The solar neutrino problem and the radiochemical lithium detector

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The current experimental data on the solar-neutrino problem are reviewed. The possibilities offered by the radiochemical lithium detector for solving this problem, in particular, for determining the contribution of medium-energy and boron neutrinos in chlorine and gallium detectors, are discussed. A brief description is given of the prototype of the lithium detector containing a target of 300 kg of metallic lithium, which is presently under construction at the Nuclear Research Institute of the Russian Academy of Sciences. © *1997 American Institute of Physics.* [S1063-7796(97)00101-0]

1. INTRODUCTION

Twenty-five years have passed since the first solar-neutrino detector began operation. This was the chlorine–argon detector of R. Davis, which was the first to record solar neutrinos and the first to show that there is a significant deficit of high-energy neutrinos (boron neutrinos) from the Sun.[1] This result was later confirmed at the KAMIOKANDE installation in Japan.[2] Currently, solar neutrinos are being detected by four different setups, three of which are radiochemical ones (Homestake,[3] SAGE,[4] and GALLEX[5]) and one of which is electronic—the KAMIOKANDE water Čerenkov detector. The theoretical predictions of the standard solar model are given in Refs. 6–8. It has been pointed out[6] that the predictions of various authors are in good agreement with each other when identical initial parameters are used. Here we shall use the results of Ref. 6.

In summarizing the results obtained up to now, we mention the following important features. First, it has been reliably established that the flux of boron neutrinos is lower than that predicted by theory. Second, the combined contribution of low-energy (pp) and medium-energy (pep, ^{7}Be, CNO) neutrinos is lower than that expected from the standard solar model. A purely astrophysical solution of this problem encounters serious difficulties, as shown in, for example, Refs. 9 and 10. Attempts have been made to attribute the discrepancy to neutrino oscillations in a vacuum[11–13] and to resonance enhancement of neutrinos in matter (the Mikheev–Smirnov–Wolfenstein effect).[14–16] Recently, serious arguments have been advanced[17,18] in favor of a possible correlation between the magnetic field of the Sun at low latitudes and the observed effect in the chlorine–argon experiment, which would imply spin–flavor neutrino oscillations in the solar magnetic field.[19,20] However, we are still not in a position to solve the solar-neutrino problem, because there is a severe lack of data which would allow the contribution from individual neutrino sources to be determined.

Let us list the basic questions which we need to answer in order to obtain a unique interpretation of the existing data.

1. What is the contribution of boron neutrinos and ^{7}Be neutrinos to the total flux measured by the chlorine–argon detector, and what is the contribution of pp, pep, and ^{7}Be neutrinos in the gallium detector?

2. If neutrinos from ^{7}Be are found to be suppressed, is the suppression factor the same for all medium-energy neutrinos?

3. Are there variations of the solar-neutrino flux associated with the 22-year solar cycle and/or with fluctuations of the solar magnetic field?

4. What is the spectrum of boron neutrinos at Earth compared to the generated spectrum?

5. Is there an admixture of neutrinos of other flavors, in addition to electron neutrinos, in the solar-neutrino flux at Earth?

The solution of the solar-neutrino problem requires answers to these questions, and new solar-neutrino detectors are being designed for this. The large water Čerenkov detector SUPERKAMIOKANDE in Japan started collectoing data,[21] and the SNO-Čerenkov detector containing 1000 tons of heavy water in Canada will soon go into operation.[22] If the background problems are successfully overcome, the results of the measurements at these installations will provide answers to questions 3, 4 and 5. In addition, active work is proceedings on the design of a scintillation solar-neutrino dectector, BOREXINO.[23] We think that the background problems for the scintillation detector are unusually complicated. This detector doesn't have a directionality, i.e., it can't distinguish the direction from which a neutrino arrives, like the KAMIOKANDE installation, for example. And it cannot perform a ''blank run'' which in some way mimics the case when the Sun is turned off in radiochemical experiments allowing determination of the background. It seems to us that it will be particularly difficult to deal with the background from radioactive impurities with a half-life of from several year to several hundred years, espacially if these impurities undergo purely beta decay with a spectrum mimicking the signal from 7Be neutrinos (an example is the isotope ^{113m}Cd with half-life equal to 13.6 years). Even very low concentration (about 10^{-25} g/g) of this impurity in the scintillator can simulate the effect from solar neutrinos, and there is no technique to detect the concentration of this isotope at such a low level. However, if the background problem is solved, the BOREXINO detector will be able to answer question 1 above. Now in this context let us describe the role which can be played by the lithium detector and the possibilities that it offers.

TABLE I. Solar-neutrino capture rates for chlorine and lithium detectors according to the standard solar model.

