Report

NSAC Solar Neutrino Subcommittee

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Table of Contents

I. EXECUTIVE SUMMARY

This NSAC Subcommittee has been charged with reviewing the scientific importance of new solar neutrino experiments and with recommending the best and most cost effective way to do such experiments in order to obtain sufficient information to resolve the present solar neutrino problem. The charge to the Subcommittee also mentioned reviewing the quantitative aspects of a gallium detector and considering the practicality of collaboration with groups outside of the United States.

Study of neutrinos emitted by the sun is of great scientific importance. The development of an understanding of our sun, the closest star in the universe, has long been an important and fascinating scientific endeavor. Neutrinos are the only particles that escape directly from the solar interior, and thus they provide the most immediate probe of the deep interior of the sun.

An experiment designed to measure the flux of neutrinos from the core of the sun has been in nearly continuous operation for over 20 years by Davis and collaborators. This experiment, using a ^{37}Cl detector, has observed only one third the number of neutrino captures expected on the basis of the best available theoretical solar models combined with the assumption that the neutrinos traverse the sun-earth distance without changing their character. We refer to this major discrepancy as the "solar neutrino problem."

Because ^{37}Cl detects mainly high energy neutrinos from the decay of solar ^{8}B, its predicted detection rate is extremely sensitive to conditions inside the sun, and it is not possible to determine whether the cause of this discrepancy lies in the theoretical solar models or in the intrinsic properties of neutrinos. A solar neutrino detector with very different sensitivities than the ^{37}Cl detector is needed to help resolve this problem. The important p-p component of the solar neutrino flux (to which the ^{37}Cl detector is completely insensitive) depends essentially on the solar luminosity and is almost completely independent of conditions inside the sun; therefore their detection will provide a test that could distinguish between the suggested causes of the present problem. The solution to the problem will have vital consequences both for astrophysics − by providing a necessary experimental check on our theoretical understanding of stellar interiors and stellar evolution − and for particle physics − by providing a test for neutrino mass differences with a sensitivity unavailable in purely terrestrial measurements.

The solar neutrino problem is a major anomaly in the understanding of the physical world in the 1980's, cutting across the disciplines of astronomy and astrophysics, elementary particle physics, nuclear chemistry and physics, and the interface between high temperature atomic physics and plasma physics. Because our present understanding of the production and possible oscillatory

nature of solar neutrinos is inadequate, calling into question our beliefs about the environment in which energy production takes place in our sun, the ages of stars and galaxies, and the nature and stability of fundamental particles, at least one new experiment would help resolve the present impasse in finding the source of the solar neutrino problem. The only presently feasible experiment sensitive to the crucial p–p neutrino flux is a ^{71}Ga radiochemical experiment.

Therefore, we make the following recommendations:

The scientific questions currently surrounding the solar neutrino problem can best be addressed by a detector using 30 metric tons of gallium. The technical feasibility of a ^{71}Ga detector for measuring the p–p neutrino flux has been demonstrated. A gallium experiment should be initiated immediately with sufficient funding to acquire a practical fraction of the 30 tons of gallium which we deem necessary to complete this experiment.

It is important that systematic development work on detector backgrounds commence very soon in the U.S., and that substantial experience and statistical information on detector backgrounds be available by the time gallium is being procured.

Due to the interdisciplinary nature of the problem a special funding initiative from a governmental level above the normal ones appropriate for the standard compartmentalization of science is required.

In order to avoid further delays in these crucial measurements it is important that consideration of this project should proceed, for the present, on the assumption that its funding must come from within the United States, but at the same time the question of resuming collaboration with the European GALLEX group should be kept open. It is not likely to be a sensible or practical allocation of resources to have two gallium experiments carried out in parallel.

We further point out that complementary experiments are likely to be important and recommend that development of new detection methods should be encouraged. Direct counting experiments capable of providing spectral information, directional information, or sensitivity to neutral–current interactions (e.g. an experiment employing a D_2O Cherenkov detector) are particularly important.

