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Abstract

We consider the scattering of solar neutrinos by electrons as a means for distinguishing between different MSW solutions of the solar neutrino problem. In terms of the ratio R between the observed cross-section and that for pure electron-type neutrinos, we find that some correlation between the value of R and the appropriate solution. A value of $R \leq \frac{1}{3}$ implies that the adiabatic solution is correct, while values between $\frac{1}{3}$ and $\frac{3}{5}$ are consistent with the large angle solution. A value close to $\frac{1}{2}$ is also consistent with the non-adiabatic solution, and a value less than $(\frac{1}{6} \quad \frac{1}{7})$ implies oscillations into sterile neutrinos.

1. Introduction

The MSW/1/ effect provides an elegant explanation of the solar neutrino anomaly observed by Davis and his collaborators in the ^{37}Cl experiment/2/, but it does not yield a unique solution for the problem in the parameter space of mixing-angles ($\sin^2 2\Theta$) and mass differences (Δm^2). It gives instead three families of solutions corresponding to adiabatic/3/, non-adiabatic/4/, and large mixing-angle/5/ transitions respectively. Fortunately these families vary in their predictions for other solar neutrino experiments, and so we may hope eventually to be able to choose between them. In this talk, we consider the scattering of solar neutrinos by electrons as a means for making the choice.

The essential feature of neutrino-electron scattering is that, in the standard electroweak theory, the cross-section for the process decreases by a factor between 6 and 7 when the flavor of the incident neutrino changes from electron-type to muon- or tau-type/6/. This happens because the scattering of electron-type neutrinos involves both a neutral-current diagram and a charged-current one (the self-same diagram, in fact, that gives rise to the MSW effect), whereas the scattering of other neutrino types involves only the neutral-current diagram. Since the charged-current coupling constant is larger than the neutral-current one, the corresponding cross-section will also be larger.

In the experiments we consider here/7/, recoil electrons with kinetic energies greater than some minimum value, T_{min}, are detected. Since T_{min} is likely to be in the range of 5 to 10 MeV, the experiments are sensitive mainly to the higher energy part of the spectrum of ^8B neutrinos. Now the different MSW solutions for the ^{37}Cl experiment make different predictions for the flavors of solar neutrinos as a function of their energies, and hence they will yield different predictions for the neutrino-electron scattering experiment.

As originally emphasized by Bethe/3/, adiabatic solutions have the property that "high" energy solar neutrinos are almost entirely converted into muon- or tau-types, while "low" energy ones remain as electron-type neutrinos. The point of separation between "high" and "low" energies lies between 5 and 7 MeV depending upon the value of $\sin^2 2\Theta$. Non-adiabatic solutions tend to have the opposite property/4/; low energy neutrinos are strongly converted to non-electron types, but high energy ones have a probability of order 50% for remaining as electron neutrinos. In contrast to both of these solutions, the large mixing-angle solution discussed by Parke and Walker/5/ yields a probability for ν_e to remain ν_e which is approximately independent of energy. We therefore expect that the cross-sections arising from the non-adiabatic and large mixing-angle solutions will be larger than these arising from the adiabatic solution; however, the choice between the first two solutions, involving as it does the integration over neutrino energies may be more delicate.

To understand the behavior of these cross-sections we consider the $\sin^2 2\Theta$ - Δm^2 plane and the familiar triangle of solutions in Figure (1). Now imagine travelling down a line of small, but constant $\sin^2 2\Theta$ from the region of $\Delta m^2 \approx 10^{-4}(eV)^2$ to $\Delta m^2 \approx 10^{-8}(eV)^2$ and smaller. As we move through the triangle from the upper edge to the central area the ^{37}Cl signal becomes weaker and reaches some minimum value, meaning that more and more of the energetic ^8B neutrinos are converted to non-electron types. For increasing values of $\sin^2 2\Theta$, the minimum value in the central area moves closer to zero as the degree of conversion for the higher energy neutrinos becomes larger. Moving down from the central area to the lower edge of the triangle, we find that this degree of conversion decreases and so the ^{37}Cl signal grows stronger. Eventually we move out of the triangle and into a region in which only "in vacuo" oscillations take place, the fraction of electron neutrinos remaining is then the same, namely $(1 - \frac{1}{2}\sin^2 2\Theta)$ for all energies. Finally for extremely small values of Δm^2, the oscillation length becomes comparable to the astronomical unit and we observe real oscillations in the signal.

