New Solar-Neutrino Flux Calculations and Implications Regarding Neutrino Oscillations

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The results of new calculations of solar-neutrino fluxes are presented; the fluxes are obtained from detailed solar models that make use of improved opacities and nuclear-physics cross sections. By evaluating known uncertainties in the predicted capture rate for the ^{37}Cl solar-neutrino experiment, we find that the ratio of theoretical to (best-estimate) observed capture rate lies in the range 4.0 to 2.6. These results constitute a strong constraint on models of neutrino oscillations if the entire discrepancy is ascribed to neutrino oscillations.

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The discrepancy[1,2] between the observed and the predicted capture rate in the ^{37}Cl solar-neutrino experiment has been used recently by a number of authors as evidence for neutrino oscillations.[3-5] We show below that the ratio between the current best-estimate theoretical value and the rate observed[2] by Davis and his associates is a factor of 3.3. This result would require, if there were no uncertainties in the theoretical prediction, that all mixing angles be near their most-effective values if there are only three neutrino flavors. It is important therefore to know what are the uncertainties in the theoretical predictions of the solar-neutrino–capture rate for the ^{37}Cl experiment. Fortunately, we have for some years been carrying out extensive calculations, including new information regarding low-energy nuclear-physics experiments and improved calculations of opacity, just in order to be able to evaluate the uncertainties in the the theoretical capture rate (and to update our last published calculations which appeared[6] in 1973).

We summarize our detailed results in this Letter and show below that the calculated uncertainty in the current best-estimate theoretical value is about 1.5 solar neutrino units (SNU) (excluding unknown systematic errors in experimental parameters). This corresponds to a range for the ratio of predicted to (best-extimate) observed capture rates of 4.0 to 2.6. The above result provides a strong constraint on models of neutrino mixing if the entire discrepancy is attributed to neutrino oscillations.[3-5]

We have calculated evolutionary models for the sun, using the same procedures as described in previous papers in this series.[6] We have taken advantage of more recent experimental data to determine different best estimates for several nuclear parameters that enter the solar-neutrino calculations in an important way. These parameters are (S_{ij} are the usual[7,8] low-energy cross-section factors) $S_{11} = 3.82\times10^{-25}$ MeV b (for the p-p reaction)[9]; $S_{33} = 5.5$ MeV b [for[10] the reaction ^{3}He(^{3}He, $2p$)^{4}He]; $S_{34} = 0.52$ keV b [for[11] ^{3}He(α, γ)^{7}Be]; and $S_{17} = 0.031$ keV b [for ^{7}Be(p,γ)^{8}B].[12] The recognized sources of error and uncertainty are of order 2% for S_{11} and of order 10% for all the other quantities given above. Systematic errors may, of course, be much larger. We return to this point below. Other nuclear parameters are less important (or are known more accurately) and are the same as in previous papers in this series.[6]

We have used new opacities[13] computed for the estimated solar composition and physical conditions by the Los Alamos Scientific Laboratory (LASL) and Lawrence Livermore Laboratory (LLL) groups with the aid of their independent opacity codes. This is the first time we have been able to compare opacities from both groups. The opacities have been computed by the LASL group using the astrophysical opacity library for a variety of assumed solar compositions and by the LLL group for a best-estimate set of elemental abundances based on the Ross-Aller compilation.[14] The present LASL opacities are somewhat higher (~ 15% in the central regions of the solar model) than the values we used in 1973. The principal reasons for this change are the replacement of hydrogenic photoelectric cross sections by nonhydrogenic cross sections and the inclusion of a large number of weak absorption lines, many of them in spectral regions that previously had a low extinction. The LLL opacities are in generally good agreement with the present LASL results for the Ross-Aller composition, although somewhat smaller (~ 10%) in the central regions of the models and somewhat larger (~ 15%) in the outer regions.

Our main results are shown in Table I. The standard model, Case 1, was computed using new LASL opacities for the Ross-Aller composition and the best-guess nuclear parameters described above. The predicted capture rate is 7.8 SNU.

