product for the carbon-nitrogen cycle to be 3.5×10^{-35} $\sec^{-1}$ per Cl^{37} atom, based on this cycle being the only source of the sun's energy. With the limit given above one can conclude that less than 9 % of the sun's energy is produced by the carbon-nitrogen cycle.

It is possible to improve the sensitivity of the present experiment by reducing the background of the counter. However, background effects from cosmic-ray muons will eventually limit the detection sensitivity of the experiment at its present location. Detailed studies of the cosmic-ray background are in progress.

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PRESENT STATUS OF THE THEORETICAL PREDICTIONS FOR THE ^{36}Cl SOLAR-NEUTRINO EXPERIMENT*

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The theoretical predictions for the ^{37}Cl solar-neutrino experiment are summarized and compared with the experimental results of Davis, Harmer, and Hoffman. Three important conclusions about the sun are shown to follow.

The experiment of Davis, Harmer, and Hoffman,[1,2] designed to detect solar neutrinos with a ^{37}Cl target, has prompted a continuing investigation[3-7] of the accuracy with which the flux of neutrinos produced by nuclear reactions in the sun's interior can be predicted. We report here calculations of the solar-neutrino fluxes made using the more accurate rate for the proton-proton reaction recently derived by Bahcall and May[8] and the improved determination of the abundance ratio of heavy elements to hydrogen recently obtained by Lambert and Warner.[9] We also discuss some of the important, recognized uncertainties that influence the predictions of the solar-neutrino fluxes and conclude that the present results of Davis, Harmer, and Hoffman[1] are not in obvious conflict with the theory of stellar structure. We show, however, that a counting rate of less than $0.03 \times 10^{-35}/{}^{37}Cl$ atom sec would cast serious doubt on the correctness of current ideas con-

Table I. Some important quantities for five solar models.

Model	S_{11} (10^{-25} MeV b)	X	Y	Z	T_c (10^6 °K)	ρ_c (10^2 g/cm^3)
A	3.36	0.715	0.258	0.027	15.7	1.7
B	3.36	0.768	0.217	0.015	15.2	1.6
C	3.78	0.764	0.221	0.015	14.9	1.5
D	3.93	0.800	0.190	0.010	14.5	1.4
E	3.63	0.740	0.240	0.020	15.2	1.6

cerning the way nuclear fusion reactions produce the sun's luminosity. We then enumerate some of the most important experiments that are necessary to limit the uncertainties in the theoretical predictions. Finally, we show that the experiment of Davis, Harmer, and Hoffman implies the following: (1) that the sun does not derive most of its radiated energy from the CNO cycle, (2) the heavy-element mass fraction in the sun is probably less than 2 %, and (3) the primordial helium content was of the order of 22 % by mass. The latter two inferences depend upon the validity of current theoretical models for the solar interior.

In Table I we list some important quantities derived from five evolutionary models for the sun that were obtained by numerically integrating the relevant equations of stellar structure[10] as described in Ref. 7. In Table II we give the neutrino fluxes and predicted counting rates for the experiment of Davis, Harmer, and Hoffman[1,2] that were calculated from the same solar models. The quantities X, Y, Z, T_c, and ρ_c of Table I are, respectively, the primordial hydrogen mass fraction, the primordial helium mass fraction, the heavy-element (atomic number greater than four) mass fraction, the central temperature, and the central density. It is assumed that the heavy-element abundance observed on the surface of the sun is the same as the primordial (and present) heavy-element abundance in the center of the sun. This assumption requires further theoretical investigation, but is supported by the agreement between our inferred helium abundance [cf. conclusion (3)] and rocket measurements of the helium abundance in solar cosmic rays (cf. Ref. 9). The neutrino fluxes from the various neutrino-emitting isotopes[11,12] are given in columns two through six of Table II; the neutrinos from the reaction $^1H+{}^1H \rightarrow {}^2D+e^- +\nu$ are represented by the flux $\varphi_\nu(^1H+{}^1H)$ and those from the reaction $^1H+{}^1H+e^- \rightarrow {}^2D+\nu$ are represented by the flux $\varphi_\nu(^1H+e^-+{}^1H)$. The quantities $\sum_{\rm all}(\varphi_\nu\sigma_\nu)$ and $\sum_{\rm all\ but\ B}(\varphi_\nu\sigma_\nu)$ are the predicted capture rates per ^{37}Cl atom. The cross sections are taken from the work of Bahcall.[5,12] All of the models listed in Tables I and II have a luminosity, after 4.7×10^9 yr of nuclear burning, that equals the solar luminosity[13] of 3.83×10^{33} erg/sec within ±0.2 %; all of the nuclear parameters, with the exception of the rate of the proton-proton reaction, are taken from the recent review by Fowler, Caughlan, and Zimmerman.[14]

