Global Analysis of Solar Neutrino Data

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The data from all solar neutrino experiments presented at the Neutrino 98 conference has been analyzed and a brief summary of the status of the two most popular neutrino solutions of the solar neutrino problem, the MSW mechanism and vacuum oscillations, is presented here. The inclusion of the recoil-electron data and of the zenith angle distribution of events in the SuperKamiokande detector, together with the routine analysis of the rates, into a global χ^2 fit impose stringent constraints on these neutrino oscillation scenarios.

I. INTRODUCTION

Analyses of solar neutrino data in the past have focused mostly on fitting the observed rates from the four pioneering experiments [1]+ [2]+ [3]+ [4] and finding the allowed regions in the relevant parameter space. The recoil electron data, as well as the zenith angle dependence of events in the Kamiokande experiment, have been also used separately to constrain, independently of the predicted ^{8}B flux, neutrino oscillation parameters. The latest data from SuperKamiokande [5]+ [6] is remarkable and unprecedented in it's precision. The time has come for a global approach in which data from the measurement of the rates in all solar neutrino experiments is combined in a single fit with data from the recoil electron spectrum and zenith angle distribution of events in this detector. This procedure results in more stringent constraints on the neutrino parameters, as well as a better understanding of the status of the neutrino oscillation solutions to the solar neutrino problem.

II. RATES ONLY

The analysis of the rates from all experiments is a first step in the global approach. The rates are probably the most robust piece of data. The experimental results together with the predictions from the standard solar model (SSM) [7] are summarized in Table.I. Different groups have shown [8] that the analysis of the rates from Homestake, Kamiokande, GALLEX and SAGE leave little hope for an astrophysical solution. The primary reason is that the combined solar neutrino data appears to indicate that the beryllium neutrinos are missing [9]. This important result is reconfirmed by the analysis of the latest solar neutrino data including the SuperKamiokande result. Allowing for all fluxes to vary as free parameters, but keeping the shape of the spectrum from individual sources unchanged, provides a poor fit to the measured rates from all solar neutrino experiments. Any such solution is ruled out at 99 % C.L. The resulting 1-, 2-, and 3-σ contours in the space of ^{8}B-^{7}Be flux are shown in Fig.1 together with the predictions of 19 solar models (see [10] for details).

TABLE I. Solar neutrino data and SSM predictions used in the analysis. The units in the second and third columns are SNU for all of the experiments except Kamiokande and SuperKamiokande, for which the measured (predicted) ^{8}B flux at the earth is given, correspondingly above 7.5 MeV and 6.5 MeV, in units of $10^6\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The ratios of the measured values to the corresponding predictions in the Bahcall-Pinsonneault SSM of Ref. [7] are given in the fourth columnwhere only the experimental errors are included. The results cited for the Kamiokande and SuperKamiokande experiments assume that the shape of the ^{8}B neutrino spectrum is not affected by physics beyond the standard electroweak model.

Experiment	Result	Theory	Result/Theory	Reference
Homestake	$2.56 \pm 0.16 \pm 0.14$	$7.7^{+1.2}_{-1.0}$	0.33 ± 0.028	[1]
Kamiokande	$2.80 \pm 0.19 \pm 0.33$	$5.15^{+1.0}_{-0.7}$	0.54 ± 0.07	[2]
SAGE	$70.3^{+8}_{-7.7}$	129^{+8}_{-6}	0.54 ± 0.06	[3]
GALLEX	$76.4 \pm 6.3^{+4.5}_{-4.9}$	129^{+8}_{-6}	0.59 ± 0.06	[4]
SuperKamiokande	$2.37^{+0.06}_{-0.05}{}^{+0.09}_{-0.07}$	$5.15^{+1.0}_{-0.7}$	0.46 ± 0.020	[6]