We have also calculated a LLL standard model in which we used opacities obtained from the LLL code but kept all other parameters the same as in our standard (Case 1) model. The LLL standard model yielded a predicted counting rate of 6.85 SNU. The reasonable agreement between the results obtained with the LASL and with the LLL opacities increases our confidence in the calculated capture rates.

We conclude that the present best estimate for the predicted capture rate in the ^{37}Cl experiment is about 7 to 8 SNU, with an uncertainty of order 0.5 SNU due to uncertainties in opacities.

Case 2 of Table I shows the fluxes that would be obtained from a model that used the old (1973) nuclear parameters and solar luminosity, but the new LASL opacities. We find 6.5 SNU for this case.

The present results are significantly higher than our last joint published estimate.[6] By comparing with the results of Ref. 6, we have shown that about 1.8 SNU of this increase is due to the increase in the interior opacity (for the same assumed composition) discussed above. The remaining difference (~ +0.4 SNU) between the prediction of the present standard model and the result obtained[6] in 1973 is due to changes (differing signs) in a number of parameters. Some of the largest of these changes are a 0.5-SNU increase due to an improved value for the bolometric luminosity of the sun[15]; a 1.3-SNU increase suggested[9] by new measurements of the lifetime of the neutron and more complete mesonic corrections for the proton-proton reaction rate; and a decrease of about 1 SNU resulting mainly from laboratory studies of the ^{37}Ca decay and other mass-37 nuclei and a recalculation of the corresponding neutrino-capture cross sections.[16]

There has recently been a great deal of discussion of the value of the cross-section factor for the reaction ^{3}He$(\alpha,\gamma)^7$Be at low energies. The smallest value that has been discussed in recent

TABLE I. Neutrino fluxes and predicted capture rates for the ^{37}Cl experiment. All fluxes are given in units of 10^{10} cm^{-2} sec^{-1} at Earth's surface. The predicted capture rates (given in the last column) are in SNU ($=10^{-36}$ captures per target atom per second) and were all computed using the neutrino absorption cross sections given in Ref. 16. The primordial helium abundance computed for all of these models is $Y=0.24$.

Case	p-p	p-e-p (10^{-2})	^{7}Be (10^{-1})	^{8}B (10^{-4})	^{13}N (10^{-2})	^{15}O (10^{-2})	$\Sigma(\varphi\sigma)\vert_{^{37}\mathrm{Cl}}$ (SNU)
1 (standard)	6.1	1.5	4.1	5.85	4.6	3.7	7.8
2 (old parameters; new opacity)	6.0	1.45	4.2	4.82	3.5	2.6	6.5
3 ($S_{34}=0.34$ keV b)	6.2	1.55	2.8	3.99	4.7	3.7	5.5

conferences is 0.34 keV b, a value for which Rolfs[17] has provided some preliminary and tentative justification on the basis of a much smaller energy dependence for $S_{34}(E)$ at the lowest energies. We show in row 3 of Table I the neutrino fluxes and capture rate appropriate to this low value for the $^3He(\alpha,\gamma)^7Be$ cross-section factor, all other parameters being held at their best-estimate values (we have used LASL opacities); the expected counting rate is 5.5 SNU if $S_{34}=0.34$ keV b. If, following Nagatani, Dwarakanath, and Ashery,[11] we were to take $S_{34}=0.61$ keV b, then the predicted counting rate would be 8.85 SNU.

Experiments to remeasure at low energies and with modern technology[18] the cross-section factors for the reactions $^3He(\alpha,\gamma)^7Be$ and $^7Be(p,\gamma)^8B$ are needed because of the sensitivity of the predicted capture rate to these cross sections. Of the total 7.8 SNU predicted by our standard solar model (Table I), 6.3 SNU is from the reaction $^7Be(p,\gamma)^8B$, last studied in detail experimentally in 1969 in an unpublished work.[19] The total capture rate for the ^{37}Cl experiment also depends sensitively upon the cross-section factor for the reaction $^3He(\alpha,\gamma)^7Be$ approximately as follows: predicted capture rate $\propto S_{34}^{+0.8}$.