To translate this behavior into a pattern for the solar neutrino-electron scattering experiment, we work on the general principle that as the fraction of electron neutrinos at higher energies increases, so the neutrino-electron cross-section increases, and as the fraction decreases, so the cross-section decreases. Therefore, as we move down from the top of the triangle in Figure (1) to the central area, the scattering cross-section decreases to a minimum, which will, in fact, be the pure neutral-current cross-section when all high energy neutrinos are converted to non-electron types. The cross section will remain approximately constant while we move through the central area of the triangle and then it will begin to increase as we move into the region of non-adiabatic solutions. It reaches its maximum value in the Δm^2 region corresponding to "in vacuo" oscillations and eventually tends to decrease as the oscillation length approaches the astronomical unit. For small mixing-angles, the maximal cross-section is very close to that for pure electron-neutrinos. This behavior is clearly illustrated in Figure (2).

2. Distinguishing Between Solutions

Let us now consider solar neutrino-electron scattering as a tool for distinguishing between different MSW solutions for the Davis experiment. Following Bahcall, Gelb, and Rosen/8/, we write the differential cross-section for producing a recoil electron with kinetic energy T as:

$$\langle \frac{d\sigma}{dT} \rangle = \frac{1}{\phi_{\rm total}} \int dq \phi(q) \left[\frac{d\sigma}{dT}(\nu_e e) P_{ee}(q) + \frac{d\sigma}{dT}(\nu_\mu e)(1 - P_{ee}(q)) \right] \qquad (1)$$

where $\phi(q)$ is the spectrum of neutrinos of energy q produced in the sun, $\frac{d\sigma}{dT}$ is the differential cross-section for neutrino electron scattering, and $P_{ee}(q)$ is the probability for an electron-type neutrino of energy q to remain an electron neutrino. The differential cross-section depends upon q, T, and the flavor of the incident neutrino.

To calculate the total cross-section, we integrate eq. (1) between the experimentally required minimum kinetic energy $T_{\rm min}$ and the kinetically allowed maximum $T_{\rm max}$:

$$\langle \sigma(\nu e) \rangle = \int_{T_{\rm min}}^{T_{\rm max}} \langle \frac{d\sigma}{dt} \rangle dT \quad . \qquad (2)$$