Model A was constructed for a heavy-element mass fraction of $Z=0.027$ and a low-energy cross-section factor[14] for the proton-proton reaction of $S_{11}=3.36\times10^{-25}$ MeV b. A similar model was regarded as their most probable one by Bahcall and Shaviv[7] and has been used by Davis, Harmer, and Hoffman[1] in discussing the results of their experiment. The present model A, and

Table II. Neutrino fluxes and counting rates from five solar models.

Model	$10^{-7}\varphi_\nu(^8B)$ (cm^{-2} sec^{-1})	$10^{-9}\varphi_\nu(^7Be)$ (cm^{-2} sec^{-1})	$10^{-9}\varphi_\nu(^{13}N)$ (cm^{-2} sec^{-1})	$10^{-10}\varphi_\nu(^1H+{}^1H)$ (cm^{-2} sec^{-1})	$\varphi_\nu(^1H+e^-+{}^1H)$ (10^8 cm^{-2} sec^{-1})	$\sum_{\rm all}(\varphi_\nu\sigma_\nu)$ (10^{-35} sec^{-1})	$\sum_{\rm all\ but\ B}(\varphi_\nu\sigma_\nu)$ (10^{-35} sec^{-1})
A	1.35	4.7	1.1	6.0	1.6	2.1	0.27
B	0.69	3.4	0.3	6.2	1.7	1.1	0.16
C	0.47	2.9	0.2	6.4	1.7	0.77	0.13
D	0.25	2.1	0.1	6.5	1.7	0.44	0.10
E	0.70	3.7	0.4	6.3	1.6	1.1	0.17

all other models discussed in this Letter, differ from the one selected as most probable by Bahcall and Shaviv[7] in that three rather small effects not previously included have been taken account of in the present work. These effects are the Debye-Hückel correction to the equation of state,[15] the contributions of electron conduction to the opacity,[16] and partial conversion of ^{16}O to ^{14}N via the reactions $^{16}\mathrm{O}(^1\mathrm{H},\gamma)^{17}\mathrm{F}(\beta^+\nu)^{17}\mathrm{O}(^1\mathrm{H},\alpha)^{14}\mathrm{N}$. The net result of the inclusion of these effects has been to increase the predicted counting rate calculated from model A by about 15% compared with the most probable model of Ref. 7.

Since the work of Bahcall and Shaviv was completed, two important experimental data have become available. The two data are the improved measurement of the mass ratio of heavy elements to hydrogen on the surface of the sun[9] and the redetermination of the neutron lifetime.[17] Model B was constructed using the mass ratio of heavy elements to hydrogen of 0.019 obtained by Lambert and Warner,[9] and the traditional value[14] for the proton cross-section factor, $S_{11}=3.36\times10^{-25}$ MeV b. Note that $\sum_{\mathrm{all}}(\varphi\sigma)$ is lowered by about a factor of 2 when the newer composition is used. Model C was constructed using the values of the low-energy proton cross-section factor $S_{11}=3.78\times10^{-25}$ MeV b and its logarithmic derivative $(d\ln S_{11}/dE)_{E=0}=11.2\ \mathrm{MeV}^{-1}$, derived recently by Bahcall and May.[8] The result quoted above differs from the previous value for S_{11} mainly because Bahcall and May used the newer lifetime measurement for the neutron[17]; small changes were also introduced because of their more accurate calculations of the nuclear matrix element and beta-decay phase-space factors, and their treatment of radiative corrections. Note that the 12.5% increase in S_{11} from model B to model C decreased the predicted counting rate by 32%.