II. INTRODUCTION

This report is in response to a request from the Department of Energy and the National Science Foundation to the Nuclear Science Advisory Committee (NSAC) to convene a subcommittee to review the scientific importance of new solar neutrino experiments, and to recommend the best approach for carrying out scientifically justified experiments. The full charge to the subcommittee is appended.

Study of neutrinos emitted by the sun is of great scientific importance

4

for several reasons. The development of an understanding of our sun, the closest star in the universe, has long been an important and fascinating endeavor. Energy production in our sun is essential to life on earth. It has been realized for over half a century that chemical or gravitational forces are inadequate for generating the energy radiated by our sun. Only nuclear processes release sufficient energy to account for its observed energy output over the long period of time – about 5 billion years – that our solar system has been in existence.

The burning of hydrogen by nuclear fusion in the deep interior of the sun is believed to be the primary source of solar energy. Neutrinos are the only particles that escape directly from the solar interior, and thus they provide the most immediate probe of the deep interior of the sun.

A unique experiment by Davis and coworkers, employing a ^{37}Cl detector and designed to measure the flux of neutrinos from the sun, has been in nearly continuous operation for over 20 years. The results from this experiment are very surprising: the number of neutrino-induced events is about a factor of three lower than one expects from models that reproduce the other properties of the sun. This observation implies either that we do not have an adequate understanding of the nature of processes inside the sun (or the initial conditions of its evolution) and hence of stellar processes in general, or the neutrinos, particles basic to the fundamental electro-weak interaction do not have a conserved flavor, but rather oscillate between several possible states. Either result would have fundamental consequences in two branches of physics: particle physics and astrophysics.

Since the Davis experiment uses chlorine as the detecting material, it is sensitive only to high energy neutrinos, mainly from ^{8}B, whose rate of production is extremely sensitive to the interior temperature of the sun and hence to the details of solar models. The yield of low energy solar neutrinos from the initial step in hydrogen fusion in the sun is, on the other hand, essentially independent of models, depending only on the solar luminosity. If the yield of these neutrinos is also low by a factor of three, then it would be difficult to blame the problem on the sun, and the probability would be high that the neutrinos do not have a conserved flavor. If, on the other hand, the yield of low-energy neutrinos is consistent with the solar luminosity, then the problem is likely to lie in the physics of the sun. In this document we recommend funding of an experiment that is sensitive to these low energy neutrinos and which should therefore allow a major advance in our understanding of this problem.

We note that in 1981 a panel chaired by G. T. Seaborg concluded that a proposed gallium solar neutrino project had outstanding scientific merit and recommended that the project be approved and authorized to proceed.

Several methods may be used to detect solar neutrinos; none of them is easy because of the very small probabilities with which neutrinos interact

with normal matter. In general, the detection techniques may be grouped into two categories: radiochemical methods and direct methods. Radiochemical detectors are based on counting the radioactivity from neutrino-induced transmutation of the detector material.

Radiochemical detectors differ depending on the length of time over which they integrate the neutrino flux, and in their neutrino energy thresholds. The latter determine the sensitivity of a detector to different components of the neutrino energy spectrum. The ^{37}Cl and ^{98}Mo detectors are primarily sensitive to the high energy neutrinos from decay of ^{8}B in the sun; the ^{37}Cl detector is, to a lesser extent, also sensitive to neutrinos from ^{7}Be electron capture. The ^{81}Br detector is mainly sensitive to ^{7}Be neutrinos and the ^{71}Ga and ^{205}Tl detectors are mainly sensitive to the low energy ("p-p") neutrinos from the basic $p + p \rightarrow {}^{2}H + e^{+} + \nu$ reaction. For radiochemical detectors, one must extract, by chemical techniques, a very few atoms of the new species from an enormous reservoir of the original species when typical yields are a few atoms in 10^{30} of detector material. The difficulties in this method are the production of the host material in sufficient purity and quantity, the efficiency of the chemical separation, and the efficiency with which the very few atoms can be detected. While extremely sensitive, radiochemical techniques indicate only that the candidate isotope has been produced; they provide no direct indication of the source of the neutrino that produced it or even whether it was produced in a neutrino interaction or a background reaction.