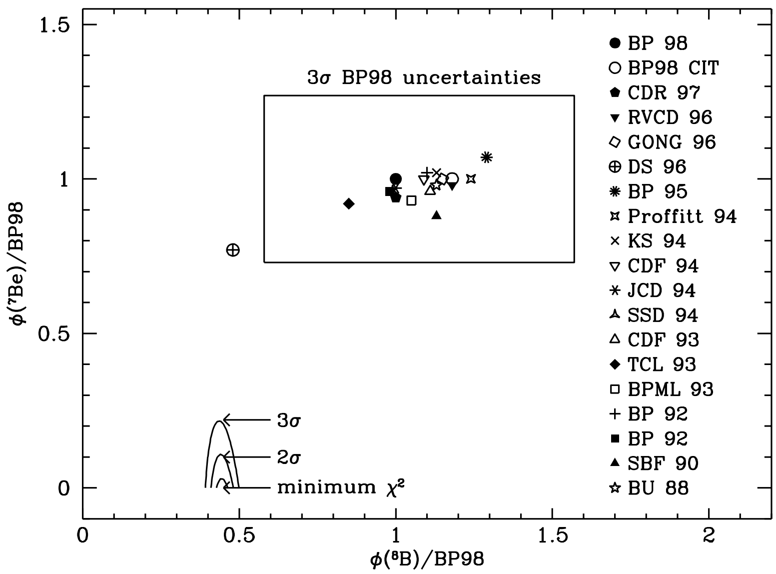

FIG. 1. Standard solar model predictions (marked by various symbols) versus a solar model independent fit (three ellipses) to all experiments assuming arbitrary neutrino flux normalization with no energy distortion.

It has been known for quite some time (see [10] and references therein) that since different experiments measure the solar neutrino flux from different sources (pp, ^{7}Be, ^{8}B, etc), and since the measured rates are not the same, the analysis of the rates only limits the allowed regions to just a few small areas in parameter space (Δm^2 - sin$^2 2\theta$) assuming either MSW transitions or vacuum oscillations as solutions to the solar neutrino problem. The MSW mechanism gives an excellent fit to the data from the rates only. The allowed regions are given in the upper panel of Fig.3. The minimum χ^2 is 1.7. Assuming 2 degrees of freedom (d.o.f.) this corresponds to a 57 % C.L. The vacuum oscillation solution provides a somewhat worse fit: minimum χ^2 = 4.3 (88 % C.L.). The allowed regions are shown in the upper panel of Fig.4. Although the MSW mechanism provides a better fit to the data, vacuum oscillations are still a viable solution to the solar neutrino problem.

III. SPECTRAL DISTORTIONS

Neutrino physics solutions predict, for a wide and plausible range of parameters, different suppression factors for different sources, thus leading to an energy dependent suppression of the solar neutrino spectrum. Remarkably, these solutions in general also predict distortions of some sort in the spectra of individual neutrino sources. Kamiokande and SuperKamiokande are the first detectors able to test this prediction for the boron neutrinos. The error bars of the Kamiokande data were not small enough for a definite conclusion to be reached about this important point. The data were consistent with no distortion but could not test the small distortions predicted within some of the parameter space, favored by the analysis of the rates. The data from SuperKamiokande after only 504 days of operation, are significantly more accurate. This is a result of both the superior statistics and truly heroic efforts on the part of the collaboration to reduce the systematic errors, including a calibration with a "portable" linac. The comparison of the measured spectrum of recoil-electrons with the one expected in the absence of oscillations reveals a distortion, namely the spectrum of recoil electrons is incompatible with an undistorted one at the 95 % C.L. The result of fitting a straight line to the recoil-electron data in SuperKamiokande is given in Fig.2. together with the range of values of the two parameters (slope (S_0) and intercept (R_0)) obtained when the neutrino oscillation parameters are varied within the corresponding allowed regions. Although the best fit points to the rates predict slope and intercept outside the 99 % C.L. ellipse, the experimental errors and theoretical uncertainties are still not small enough to rule out any of these solutions on the basis of the recoil-electron spectrum only.