We have also carried out[8] a number of detailed calculations of the sensitivity of the predicted counting rate to uncertainties in the chemical abundances of individual heavy elements. If we treat the uncertainties quoted by Ross and Aller[14] in the individual abundance determinations as if they were independent standard deviations from separate Gaussian distributions (which they certainly are not, but we do not know what is a better assumption), we find an uncertainty of ± 1 SNU because of estimated uncertainties in the surface abundances of heavy elements.

All of the solar models discussed above yield an initial helium abundance $Y=0.24$ in satisfactory agreement with the result obtained from conventional big-bang cosmological models.

The current best estimate for the expected capture rate is 7.3 SNU (see Table I), in accidentally good agreement with the value of 7.5 ± 3 SNU obtained in 1968 at the time when the first experimental results[20] from the ^{37}Cl experiment became available. All of the subsequent fluctuations in the predicted counting rate due to changes in parameters and opacities have resulted in best-estimate capture rates that are within the above-quoted limits. We estimate a current uncertainty of about 1.5 SNU in the predicted capture rate due to statistical uncertainties in nuclear physics parameters (see above) and to uncertainties in opacity (see above estimates for LASL and LLL opacities) and abundances (see above and Ref. 14).

The observations[5] yield a rate of production of ^{37}Ar in the detector of 2.2 ± 0.4 SNU. The production rate due to solar neutrinos could be smaller than the above-quoted value if the background (which is currently being remeasured[5,21] with greater accuracy) is larger than presently estimated.

What are the implications of this analysis relative to the possibility of neutrino oscillations?[22,23]

It is likely that the discrepancy between theory and observation of the solar-neutrino flux is a factor of order 3. This large discrepancy would be significantly reduced if the suggestions of neutrino oscillations based on the laboratory data[3-5] are confirmed. Nevertheless, it is difficult to resolve the difference between predictions based on the solar models and observations solely by invoking neutrino oscillations, if there are only three kinds of neutrinos coupled to each other.[22-24] The recent analyses of reactor experiments[1-3] suggest about a factor-of-2 reduction when properly averaged[23] over the broad energy spectrum of the solar neutrinos.

Even if the effects at the relatively small separations available with laboratory (i.e., reactor and accelerator) experiments turn out not to be measurable on Earth, it will still be important to test for much smaller neutrino oscillation masses with the large separations available in solar-neutrino experiments. Experiments based upon the astronomically secure flux of p-p neutrinos can provide important, otherwise unobtainable, information on neutrino oscillations[23]; the astrophysical uncertainties in the p-p flux are only of order a few percent[6] (provided only that the sun is currently burning nuclear fuel at its average rate) since these neutrinos constitute a good measure of the bolometric luminosity of the sun. The proposed ^{71}Ga and ^{115}In experiments[25,26] are sensitive to proton-proton neutrinos and could be used to measure neutrino-oscillation masses of order 10^{-6} eV,[23] provided laboratory experiments are performed first to calibrate the detectors with known sources of neutrinos.[16,26,27] The ^{37}Cl experiment is not as suitable for studying neutrino oscillations because of uncertainties in the prediction of the (relatively small) ^8B neutrino flux.

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[1]J. N. Bahcall and R. Davis, Jr., Science 191, 264 (1976).

[2]R. Davis, Jr., BNL Report No. BNL 50879, 1978 (unpublished), Vol. 1, p. 1.

[3]V. Barger, K. Whisnat, D. Cline, and R. J. N. Phillips, to be published.

[4]F. Reines, H. Sobel, and E. Pasierb, to be published.

[5]V. Barger, K. Whisnat, D. Cline, and R. J. N. Phillips, to be published; V. Barger, K. Whisnat, and R. J. N. Phillips, to be published.

[6]J. N. Bahcall, W. F. Huebner, N. H. Magee, Jr., A. L. Merts, and R. K. Ulrich, Astrophys. J. 184, 1 (1973), and references quoted therein. For comparison, the value obtained in 1973 was 5.6 SNU; this was revised downward to 4.7 SNU by J. N. Bahcall, Astrophys. J. Lett. 216, L115 (1977), as a result of the recalculation of the neutrino absorption cross sections. J. N. Bahcall, N. A. Bahcall, and G. Shaviv, Phys. Rev. Lett. 20, 1209 (1968), calculated 7.5 ± 3 SNU at the time the first observational results became available.