In direct methods one relies on the pulses produced when a neutrino is scattered by an electron, or induces an inverse beta decay, or disintegrates a nucleus by a weak neutral-current interaction. In this last case, the weak neutral-current interaction is sensitive to all types of neutrinos and may play a special role in establishing the existence of neutrino oscillations. From the characteristics of the process one may, with suitable techniques, infer the original neutrino's energy, the direction from which it came, and even the kind of neutrino that caused the event. While such experiments can be more informative, they are also considerably more difficult because of very low rates and the attendant backgrounds. Nevertheless, there are serious endeavors evolving towards the design of such experiments. They are likely to play an increasingly important role in the future. The direct counting detectors that are currently being discussed produce a nearly instantaneous signature of a neutrino interaction, either due to neutrino scattering off electrons (Cherenkov, cryogenic liquids, and silicon bolometry) or due to neutrino-induced disintegration of the deuteron (D_2O Cherenkov detectors), or due to prompt radiation following neutrino capture (^{115}In detector).

III.   THE SOLAR NEUTRINO PROBLEM

The initial priority of the Committee was to convince itself that there

is indeed a solar neutrino problem. Since the result of the ^{37}Cl experiment is a single number, the experiment itself does not help one to determine the causes of the discrepancy. It could reside in an uncertainty in the detector efficiency, in the rates of the nuclear reactions that produce neutrinos in the sun, in the solar physics that determines the temperature and density at the center of the sun, or in the particle physics describing the behavior of neutrinos in traveling from the sun to the earth.

The Cl detector is well understood. This topic has been investigated in detail in the past, and the subcommittee felt it could add nothing of significance to these investigations. In principle, further light could be shed on system efficiency by irradiation with a terrestrial, reactor produced, neutrino source such as ^{65}Zn; however this relatively long and costly process does not address the more likely uncertainties involved in the problem.

The precision of estimates of the cosmic ray background at the site of the ^{37}Cl experiment are based on a relatively long extrapolation from background measurements at several depths. Better background measurements alone, however, cannot resolve the discrepancy with the standard solar model since even assuming that the background is zero still leaves a statistically significant difference between prediction and observation.

A. The Standard Solar Model and its Uncertainties

In this section we review the standard model of the sun on which the prediction of a 5.8 SNU* flux for the ^{37}Cl experiment is based; we indicate possible uncertainties in the model and hence in its prediction of the flux. The solar model is the prototype for all stellar models because observations (which yield precise information on its mass, luminosity, radius, surface conditions, rotation rate, etc.) provide strong constraints on its interior. Unlike other stars, the sun's age is constrained by the deduced ages of the earth, moon, and meteorites and is taken to equal that of the earth.

The standard solar model assumes the entire structure to be in quasi-static equilibrium, without significant centrifugal forces or magnetic pressures. The sun is assumed not to have been subject to significant accretion or loss of matter since its formation. Its mechanical and thermal structure is then determined by the balance of pressure forces against gravity and by the transport of energy produced by thermonuclear burning, primarily the conversion of hydrogen into helium. Input needed for integrating the equations of stellar structure includes the elemental composition, the nuclear burning rates, and the opacity of the solar material. The particle interactions involved are thermonuclear reactions, knowledge of which is discussed in the following section C, together with quantum-mechanical electromagnetic interactions of the ions, electrons and radiation. The thermal structure is constrained by the requirement that energy be released by

* One SNU is defined as 10^{-36} captures/(target-atom sec).

7

nuclear reactions in the central core at a rate equal to the luminosity.

The primordial solar abundance of helium of about one atom in thirteen is inferred from the helium abundance in old stars and in prominences in the solar corona (where the gas is hot enough to excite the atomic lines from helium). This abundance is consistent with cosmological considerations on primordial helium. [We note that the solar corona, whose expansion to form the solar wind yields gases at the orbit of earth, is generally markedly deficient in helium (one helium in forty atoms).] Over the inner two-thirds of the solar radius the calculations of the solar interior indicate a temperature that declines outward from the center less rapidly than the adiabatic temperature gradient. Such a gradient implies that the gas is stably stratified and probably does not mix vertically, in spite of the rotation of the core. Hence the present helium abundance in the central core is inferred to be equal to the primordial abundance plus the helium accumulated from thermonuclear burning of hydrogen, yielding about one helium atom out of six at the present time. Helium is produced and accumulates in the core with the passage of time, so that the mean molecular weight, which is set primarily by the relative abundance of H and He, increases with age.