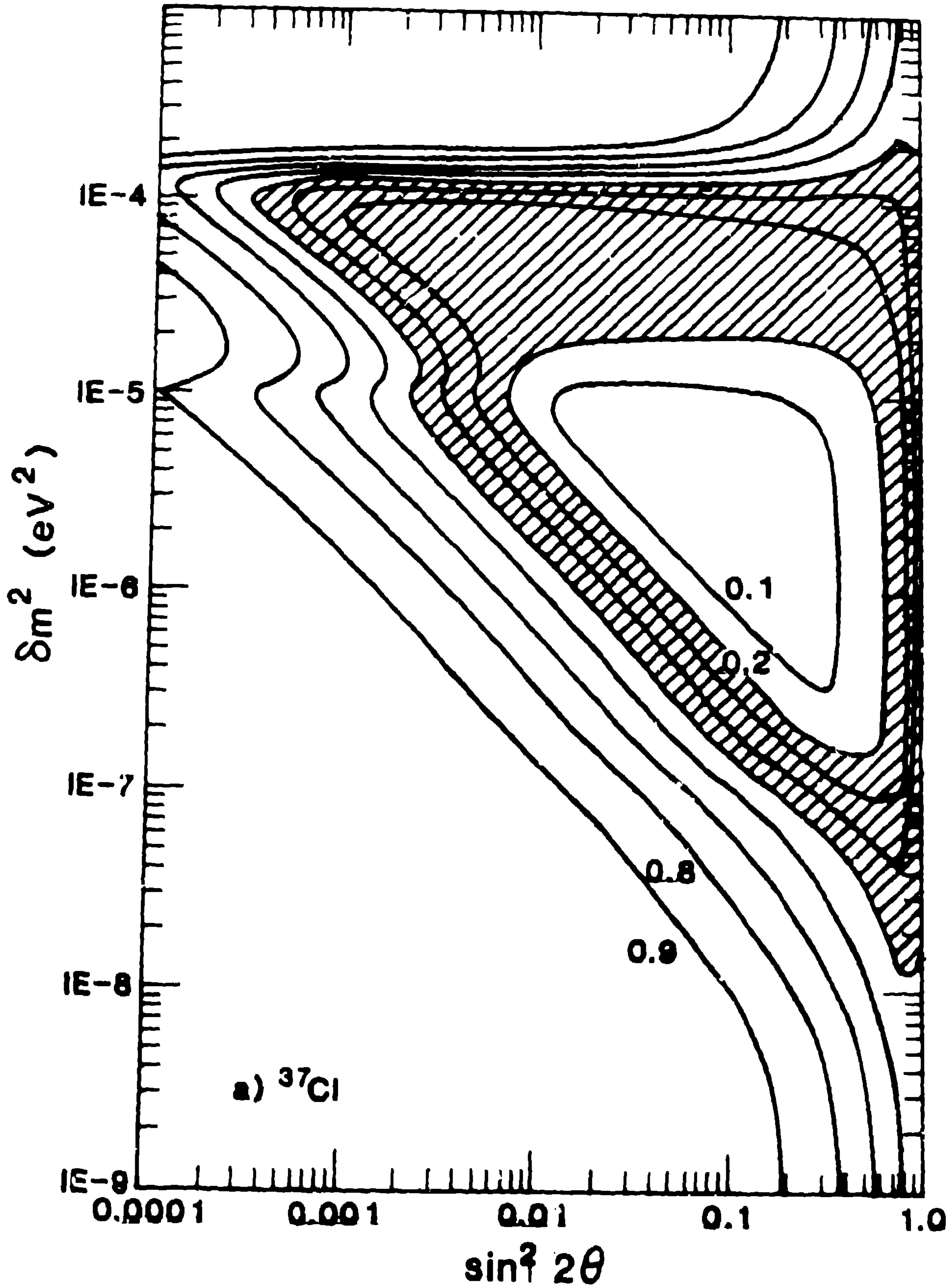

Fig. 1 Contours of equal suppression for the ^{37}Cl experiment. (From Haxton 4). The shaded area represents the specific solutions for the Davis experiment.