[7]See, e.g., D. D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis* (McGraw-Hill, New York, 1968); W. A. Fowler, G. R. Caughlan, and B. A. Zimmerman, Annu. Rev. Astron. Astrophys. 5, 525 (1967).

[8]The analysis that justifies these parameter choices, as well as the new opacity calculations, is described in a paper in preparation by the authors of the present Letter.

[9]This estimate takes account of the recent remeasurement of the neutron lifetime by J. Byrne, J. Morse, K. F. Smith, F. Shaikh, K. Green, and G. L. Greene, Phys. Lett. 92B, 247 (1980), the calculation of mesonic corrections by C. Bargholtz, Astrophys. J. Lett. 233, L161 (1979), and the estimate of the nuclear matrix element by J. N. Bahcall and R. M. May, Astrophys. J. 155, 501 (1969).

[10]M. R. Dwarakanath, Phys. Rev. C 9, 805 (1974).

[11]This value is obtained by a reanalysis (see Ref. 8) of the original data by K. Nagatani, M. R. Dwarakanath and D. Ashery, Nucl. Phys. A128, 325 (1969), and P. D. Parker and R. W. Kavanagh, Phys. Rev. 131, 2578 (1963).

[12]See P. D. Parker, BNL Report No. BNL 50879, 1978 (unpublished), Vol. 1, p. 77, and Ref. 8.

[13]For a general description of the calculations, see W. F. Huebner, BNL Report No. BNL 50879, 1978 (unpublished), Vol. 1, p. 107, and references quoted therein.

[14]J. E. Ross and L. H. Aller, Science 191, 1223 (1976). See also S. H. Lubow, R. K. Ulrich, M. F. Argo, W. F. Huebner, N. H. Magee, and A. L. Merts, Bull. AAS 10, 676 (1978). The values given by Ross and Aller are in agreement, taking account of the substantial uncertainties, with the Lambert-Warner composition used by us in earlier papers in this series. The solar surface ratio of heavy elements to hydrogen is, according to Ross-Aller, $Z/X = 0.0228$.

[15]C. Frolich, in *Solar Output and its Variation*, edited by O. R. White and G. Newkirk (Colorado Associated Press, Boulder, Col., 1977), p. 105. We have used $S_{\odot} = 1377$ W m^{-2} in the present calculations.

[16]J. N. Bahcall, Rev. Mod. Phys. 50, 881 (1978).

[17]C. Rolfs, private communications.

[18]See the lectures by C. A. Barnes, in Experiments in Nuclear Astrophysics, Erice School on Nuclear Astrophysics, 1980 (to be published).

[19]R. W. Kavanagh, T. A. Tombrello, J. M. Mosher, and D. R. Goosman, Bull. Am. Phys. Soc. 14, 1209 (1969).

[20]R. Davis, Jr., D. S. Harmer, and K. C. Hoffman, Phys. Rev. Lett. 20, 1205 (1968).

[21]E. L. Fireman, in Proceedings of the Sixteenth International Conference on Cosmic Rays, Kyoto, Japan, 1979 (to be published).

[22]B. Pontecorvo, Zh. Eksp. Teor. Fiz. 53, 1717 (1967) [Sov. Phys. JETP 26, 984 (1968)]; V. Gribov and B. Pontecorvo, Phys. Lett. 28B, 493 (1969).

[23]See J. N. Bahcall and S. C. Frautschi, Phys. Lett. 29B, 623 (1969). A number of current discussions, as well as the earliest papers on this subject (Ref. 18), do not take account of the broad energy spectrum of the solar neutrinos.

[24]S. Nussinov, Phys. Lett. 63B, 201 (1976).

[25]J. N. Bahcall, B. Cleveland, R. Davis, Jr., I. Dostrovsky, J. C. Evans, Jr., W. Frati, G. Friedlander, K. Lande, K. Rowley, D. Stoner, and J. Wenesser, Phys. Rev. Lett. 40, 135 (1978).

[26]R. S. Raghavan, Phys. Rev. Lett. 37, 259 (1976).

[27]L. W. Alvarez, Lawrence Radiation Laboratory, Physics Notes, Memorandum No. 767, 1973 (unpublished).

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