The opacity of the solar material limits the rate of heat transport and plays a key role in determining the internal structure. Calculation of the opacity is a complicated and sophisticated application of quantum mechanics to a dense gas composed of hydrogen, helium, and a number of heavier elements, with the heavier elements playing an important role because of their bound electrons and large charge. Uncertainties in the opacities must be regarded as a very significant uncertainty in the standard solar model. For example, presently calculated opacities do not take into account any effects which are non-linear in the radiation field, even though the fluctuating electromagnetic fields in the solar interior are on the scale of atomic fields, nor do they include effects of density correlations in the solar material. Variation of the input opacity could lower the interior temperature (for given luminosity and surface temperature) and hence could lower the rate of ^{8}B neutrino production.

While the structure in the standard model is taken to be quasi-static, matter in the outer third of the solar radius is in a state of active convection. Uncertainties remain in our understanding of the structure of convective zones and more importantly in the energy-momentum transport by convection; one consequence is that the measured radius does not provide an important constraint on the interior model. The core of the sun is in rotation, and at smaller distances the rotation rate is thought to increase inward, although the gradient of this increase is not precisely known. The theoretical possibilities of various linear and nonlinear thermal and thermo-nuclear oscillations, waves, and overturning have been investigated for the central core, but none has been shown to work under the theoretical conditions

expected there. If, however, the supposedly stably stratified radiative interior of the sun has turned over two or three times during the life of the sun, so that the present helium abundance in the central core is near the primordial value of 1 in 13, then the central temperature would be lowered by a few percent, bringing the theoretical prediction close to the ^{37}Cl results. The mixing would double the life of the sun on the main sequence, with similar consequences for other stars, and for the estimated age of the universe.

B. Uncertainties in the Physics of Elementary Particles

At present, it is believed that the fundamental weak interaction of the neutrino with the other elementary particles via the charged current is well understood at solar neutrino energies. Since this is the interaction upon which the ^{37}Cl experiment is based, we do not expect to find an explanation of the solar neutrino problem in terms of a failure in the sector of the fundamental interaction processes. However, an explanation in terms of the properties of the neutrino is entirely possible and would be of great interest.

From laboratory experiments we have no conclusive evidence that neutrinos have mass; however, this eventuality is by no means excluded theoretically. Should the neutrino have a finite mass, then it is possible that the original neutrino, produced in the sun in an electron-type neutrino state, undergoes a transformation or decay during the passage from creation to detection on earth 10^{11} meters away. The other components in an altered state of the neutrino would be undetectable by the ^{37}Cl detector, because it is sensitive (via the charged current) only to the electron-type neutrino. Terrestrial experiments do not permit testing these transformation hypotheses in a range of energy, mass, and distance appropriate to the sun.

The possible uncertainties in the physics of elementary particles are thus of a qualitatively different sort than those discussed above in the standard solar model. They would require new phenomena: neutrino oscillations and possibly new lepton types ("generations"). Only a new solar experiment, complementary to the ^{37}Cl measurement, can isolate the source of the solar neutrino problem as lying in the area of particle physics.

C. Nuclear Reaction-Rate Uncertainties in the Sun

The mechanism responsible for energy generation in the sun is universally believed to be nuclear fusion, whereby free protons combine to form ^{4}He nuclei, releasing the relatively large alpha-particle binding energy in the process. This "p-p chain" consists of a string of different nuclear reactions, all initiated by the fundamental weak process

$$p + p \rightarrow d + e^{+} + \nu_e$$

which generates ν_e at energies up to 0.42 MeV. Other steps of the chain also produce neutrinos, most importantly ^{3}He$(\alpha,\gamma)^{7}$Be and ^{7}Be$(p,\gamma)^{8}$B.