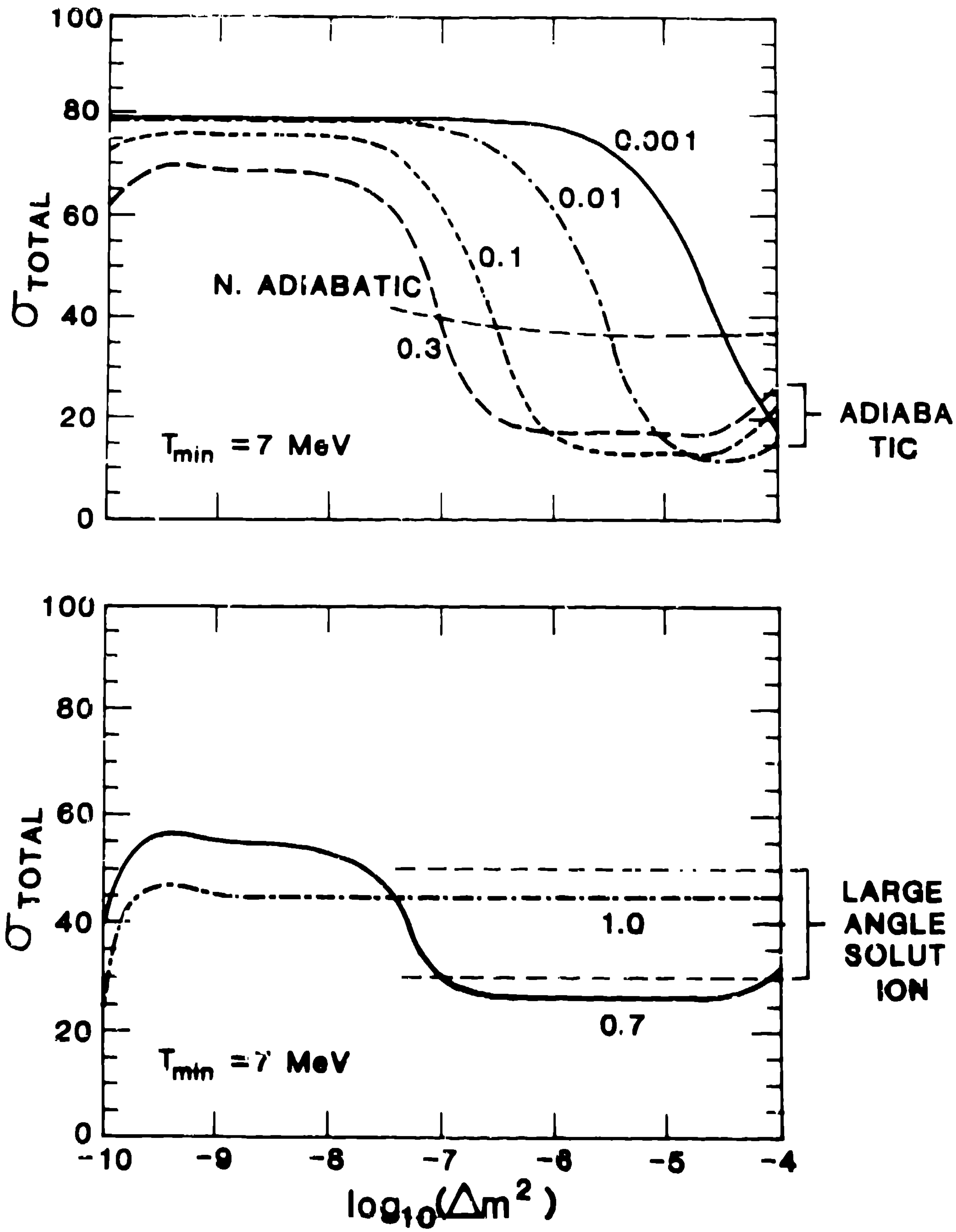

Fig. 2 Cross-sections for solar neutrino electron scattering as a function of Δm^2. The units are $10^{-46} km^2$ and the values of $\sin^2 2\Theta$ are shown next to each curve. The minimum electron energy is 7 MeV. In the upper figure we show the predictions of the small angle solutions for the Davis experiment, and in the lower figure those for the large angle solution. (From reference /8/).

It follows from eqs. (1) and (2) that $\langle\sigma(\nu e)\rangle$ is bounded from above by the cross-section for pure electron-neutrino scattering, and from below by that for pure muon-neutrino scattering:

$$\sigma(\nu_\mu e) \leq \langle\sigma(\nu e)\rangle \leq \sigma(\nu_e e) \ . \tag{3}$$

Graphs of the cross-section for different values of T_{min} are shown in Figures (2) and (3).

In any experiment we actually measure the product of the cross-section times the flux. To study the MSW effect, we must assume that the flux is given by the standard solar model in order to extract a cross-section $\langle\sigma(\nu e)\rangle$ from the measured product. We then form the ratio of the measured cross-section to its maximum value

$$R = [\langle\sigma(\nu e)\rangle/\sigma(\nu_e e)] \tag{4}$$

and note from eq. (1) that

$$1 \geq R \geq \frac{\sigma(\nu_\mu e)}{\sigma(\nu_e e)} \approx \frac{1}{6} - \frac{1}{7} \ . \tag{5}$$

