measure the spectrum of \(^{8}\)B electron-neutrinos arriving at Earth; as discussed above, this will be a key element in resolving the solar neutrino problem.

In addition to the deutron break-up processes, SNO will also be able to detect neutrino electron scattering at a level of three events per day. This is also an order of magnitude greater than KII and hence will be very useful.

A second large statistics experiment is BOREX\(^4\), which will look at charged- and neutral-current processes with \(^{11}\)\(^{\text{B}}\) as target instead of deuterium. In SSM it expects to have 6.3 charged-current events per day, but only 0.3 neutral- current ones. In this case the neutrino electron scattering rate is much more favorable at 4.2 events per day in the SSM. This experiment will be located at the Gran Sasso Laboratory, in close proximity to GALLEX.

A variety of other detectors have been discussed in the literature. Some make use of Indium as the target, another makes use of Bromine, and yet another Iodine. These experiments are in much earlier stages of development and it will be some time before they come into being.

CONCLUSIONS

I believe that we are approaching some very interesting times in the solar neutrino problem. The next experiments to report results will be the SAGE and GALLEX \(^{71}\)Ga ones, and the most exciting possibility will be that they both report signals well below the predictions of SSM. If this happens, and I for one most earnestly hope that it does, then we shall learn at one fell swoop that neutrinos oscillate, that MSW works, and that neutrino masses are most likely to be in the neighborhood of \(10^{-3}\) eV. What a bonanza for physics beyond the standard model that would be!

To settle the issue of time dependence, we shall have to wait for SNO and BOREX. They should turn on in about 5 years, and so we should have an answer by the end of the next sunspot cycle. I look forward to the outcome with definite prejudice.

REFERENCES

2. For another point of view, see the summary talk by R. G. H. Robertson in these proceedings.
3. See the talk by Dr. Davidson in these proceedings.
4. See the talk by Dr. Raghavan in these proceedings.
6. See talk by Dr. S. B. Kim in these proceedings.
8. See talk by D. J. Wilkerson in these proceedings.
9. See talk by Dr. Bernabei in these proceedings.