The Subcommittee considered the rates of reactions producing neutrinos in some detail. This consideration was motivated by the spate of recent results for the important reactions bearing on the problem and in particular by one recent measurement which, if correct, would have lead to appreciably lower predicted detection rates in the ^{37}Cl detector. The Subcommitte performed its own evaluation of the present status of these rates and heard an independent evaluation of them. The common result of these evaluations is that the nuclear rates are well enough known to establish that uncertainties in them are not a likely explanation of the discrepancy. Some experiments which appeared to offer at least a partial explanation have been shown to be in error. It appears that a conspiracy of errors would be necessary to reduce the discrepancy below the three-standard-deviation level. The predicted rate of the ^{37}Cl experiment of 5.8±2.2 SNU (3σ uncertainty) as determined by Bahcall et al. (1985) may be compared to the measured result of 2.1±0.3 SNU (1σ uncertainty).

D. Uncertainties in Nuclear Cross Sections Determining Detector Efficiencies

Nuclear cross sections also enter into the evaluation of the efficiency of the various detectors. In some cases, these cross sections can be calculated from the properties of the basic interactions (e.g., $\nu_e + e^-$ scattering in the case of some direct counting detectors) while in others they must be deduced from other information. In the case of the ^{37}Cl and ^{71}Ga radiochemical detectors the cross sections are strongly constrained by the results of beta decay and (p,n) charge exchange measurements, and their uncertainties are smaller than or comparable to other uncertainties. For certain other detectors (e.g., ^{81}Br, ^{98}Mo, ^{115}In) the uncertainties are larger, roughly ±20 to ±30% and need to be reduced if these experiments are to provide sharp constraints. It appears likely that this can be achieved, and ±15% errors seem to be a reasonable goal. Finally, in other cases (e.g., ^{205}Tl), it is not clear whether the desired accuracy can be obtained.

IV. SCIENTIFIC IMPORTANCE

A. Importance for Astrophysics

The theory of the internal structure of the stars and of their evolution has led to results that are of basic importance to modern astrophysics in at least three areas. First, the major classes of stars, characterized by their observed luminosity and surface temperature, have been identified with specific phases of stellar evolution for stars differing in mass, age and initial composition. Second, the theory has provided a general picture for the origin of the elements heavier than helium. Third, it has led to a determination of the ages of the stars in clusters, from the youngest galactic clusters to the oldest globular clusters. The latter set a lower limit for the age of the galaxy, which is a decisive input into cosmological models.

The solar neutrino problem is cause for concern with regard to the adequacy of the physical models basic to these results. The sun cannot be excused as being peculiar. Its mass falls in the middle of the range of stellar masses, its composition is normal for its galactic surroundings, and its present stage of evolution corresponds to a most stable and simple structure according to present theory. If something is wrong with the physics of the standard solar model, much may be much wrong in many stellar models.

Over the last decade astrophysicists have concentrated a major effort on attempts to resolve the solar neutrino problem by modifying the solar model. No such new solar model that can be properly justified by known physical processes has been found. A new experiment, most effectively one that counts directly the p-p neutrinos emitted by the core of the sun, would provide valuable new direction in resolving the present impasse in solving the solar neutrino problem.

A resolution of the solar neutrino problem requiring modification of our understanding of the properties of neutrinos could also have profound implications for other problems in astrophysics where neutrinos play a vital role, including gravitational collapse and supernovae, galactic structure, the early universe and its later evolution and large scale structure.

B. Importance for Elementary Particle Physics

Although more than fifty years have elapsed since the postulation of the neutrino in beta decay, the neutrino still retains its position as the most enigmatic of particles. On the one hand, it has apparently simple and unique properties; for example, it undergoes only weak interactions with the rest of matter in the universe. Consequently it has played a crucial role in our present understanding of the weak interactions in general and in their unification with the electromagnetic interaction specifically. On the other hand we have little understanding of why the neutrino should have this simplicity. Are neutrinos truly massless? Do they obey absolute conservation of lepton number and "flavor" (i.e., electron-, muon-, tau-type)? If they have mass, do they mix in analogy to other particles such as the quarks or the neutral kaons? Are there only three flavors? At the present time these questions, are wide open and represent an important uncertainty which needs to be resolved as part of any solution to the solar neutrino problem.