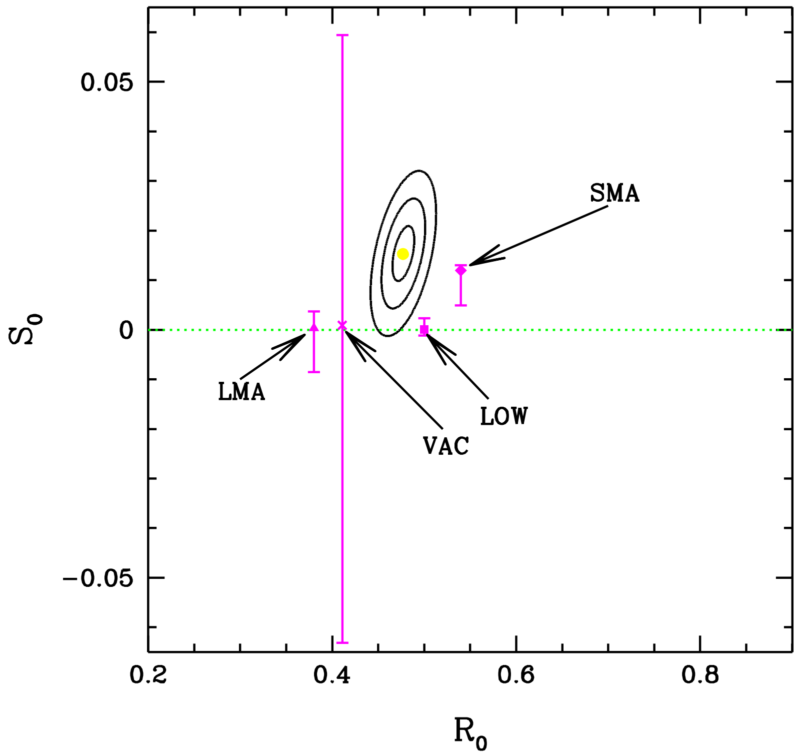

FIG. 2. The results of a fit of a straight line parameterized by an intercept (R_0) and slope (S_0) to the ratio of the measured by SuperKamiokande recoil-electron spectrum to the expected undistorted spectrum. The three ellipses are the 1-, 2- and 3-σ contours representing the fit. Also shown are the predicted values for the slope and intercept parameters in four neutrino oscillation solutions together with the respective error bars on R_0. The corresponding error bars on R_0 are not shown but they are wide enough to cross at least some of the ellipses.

IV. RATES AND RECOIL-ELECTRON SPECTRUM

When the data from the rates measured in all solar neutrino experiments are analyzed together with the data from the spectrum of recoil-electrons in SuperKamiokande, the combined χ^2 fit becomes worse than in either of the two separate fits. The MSW solution provides a minimum χ^2 of 26.5 % corresponding to a 93 % C.L. (17 d.o.f.). The 99 % C.L. allowed regions are shown in the middle panel of Fig.3. The vacuum oscillations solution gives a slightly better fit: $\chi^2_{\rm min}$ = 22.8 (84 % C.L.). The corresponding 99 % C.L. allowed regions are shown in Fig.3. The primary reason for the not particularly good fit is the mismatch between the best fit points in the two separate fits. Since the fit to the rates-only is considerably better than the fit to the spectrum, the first is driving the combined fit. Vacuum oscillations fit better the high-energy part of the spectrum near the end point of the ^{8}B spectrum. This is explained by the steeper increase of the survival probability with energy that vacuum oscillations can provide, if the parameters Δm^2 and $\sin^2 2\theta$ are chosen properly. Future refinements of the measurement of the spectrum can change the situation. A confirmation of the excess of events above 13 MeV would favor vacuum oscillations or a higher flux of hep-neutrinos (see section VI). Note also that the more recently published 708 days of data [11] show a smaller distortion of the spectrum which almost certainly will improve the overall fit.

V. RATES, ELECTRON SPECTRUM AND ZENITH ANGLE DISTRIBUTION

The inclusion of the zenith angle distribution data from SuperKamiokande is a very important step in the global fit. A significant virtue of the SuperKamiokande detector is its directionality. The direction of the electrons scattered from solar neutrinos points backwards to the sun. The zenith angle dependence of these events must have a particular shape that can be accurately calculated. Since for a wide range of masses and mixing angles the MSW effect predicts a significant regeneration of electron neutrinos, and therefore an enhanced signal at night, while neutrinos pass through the earth, the zenith angle distribution should be distorted in a specific and calculable way [12]. The comparison of the measured zenith angle distribution with the one predicted in the MSW mechanism limits the allowed parameter space. A large region is ruled out independently of the absolute flux of boron neutrinos (see Ref. [10] for references and details).