Neutrino source	Chlorine, SNU	Lithium, SNU
pep	0.22	9.2
^{7}Be	1.24	10.2
^{8}B	7.36	25.2
^{13}N	0.11	2.1
^{15}O	0.37	5.1
B sum	$9.3^{+1.2}_{-1.4}$	$51.8^{+3.5}_{-4.2}$

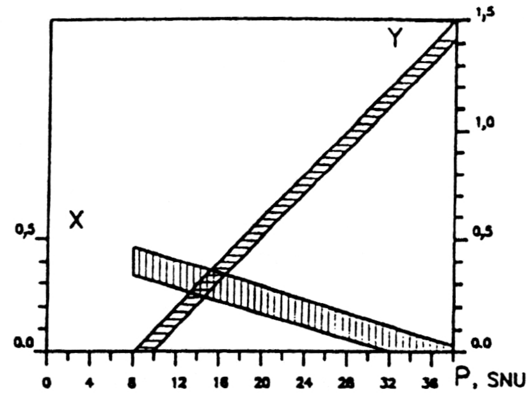

FIG. 1. Suppression factors for boron neutrinos and medium-energy neutrinos (X and Y are the ratios of the measured and calculated fluxes).

2. THE LITHIUM SOLAR-NEUTRINO DETECTOR

The study of Ref. 6 presents the calculated solar-neutrino fluxes obtained from the standard solar model taking into account the diffusion of heavy elements and helium for the improved data incorporated in the model. The solar-neutrino capture rates for chlorine and lithium detectors given in this study are presented in Table I.

Since the detection thresholds for these detectors are close, 0.8 MeV for chlorine and 0.86 MeV for lithium, the solar neutrinos giving the dominant contribution in these detectors can be split into two groups: high-energy (boron) neutrinos and medium-energy neutrinos with the effective energy corresponding to the main contribution for lithium near 1 MeV. In our opinion, understanding the degree of suppression of high- and low-energy neutrinos is very important, especially for understanding the role of such perhaps real effects as the Mikheev–Smirnov–Wolfenstein (MSW) effect[16] and also vacuum neutrino oscillations.[13] Therefore, we can sum the effects of medium-energy neutrinos for these two detectors, which gives a system of two equations in two unknowns (if the capture rate of solar neutrinos in lithium is measured):

$$\begin{cases} 7.36\cdot X+1.94\cdot Y=2.55\pm0.25 \\ 25.2\cdot X+26.4\cdot Y=P \end{cases} . \quad (1)$$

Here P is the rate of ^{7}Be production in lithium, X is the suppression factor for boron neutrinos, and Y is the suppression factor for medium-energy neutrinos. The equations involve only the measurement errors. The uncertainties in the theoretical predictions are mostly canceled when the factors X and Y are used. A small uncanceled term remains, owing to the difference of the values from different medium-energy sources. The first equation of this system, describing the result of the chlorine–argon measurements, gives bounds on the values of X and Y: $1\geqslant Y\geqslant 0$ and $0.40\geqslant X\geqslant 0.05$.

It should also be noted that for the chlorine–argon detector we have used the average value over the entire measurement time. If the indications of an anticorrelation with the solar magnetic field are subsequently confirmed, it will be necessary to take average values over smaller time intervals. However, since here the important thing is to describe the general approach to the problem, we neglect the detailed analysis.

The system of equations (1) has the trivial solution

$$\begin{cases} X=0.46\pm0.045-0.013\cdot P \\ Y=0.05\cdot P-0.44\pm0.043 \end{cases} . \quad (2)$$

In Fig. 1 we show the regions corresponding to these equations. We see that the expected result from the lithium detector, which can be combined with that from the chlorine detector in this scenario, lies in the range from 8 to 38 SNU. It should also be noted that the maximum value of X obtained here is 0.4, which coincides within 1σ with the result (0.45 ± 0.08) obtained at the KAMIOKANDE setup; the lithium detector should give 8–10 SNU of the solar neutrinos. This case is apparently of special interest, because it implies strong suppression of medium-energy neutrinos with the attendant possibility of fixing the parameters of neutrino oscillations.

Estimates indicate that a lithium detector containing 10 tons of metallic lithium, which we are currently developing, will measure the solar-neutrino flux with an accuracy of order 12% in a single measurement, assuming that the solar-neutrino capture rate is 20 SNU. Of course, this will be possible only if ^{7}Be detection is successfully accomplished using a cryogenic detector. We think that this detection technique will be effective, owing to the rapid progress in this area after the pioneering studies of Fiorini *et al.*[24] For example, the Vitale group in Genoa has already demonstrated[25] the reliable detection of the M peak of Mn from a ^{55}Fe source with an energy release of 82 eV. We plan to make four measurements in one year using the lithium detector, so that we should be able to obtain an accuracy of order 6%. As seen from Fig. 1, this will single out a very narrow region in X and Y.