The search for answers to questions about the properties of neutrinos and their role in unification theories represents a major and intense activity in elementary particle physics. For example, in "grand unified theories," which attempt to unify the electroweak interaction with the strong (and even in some cases, the gravitational) interaction, the neutrino plays a key role.

The current experimental program to answer these fundamental issues is terrestrially limited in the sense that both the sources and the detectors of neutrinos are located on the earth or in its atmosphere; in certain crucial

areas this program does not cover the required range of parameters (mass differences or mixing angles). Of particular significance are searches for the phenomenon of neutrino oscillations.

Neutrino oscillations would result if there were non-degenerate mass states and non-conservation of lepton flavor numbers. A near degeneracy of these mass states can only be detected in very long baseline experiments because the length scale over which the oscillation occurs is inversely proportional to the difference of the squared masses.

The simplest oscillation is one which occurs between flavor states (for example from ν_e to ν_μ). However, there might be yet undiscovered new flavors (ν_x), more complicated oscillations (e.g., ν_e to $\bar{\nu}_e$), or matter-induced oscillations which could escape detection in any experiments fully based on earth. No combination of earth based experiments could definitively exclude these possibilities. Reactor and accelerator experiments will not be able to measure mass-squared differences much less than 0.01 eV^2. Present and future proton decay detectors using neutrinos produced in the earth's atmosphere are limited to the order of 10^{-4}-10^{-5} eV^2.

Thus the existing limitations of terrestrial sources and techniques emphasize the unique and perhaps critical role which experiments utilizing solar neutrinos can play. Among the notable features of the sun are its great distance (10^{11} meters leading to a mass sensitivity of 10^{-12} eV^2) and its purity as a source of initial neutrino flavor.

V. RECOMMENDATION FOR PERFORMING A GALLIUM EXPERIMENT

A. Rationale for a Gallium Solar Neutrino Detector

As discussed above, the only experiment thus far performed (the ^{37}Cl experiment of Davis et al.) is sensitive primarily to the very high energy neutrinos from the decay of ^{8}B. These neutrinos result from an end component of a weak branch of the p-p chain involved in only 10^{-4} of the proton to helium fusions and their flux is extremely sensitive to solar temperature and to the details of solar models.

In order to advance on the solar neutrino problem observationally, it is important to have a detector that is sensitive to the low energy p-p neutrinos which initiate the nuclear fusion chain. Unlike the ^{8}B neutrinos, whose flux depends exceedingly strongly on the internal temperature of the sun, the flux of p-p neutrinos, being directly proportional to the solar luminosity, is nearly model independent; therefore the detection of these neutrinos provides a test that helps distinguish between the particle-physics and solar-physics solutions to the present problem. Put very simply, if p-p neutrinos are detected at only about 1/3 the expected rate then the present problem most probably lies with particle physics and the properties of neutrinos; if p-p neutrinos are detected at close to the expected rate then the present problem

most probably lies with the solar models and the properties of the solar interior.

The neutrino capture reaction on ^{71}Ga,

$$\nu_e + {}^{71}\text{Ga} \rightarrow {}^{71}\text{Ge} + e^-$$
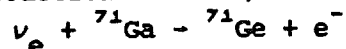
is an ideal basis for a p-p-neutrino detector. It has a low Q-value (-233 keV), and its capture rate is primarily sensitive to p-p neutrinos. The physics of the capture process is well understood, and the chemistry of the ^{71}Ge extraction has been the subject of extensive studies at Brookhaven. The ^{71}Ga detector offers the best chance to resolve the challenge to solar physics which has been presented by the Davis experiment. It should be pointed out, however, that in a question this complex and multifaceted, there is a possibility that the nature of neutrino oscillations may not be readily separable from the solar models. It may eventually take more than a single experiment to resolve the particle-physics and astrophysics questions unambiguously. The wavelength of the possible neutrino oscillations would be energy dependent and may also be affected by the matter in the sun; it is possible that these uncertainties would combine with the variety of individual uncertainties in solar models to leave ambiguities. However, at the present time a gallium experiment is clearly the best step towards the solution to this important problem.