Let us first look at the general properties of R for the various families of solution. For small mixing-angle adiabatic solutions, the range of Δm^2 decreases from $10^{-4}(eV)^2$ to a few times $10^{-5}(eV)^2$, and the cross-section decreases with Δm^2. From Figure (2), we see that the corresponding values of R are restricted to the range:

$$\frac{1}{3} \geq R \geq \left(\frac{1}{6} - \frac{1}{7}\right) \qquad (\text{adiabatic}) \ . \tag{6}$$

Non-adiabatic solutions begin in the vicinity of $\Delta m^2 \approx \text{few} \times 10^{-5}(eV)^2$ and extend down to the order of $10^{-7}(eV)^2$; here cross-sections grow as Δm^2 decreases, and for a given (small) mixing angle they lie between

$$\left(\frac{1}{6} - \frac{1}{7}\right) \leq R \leq \left(1 - \frac{1}{2}\sin^2 2\Theta\right) \approx 1 \qquad (\text{non}-\text{adiabatic}) \ . \tag{7}$$

Large-angle solutions cover roughly the same range of values for Δm^2 as non-adiabatic solutions but they yield constant values of R over this range; the actual value of R depends upon $\sin^2\Theta$

$$R = \sin^2\Theta + \left(\frac{1}{6} - \frac{1}{7}\right)\left(\cos^2\Theta\right) \tag{8}$$

and it is bounded by

$$\text{for} \begin{array}{ccccc} 0.35 & \leq & R & \leq & 0.6 \\ \frac{1}{4} & \leq & \sin^2\Theta & \leq & \frac{1}{2} \end{array} \Bigg\} \ . \tag{9}$$

Thus we see that should R turn out to be greater than $\frac{1}{3}$, then we can exclude the adiabatic solutions; values between $\frac{1}{3}$ and $\frac{3}{5}$ permit both the large-angle and non-adiabatic solutions to survive, but values greater than $\frac{3}{5}$ would allow only non-adiabatic solutions.

Now let us turn to the properties of R for the specific solutions to the ^{37}Cl anomaly. For the adiabatic solution, the range of R in eq. (6) describes reasonably well the corresponding predictions for neutrino-electron scattering, but for the non-adiabatic solution to ^{37}Cl, the actual range is much more restricted than in eq. (7). In the non-adiabatic case, the parameters $\sin^2 2\Theta$ and Δm^2 are related by