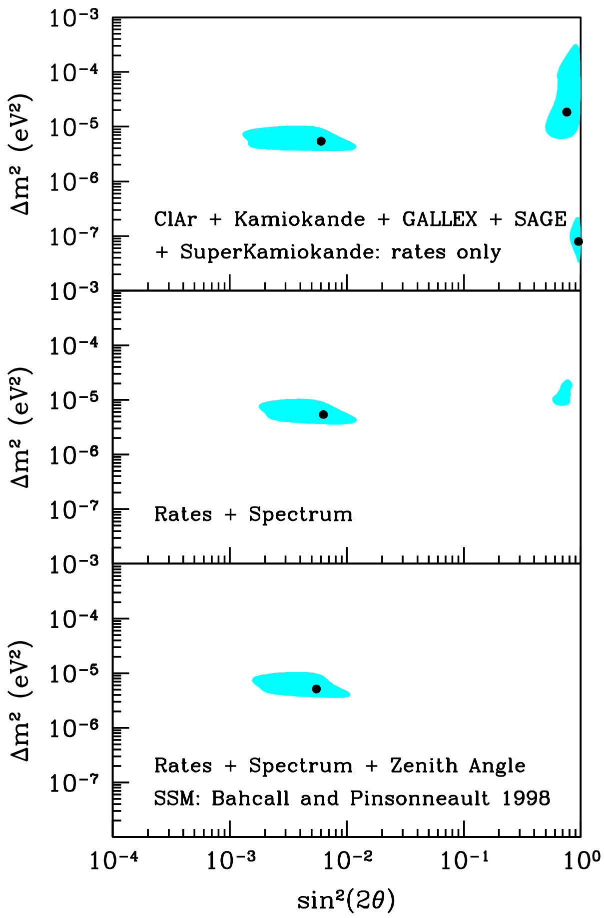

FIG. 3. Allowed regions in parameter space for resonant neutrino transitions in matter (MSW effect). The top panel is obtained by fitting only the rates from the five solar neutrino experiments. The middle panel presents the result of including the recoil-electron spectrum in SuperKamiokande and the lower panel is the final allowed region obtained by including the zenith angular distribution of recoil electrons in the global fit.

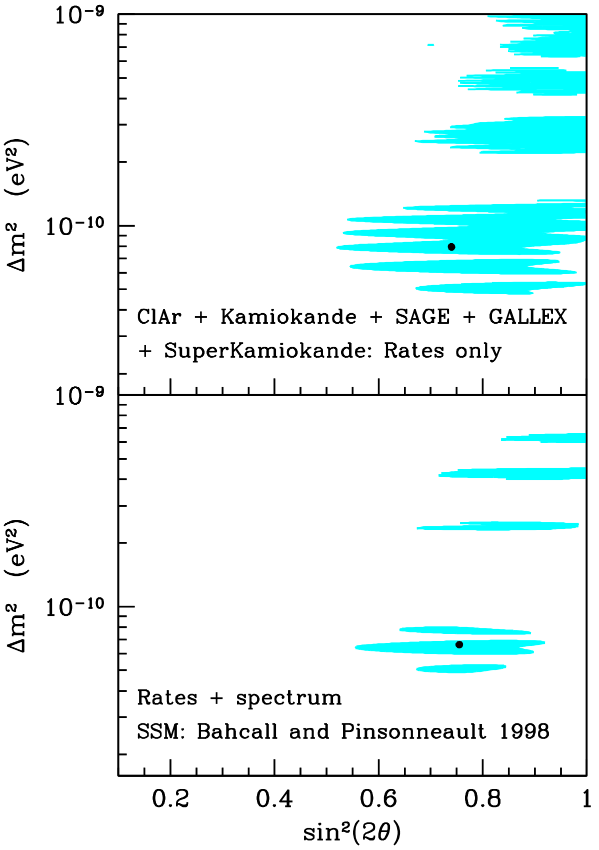

FIG. 4. Allowed regions in parameter space for neutrino oscillations in vacuum. The top panel describes the allowed regions obtained by fitting only the rates from all solar neutrino experiments. The lower panel shows the result of including the information from the recoil-electron spectrum in SuperKamiokande.

A common misconception sometimes comes up when discussing either the spectral distortions, or the zenith angle distribution of events in water-Cherenkov detectors. It is occasionally being used as an argument against neutrino physics solutions to the solar neutrino problem. Since none of these distortions has been observed, some researchers tend to make the wrong conclusion that either MSW or vacuum oscillations, or both, are either ruled out or are at least in a serious trouble. In fact both the MSW mechanism and vacuum oscillations predict a wide range of spectral distortions. The MSW effect predicts quite strong but also negligible small zenith angle distortions. The data is just not sufficient yet to rule the predicted distortions of either type, if the global best fit points are the ones chosen by nature. The predicted distortions corresponding to the best fit points can be tested at the 3-σ level with a data set at least three times larger than the present data, assuming the systematic errors can be reduced correspondingly (see Ref. [12] and [13] for details).