B. Technical Feasibility of Gallium Experiment

The technical feasibility of a ^{71}Ga solar neutrino detector has been demonstrated by a series of tests carried out over the past several years utilizing a pilot detector containing 1.3 tons of gallium (similar to one complete module of the 18 modules that would make up a 30-ton full-scale detector). More than 30 runs have been made with the pilot detector to test its extraction and conversion efficiencies using minute quantities of germanium introduced into the detector either as carrier gas (in quantities as small as 10 μg) or as atoms of ^{71}Ge produced in the tank by cosmic-ray bombardment, by neutron bombardment, or by the decay of ^{71}As. In all of these cases the product of the extraction and conversion efficiencies gave an overall efficiency of >95% in going from the gallium tank to the gas proportional counter.

At the present time a detection efficiency of 70% can be achieved for the ^{71}Ge in the proportional counter by counting both the K-peak (at ≈10.4 keV) and the L-peak (at ≈1.2 keV). The Heidelberg group has built detectors whose average background is about 0.28 counts/day. This is to be compared with expected counting rates due to solar-neutrino-produced ^{71}Ge in a 30 ton detector which range from ~0.75 counts/day to ~0.25 counts/day, depending on the different flux scenarios. Improvements in the average background to about 0.2 counts/day should be achievable. It is important that systematic development work on detector backgrounds commence very soon in the U.S., and

that substantial experience and statistical information on detector backgrounds be available by the time the gallium is being procured.

Studies of the gallium (looking for impurities such as uranium, radium, zinc, selenium, etc.) and of the materials making up the glass-lined 750-gallon modular tanks have shown that in a 30-ton detector these would produce a background of <0.01 atoms of ^{71}Ge per day. Sites at great depth and in low background rock (such as the 5400 feet level in the INCO mine near Sudbury, Ontario) would provide both a low neutron flux (≈ 0.002 ^{71}Ge per day for a 30-ton detector) and good cosmic ray shielding resulting in a background of <.005 ^{71}Ge per day from cosmic ray muons for a 30-ton detector. It is therefore clear that the background in this experiment is almost entirely (>90%) due to the gas proportional counter.

With regard to questions about the confidence with which one can extrapolate these pilot-detector results to a full-scale experiment, it should be noted that given the modular design of the detector, the pilot-tank results involving one complete module can be extrapolated with very little uncertainty. Concerning any nuclear physics uncertainties in the ^{71}Ga$(\nu,e^-)^{71}$Ge reaction, the rate for the ground-state transition ^{71}Ga$(\nu,e^-)^{71}$Ge is well known (the Q-value and the half-life for the inverse reaction have recently been accurately remeasured; Q=233.2±0.5 keV and $t_{1/2}$=11.43±0.03 days), and studies of the ^{71}Ga$(p,n)^{71}$Ge reaction have recently demonstrated that (ν,e^-) transitions involving the excited states of ^{71}Ge contribute only 12±4% to the total ^{71}Ge production rate.

C. Amount of Gallium Required

The practical question of just how large such a detector should be in order to provide the necessary scientific information, in a reasonable time and at a minimum cost, has to be considered as follows: (1) With the presently anticipated counter backgrounds (≈ 0.2 counts/day) a 15-ton detector after 4 years of operations could not, for instance, distinguish,at the two-standard-deviation level of confidence, a model in which all of the solar luminosity is produced by the energy from the p-p chain alone (≈ 80 SNU) from those corresponding either to the standard solar model (120 SNU) or the model in which the neutrinos oscillate equivalently over three flavors (40 SNU), while a 30-ton detector could. (2) The background counting rates in a gallium solar neutrino detector are almost entirely (>90%) associated with the gas proportional counter, and therefore the quality of the signal-to-noise characteristic of such a detector is directly proportional to the amount of gallium in the detector and will be twice as good for a 30-ton detector compared to a 15-ton one. (3) When considering the total cost of this project (operating costs as well as materials and equipment costs) spread over a realistic 8-10 year period, the cost of 30 tons of gallium is only 50% of the total, so that cutting the size of the detector in half to 15 tons would

reduce the cost of the project by only 25% while reducing the significance and credibility of its results by at least a factor of 2.