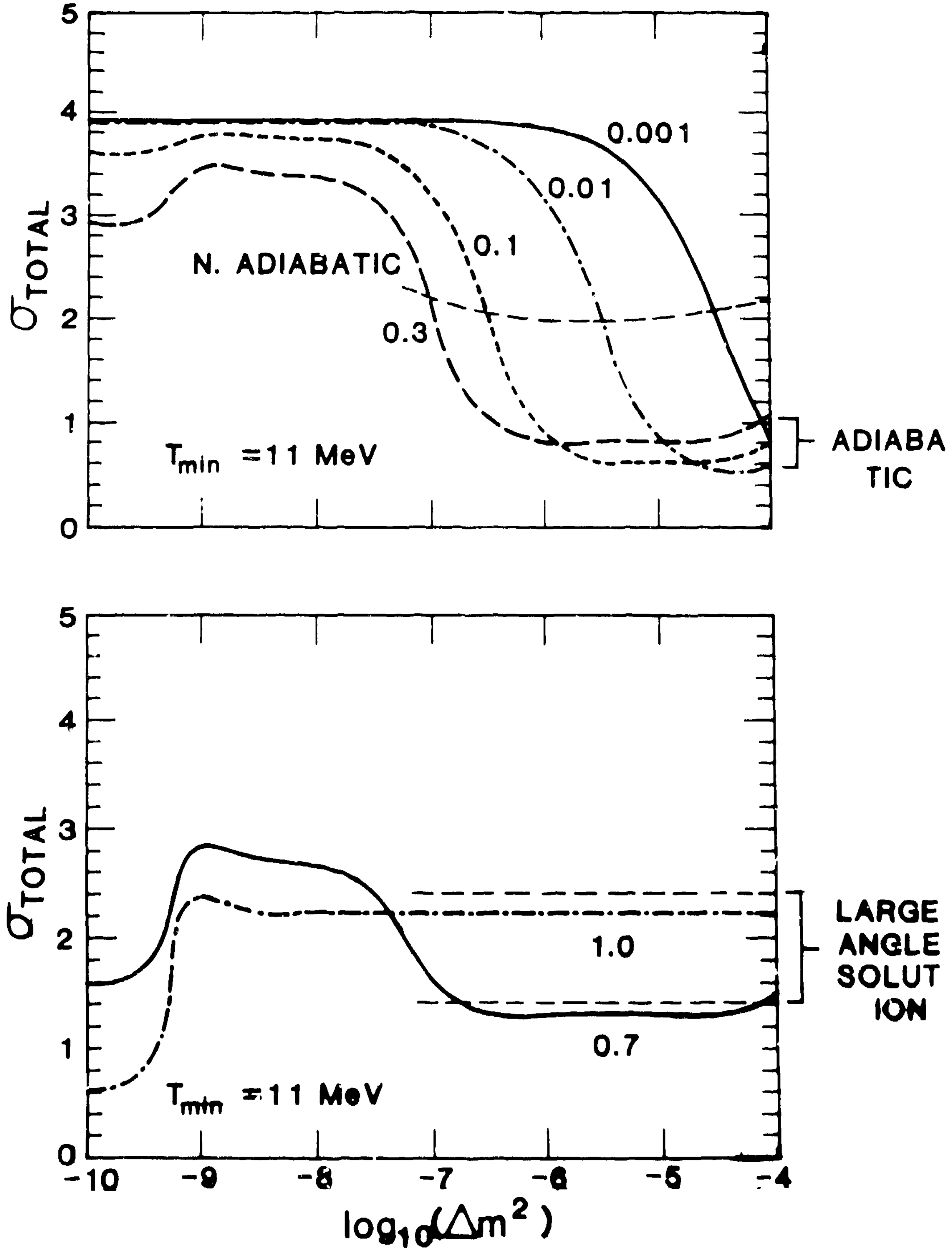

Fig. 3 Same as Fig. 2, but with minimum electron energy of 11 MeV.

in the small angle limit; from Figures (2) and (3), we see that the corresponding values of R are almost independent of Δm^2 and are restricted to the range:

$$0.44 \leq R \leq 0.5 \quad . \tag{11}$$

The large-angle solution for ^{37}Cl gives the broad range of values found in eq. (9).

From this discussion we conclude that should R fall between $\frac{1}{6}$ and $\frac{1}{3}$, the adiabatic solution for ^{37}Cl will be the correct one. Should it fall between $\frac{1}{3}$ and $\frac{3}{5}$, then the large-angle solution would be the correct one unless the actual value is in the narrow range of eq. (11). In this eventuality, both the large-angle and non-adiabatic solutions would survive and we would have to turn to another experiment, for example ^{71}Ga, to attempt to decide the issue: the large-angle solution should yield essentially the same suppression for ^{71}Ga as for ^{37}Cl, whereas the non-adiabatic solution could give a much greater suppression.

The minimum value for R between $\frac{1}{6}$ and $\frac{1}{7}$ occurs in this discussion because we have assumed that the electron-type neutrino always oscillates into non-sterile neutrinos which interact with electrons through neutral currents. A value of R less than $(\frac{1}{6} - \frac{1}{7})$ would imply that the electron-neutrino must oscillate into a neutrino-type that does not interact with electrons via standard neutral-currents. Such a neutrino is likely to be sterile./9/

Recently, the Kamiokande II collaboration/7/, has searched for solar neutrino-electron scattering in the KII water Cerenkov detector and has not observed a signal above background for recoil electrons with energies greater than 9.5 MeV. The limit on the flux of electron neutrinos (or alternatively on the cross-section), is less than $\frac{1}{2}$ the standard model prediction. This result is on the verge of probing a very interesting region for R, and we look forward to future results based on lower thresholds with much anticipation.

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