The global fit to the rates, recoil-electron spectrum and zenith angle distribution is not particularly good. The minimum χ^2 for MSW is 37.2 (93 % C.L. for 26 d.o.f). The resulting 99 % C.L. allowed region is shown in the lower panel in Fig.3. The two large mixing angle solutions are ruled out at this C.L. Vacuum oscillation give a minimum $\chi^2 = 28.4$ (94 % C.L., 18 d.o.f.). The C.L. for the MSW and vacuum oscillation solutions are very close and therefore none of these solutions can be claimed to be better than the other. In future the fit can go in either direction as a result of refined measurements of the spectrum and/or of the zenith angle distribution of events.

VI. HEP NEUTRINOS

In the standard solar model the flux of (hep) neutrinos from the ^{3}He(p, e$^+\nu_e$)^{4}He reaction is about 2000 times smaller than the flux of ^{8}B neutrinos. This result is due to the very small calculated cross-section for this reaction. Experientally it is very difficult, if not impossible, to measure the cross-section of the above reaction in a laboratory on earth. However, an amusing feature of this reaction is that the hep-neutrinos have a higher endpoint (18.8 MeV) than the ^{8}B (16 MeV) neutrinos. This could explain the apparent sharp rise of the recoil electron spectrum above 13 MeV (which in fact was indicated also in the old Kamiokande data), if the flux of hep-neutrinos is higher by a factor of about 20-30 [14] than in the standard solar model. The predicted spectrum assuming Δm^2 and $\sin^2 2\theta$ equal to the best fit points from a global χ^2 analysis including rates, electron spectrum, zenith angle distribution and an arbitrary hep-neutrino flux, is shown in Fig.5. By accurately measuring the spectrum above 13 MeV the SuperKamiokande collaboration can test this interesting possibility.

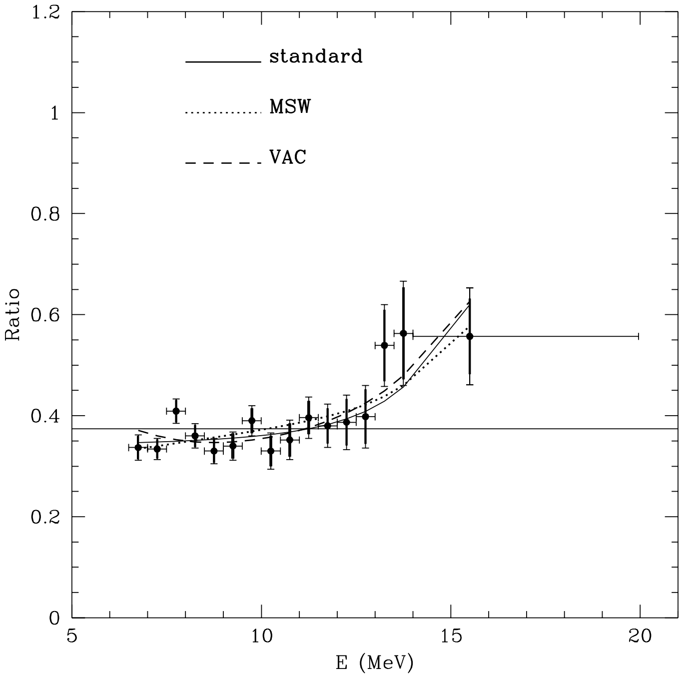

FIG. 5. The recoil electron spectrum measured by the SuperKamiokande collaboration (504 days of data) is fitted with a hep-neutrino flux 26 times larger than the one in the standard solar model. The rise of the predicted spectrum at the end-point is due to hep neutrinos

VII. CONCLUSIONS

With the latest data from the SuperKamiokande experiment a global analysis of all available solar neutrino data becomes a necessity. The first results of such an analysis are summarized above for oscillations into active neutrinos. The correspoding results for sterile neutrinos can be found in [10]. Results presented by the SuperKamiokande collaboration at this meeting [11] show smaller excess of events near the end-point of the ^{8}B spectrum. The corresponding implications for neutrino oscillation solutions of the solar neutrino problem are underway. The results are likely to change quantitatively by a small amount but are unlikely to change qualitatively the whole picture. Further studies with detectors like SNO [15], Icarus [16], Borexino [17] and Hellaz [18] remain indispensible.