Model C yields our most probable theoretical results. We find that[18]

$$\sum_{\mathrm{all}}(\varphi\sigma)|_{\text{most probable}} = (0.75\pm0.3)\times10^{-35}\ \mathrm{sec}^{-1}\frac{S_{17}}{0.043\ \mathrm{keV\ b}}. \quad (1)$$

The quantity S_{17} is the low-energy cross-section factor for the reaction $^7\mathrm{Be}(^1\mathrm{H},\gamma)^8\mathrm{B}$. If we use in Eq. (1), as we have throughout Table II, the value of 0.043 keV b obtained for S_{17} by Parker,[19] the most probable predicted counting rate is about a factor of 2 larger than the probable upper limit set by Davis, Harmer, and Hoffman.[1] However, the preliminary results of Vaughn et al.[20] suggest that Parker's value may require revision downward. The error estimate in Eq. (1) was made by constructing models D and E in which Z and S_{11} were chosen equal to their probable extreme values.[8,9] The opacities used in all of the above-described calculations were obtained in the usual way[7] by interpolation within published tables of Cox, Stewart, and Eilers.[21] As an additional check, J. N. Stewart and A. N. Cox kindly supplied us with opacity tables for precisely the solar composition of heavy elements that was obtained by Lambert and Warner.[9] A recalculation of model C using this more direct approximation to the solar opacity yielded values for the most important quantities that were within a few percent of the values listed in Tables I and II.

It is apparent from Eq. (1) that there is no irreconcilable discrepancy between our predictions and the experiment of Davis, Harmer, and Hoffman[1] when the uncertainties in the various parameters that enter the calculation are taken into account.[22]

The neutrino flux from the reaction $^1\mathrm{H}+{}^1\mathrm{H}+e^-\to{}^2\mathrm{D}+\nu$ is very nearly model independent as may be seen in Table II. Hence we can predict a lower limit on the counting rate that is consistent with current ideas about the way nuclear fusion reactions produce the sun's liminosity. We find (cf. Ref. 12) that

$$(\varphi\sigma)_{\text{only } ^1\mathrm{H}+{}^1\mathrm{H}+e^-\to{}^2\mathrm{D}+\nu} = 0.03\times10^{-35}\ \mathrm{sec}^{-1}. \quad (2)$$

It is important to measure accurately several crucial quantities in order that the relationship between the observed and predicted counting rates may more clearly reveal the adequacy or inadequacy of the current theory of stellar interiors. The quantities of most importance are (1) the neutron lifetime from which the axial-vector coupling constant, and hence the rate of the proton-proton reaction, are determined,[8] (2) the low-energy cross section for $^7\mathrm{Be}(^1\mathrm{H},\gamma)^8\mathrm{B}$ to which the predicted counting rate is directly proportional, and (3) the heavy-element abundance on the surface of the sun.

We now list several conclusions that can be drawn from the results of the experiment of Davis, Harmer, and Hoffman. First, the sun does not derive most of its radiated energy from the CNO cycle since this implies, independent of the theory of stellar models (cf. Ref. 5), a counting rate of 3.5×10^{-35} sec^{-1}/^{37}Cl atom. Second, if the usual theory of stellar interiors is correct, then the heavy-element abundance Z must be less than 2% by mass in order for the predicted neutrino-capture rate not to exceed the observed value. Third, assuming the measured value[9] of $Z/X \cong 0.019$, we can deduce the primordial helium abundance of the sun by requiring that the calculated luminosity of our solar models equals, after 4.7×10^{9} yr of nuclear burning, the observed solar luminosity. We find $Y=0.22\pm0.03$, where the uncertainty in Y reflects the uncertainties in the parameters that characterize various solar models.

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