This result will shed light on the correctness of combining the results from the chlorine detector and the KAMIOKANDE setup. It will make it possible to interpret the results of the gallium experiment unambiguously, and, if the BOREXINO setup is operating by this time, it will be possible to find out if the suppression factor for medium-energy neutrinos is the same as that for ^{7}Be neutrinos by comparing the results obtained from the BOREXINO and lithium detectors. Therefore, if all the above detectors operate successfully, we will obtain answers to all the questions listed above, thereby significantly advancing the knowledge in this area. This shows yet again that in the study of solar neutrinos different measurements supplement each other, and only the success-

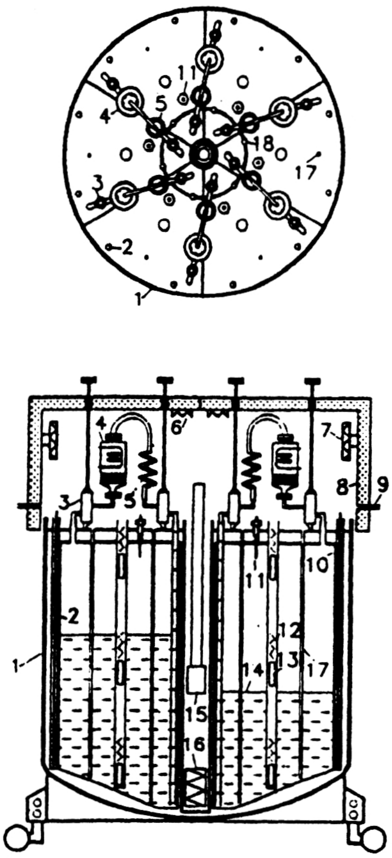

FIG. 2. Schematic diagram of the lithium detector. (1) Outer covering; (2) heaters; (3) valves for liquid lithium; (4) collectors; (5) lithium–air heat-exchange coils; (6) temperature-sensitive elements; (7) heaters; (8) thermal insulation; (9) pipes for air intake and exhaust; (10) lithium sections; (11) level indicator; (12) temperature-sensitive elements; (13) heaters; (14) melted lithium; (15) neutrino source; (16) heater; (17) channels for heat-sensitive elements.

ful operation of all the detectors will allow the solar-neutrino problem to be solved.

3. THE EXPERIMENTAL TECHNIQUE

In our development of the lithium-detector technique, we have reached the stage of constructing a prototype detector containing 300 kg of metallic lithium. The basic design is shown in Fig. 2. In addition to solving problems of a purely methodological nature, we plan to use this setup to perform the following measurements.

1. We will measure the ^{7}Be yield from cosmic-ray hadrons at sea level. This will provide proof of the feasibility of extracting beryllium atoms, produced in the target material by an external source, from metallic lithium, and will also allow us to determine the optimal depth at which the detector should be located for subsequent measurements. The idea is that the detector must be located at a depth large enough that the effect of cosmic rays will not suppress the effect of an artificial neutrino source, but also small enough to be able to obtain a calibration point with good statistics for the muon background curve as a function of depth.

2. We will measure the ^{7}Be yield from cosmic-ray muons at this depth.

TABLE II. Basic calibration characteristics of the lithium detector.

Target mass	300 kg metallic lithium
Geometrical factor	42.2 cm
Source activity	37 kCi
(ν,e^-) cross section	$2.25\cdot 10^{-44}$ cm^2
Detection efficiency	71%
Exposure time	240(4·60) days
Total number of pulses	400
Statistical error	5%

3. We will calibrate the lithium target using an artificial neutrino source based on ^{65}Zn. Here we should note that an advantage of the lithium detector over other solar-neutrino detectors is the small target mass of only ten tons. This also makes the lithium detector very attractive for performing calibrations using an artificial neutrino source. Such an experiment will be possible even with the prototype containing only 300 kg of lithium. The accuracy of the measurement will be 5% for a source with an activity of only 37 kCi, which can be obtained by bombarding 3.5 kg of naturally occurring zinc with a thermal-neutron flux of 3.2×10^{15} n/cm^2 sec for 30 days. In Table II we give the calculated characteristics for the calibration of a lithium target using a detector consisting of six sections, five of which are filled with lithium, and one of which is empty. This allows extraction by means of the pressure-transfer of lithium from a filled section to an empty one via a beryllium collector.