VIII. ACKNOWLEDGEMENTS

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[1] B. Cleveland *et al.*, Astrophys. J. **496**, 505 (1998); B. Cleveland *et al.*, Nucl. Phys. B (Proc. Suppl.) **38**, 47 (1995); R. Davis, Prog. Part. Nucl. Phys. **32**, 13 (1994).

[2] KAMIOKANDE Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **77**, 1683 (1996).

[3] SAGE Collaboration, V. Gavrin *et al.*, in *Neutrino 96*, Proceedings of the XVII International Conference on Neutrino Physics and Astrophysics, Helsinki, edited by K. Huitu, K. Enqvist and J. Maalampi (World Scientific, Singapore, 1997), p. 14; V. Gavrin *et al.*, in *Neutrino 98*, Proceedings of the XVIII International Conference on Neutrino Physics and Astrophysics, Takayama, Japan, 4–9 June 1998, edited by Y. Suzuki and Y. Totsuka. To be published in Nucl. Phys. B (Proc. Suppl.).

[4] GALLEX Collaboration, P. Anselmann *et al.*, Phys. Lett. B **342**, 440 (1995); GALLEX Collaboration, W. Hampel *et al.*, Phys. Lett. B **388**, 364 (1996).

[5] SuperKamiokande Collaboration, Y. Suzuki, in *Neutrino 98*, Proceedings of the XVIII International Conference on Neutrino Physics and Astrophysics, Takayama, Japan, 4–9 June 1998, edited by Y. Suzuki and Y. Totsuka. To be published in Nucl. Phys. B (Proc. Suppl.).

[6] SuperKamiokande Collaboration, Y. Fukuda *et al.* Phys. Rev. Lett. **81**, 1158 (1998); Erratum-*ibid.* **81**, 4279 (1998).

[7] J. Bahcall, S. Basu, and M. Pinsonneault, Phys. Lett. B **433**, 1 (1998).

[8] N. Hata, S. Bludman, and P. Langacker, Phys Rev D **49**, 3622 (1994); S. Parke, Phys. Rev. Lett. **74**, 839 (1995); K. M. Heeger and R. G. H. Robertson, Phys Rev Lett **77**, 3720 (1996); J. Bahcall and P. Krastev, Phys. Rev. D **53**, 4211 (1996).

[9] J. Bahcall and H. Bethe, Phys. Rev. Lett. **65**, 2233 (1990).

[10] J. Bahcall, P. Krastev and A. Smirnov, Phys. Rev. D **58**, 096016 (1998).

[11] M. Smy, see talk in the Proceedings, hep-ex/9903034.

[12] J. Bahcall and P. Krastev, Phys. Rev. C **56**, 2839 (1997).

[13] J. Bahcall, P. Krastev and E. Lisi, Phys. Rev. C **55**, 494 (1997).

[14] J. Bahcall and P. Krastev, Phys. Lett. B **436**, 243 (1998).

[15] G. T. Ewan *et al.* (SNO Collaboration), Sudbury Neutrino Observatory Proposal, Report No. SNO-87-12, 1987 (unpublished); Scientific and Technical Description of the Mark II SNO Detector, edited by E. W. Beier and D. Sinclair, Queen's University Report No. SNO-89-15, 1989 (unpublished); A. B. McDonald, in *Particle Physics and Cosmology*, proceedings of the 9th Lake Louise Winter Institute, edited by A. Astbury *et al.* (World Scientific, Singapore, 1994), p. 1.

[16] A First 600 Ton ICARUS Detector Installed at the Gran Sasso Laboratory, addendum to proposal LNGS-94/99 I&II, Report No. LNGS-95/10, 1995 (unpublished); J. N. Bahcall, M. Baldo-Ceollin, D. Cline, and C. Rubbia, Phys. Lett. B **178**, 324 (1986).

[17] C. Arpesella *et al.*, BOREXINO proposal, Vols. 1 and 2, edited by G. Bellini *et al.* (Univ. of Milano, Milano, 1992); R. S. Raghavan, Science **267**, 45 (1995).

[18] G. Laurenti *et al.*, in *Proceedings of the Fifth International Workshop on Neutrino Telescopes, Venice, Italy, 1993*, edited by M. Baldo Ceolin (Padua Univ., Padua, Italy 1994), p. 161; G. Bonvicini, Nucl. Phys. B. **35**, 438 (1994).