The geometrical factor given in Table I is $G=(1/4\pi)\int dV/r^2$. We obtain the production rate $N=\sigma nSG$, where σ is the cross section of the (ν,e^-) reaction, n is the number of target atoms per cubic centimeter, and S is the source strength. The successful performance of an experiment using an artificial neutrino source with ^{7}Be detection by means of a cryogenic detector will be decisive proof of the feasibility of the technique for performing a full-scale experiment to detect solar neutrinos.

Currently, we are at the stage of assembling the prototype lithium detector. We have designed and are building a version of the sectional detector as a single body, which will significantly speed up the beryllium extraction process and which also possesses a number of purely technical advantages. As mentioned above, an important component of this work is progress in ^{7}Be detection using a cryogenic detector.

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[1] R. Davis, Jr., in *Frontiers of Neutrino Astrophysics*, edited by Y. Suzuki and K. Nakamura (Universal Academy Press, Stanford, Calif., 1993).
[2] Y. Suzuki, in *Proc. of the Sixth Intern. Workshop on Neutrino Telescopes*, Venice, February 1994, edited by M. Baldo-Ceolin.
[3] B. T. Cleveland *et al.*, Nucl. Phys. (Proc. Suppl.) **B38**, 47 (1995).
[4] J. N. Abdurashitov *et al.* (SAGE Collaboration), Phys. Lett. **328B**, 234 (1994).
[5] P. Anselmann *et al.* (GALLEX Collaboration), Phys. Lett. **357B**, 237 (1995).
[6] J. N. Bahcall and M. H. Pisonneault, Preprint IASSNS-AST 95/24, Institute for Advanced Study, Princeton (1995).
[7] S. Turch-Chieze and I. Lopes, Astrophys. J. **408**, 347 (1993).
[8] G. Shaviv, Nucl. Phys. (Proc. Suppl.) **B38**, 81 (1995).

[9] J. N. Bahcall and H. A. Bethe, Phys. Rev. D **47**, 1298 (1993).
[10] N. Hata, S. Bludman, and P. G. Langacker, Phys. Rev. D **49**, 3622 (1994).
[11] B. Pontecorvo, Zh. Éksp. Teor. Fiz. **33**, 549 (1957) [Sov. Phys. JETP **6**, 429 (1958)]; **34**, 247 (1958) [**7**, 172 (1958)].
[12] S. M. Bilenky and B. Pontecorvo, Phys. Rep. **41**, 225 (1978).
[13] P. I. Krastev and S. T. Petcov, Preprint IASSNS-AST 95/40, Institute for Advanced Study, Princeton (1995).
[14] L. Wolfenstein, Phys. Rev. D **17**, 2369 (1978).
[15] S. P. Mikheev and A. Yu. Smirnov, Yad. Fiz. **42**, 913 (1985) [Sov. J. Nucl. Phys. **42**, 579 (1985)].
[16] P. I. Krastev and A. Yu. Smirnov, Phys. Lett. **338B**, 282 (1994).
[17] D. S. Oakley, H. B. Snodgrass, R. K. Ulrich, and T. K. VanDeKor, Astrophys. J. **437**, 63 (1994).
[18] V. N. Obritko and Yu. R. Rivin, Izv. Akad. Nauk SSSR, Ser. Fiz. **59**, 110 (1995) [Bull. Acad. Sci. USSR, Phys. Ser.].
[19] M. B. Voloshin and M. I. Vysotskiĭ, Yad. Fiz. **44**, 845 (1986) [Sov. J. Nucl. Phys. **44**, 544 (1986)].
[20] M. B. Voloshin, M. I. Vysotskiĭ, and L. B. Okun', Zh. Éksp. Teor. Fiz. **91**, 754 (1986) [Sov. Phys. JETP **64**, 446 (1986)].
[21] T. Kajita, *Physics with the Super Kamiokande Detector*, Report 185-89-2, ICRR (1989).
[22] G. Ewan *et al.*, *The Sudbury Neutrino Observatory Proposal*, SNO-87-12 (1987).
[23] C. Arpesella *et al.*, *The BOREXINO Proposal*, edited by G. Bellini, R. Raghavan *et al.* (Univ. of Milan, Milan, 1992).
[24] A. Alessandrello, C. Brofferio, D. V. Camin *et al.*, in *Proc. of the Third Conf. on Low-Temperature Detectors for Neutrinos and Dark Matter*, Gran Sasso, Italy.
[25] F. Fontanelli, M. Galeazzi, F. Gatti *et al.*, in *Proc. of the Intern. Conf. LTD-6*, Interlaken, Switzerland, 1995.

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