In order to begin to resolve the scientific questions currently surrounding the solar neutrino problem, (possibly discriminating, for example, between solutions based on solar physics uncertainties and the untested behavior of neutrinos over 10^{11} m flight paths) we conclude that a ^{71}Ga solar neutrino detector should contain about 30 tons of gallium. This recommendation is based on the assumption of an average detector background of 0.2 counts/day. A 20 ton experiment with a background of 0.1 counts/day will give about the same precision, and, if such an average background could be established by the time that procurement of the last 10 tons of Ga has to be made final, this procurement would be unnecessary.

D. Initial Funding

The technical feasibility of this experiment has been established. An initial funding level sufficient to make an initial procurement of a practical fraction of the 30 tons of Ga should be provided.

E. Scope of Our Review

The charge to our committee did not include a request to review specific proposals. Several proposals in draft form were made available to the committee for informational purposes. As draft proposals they did not include a statement of the fraction of effort to be provided by the investigators listed. We assume that before funding a Ga experiment the appropriate funding agencies will assure themselves that the proposing institution have sufficient technical and personnel resources (at the appropriate level of commitment and expertise) to carry out this demanding experiment.

A lead institution and a principal investigator need to be identified. We also assume there will be periodic reviews of progress on the preparations for this experiment, especially with respect to the production of detectors with the required low background.

F. Possible International Collaboration

In order to avoid further delays, we recommend that consideration of the U.S. gallium experiment proceed for the present on the assumption that its funding must come entirely from within the United States basic research programs. The importance of resolving the solar neutrino question is recognized by the international community of scientists. A European collaboration (GALLEX) is proposing a gallium-based solar neutrino experiment in the Gran Sasso tunnel. The planning of this project had originally been started by a Heidelberg group in collaboration with United States scientists, but because of the lack of success in obtaining financial support for the United States' end of the costs, the European project is now being pursued without U.S. participation. Considerable development in low-background

detectors has been carried out by the participating Heidelberg group. The GALLEX proposal is being considered now by the appropriate European funding agencies.

The question of resuming collaboration with the European group should be kept in mind. However, since the earlier attempts at collaboration had fallen through, discussions of collaboration should probably be resumed only after the funding of the project in the United States is assured. It seems clear, however, that it is not likely to be a practical or sensible allocation of resources to have two separate gallium experiments, each requiring several tens of tons of gallium, carried out in parallel. Should both experiments be funded, we would strongly recommend that the U.S. encourage combining forces and sharing costs in order to strengthen knowledgeable manpower and save on the cost of gallium as well as on the costs of other aspects of the experiment.

A group in the Soviet Union is also planning to carry out a gallium-based experiment. In this case the gallium seems to be available in sufficient quantities, but a decision has apparently been made to follow a different technique for the chemical separation of the germanium, and the status of the underground laboratory where the measurement would be carried out is not entirely clear. Any collaboration, if at all practical, would likely have to be carried out within the borders of the Soviet Union. The technical problems in the experiment are likely to be formidable implying long delays in obtaining a definitive result. While contact should certainly be maintained, a Soviet-U.S. collaborative experiment does not appear to be practical at this time.

VI. COMPLEMENTARY EXPERIMENTAL APPOACHES AND LONG RANGE RESEACH AND DEVELOPMENT

A. The ^{37}Cl Experiment

The pioneering ^{37}Cl experiment of Davis established the solar neutrino problem and thereby motivated an examination of stellar physics models which has greatly clarified our understanding of their strengths and limitations. Moreover, the sensitive techniques that were developed have made possible a whole new group of experiments, including the gallium experiment whose funding is recommended above. The question of whether to continue the ^{37}Cl experiment involves an evaluation of what additional information can be obtained by a few more years of operation. A majority of the Subcommitee feel such a continuation would not be cost effective. Only rather small improvements in the accuracy of the detection rate can be anticipated. Nor does it seem possible that sufficient statistical accuracy will be obtained to establish the existence of correlations with the solar cycle. On this basis the majority of the Subcommittee does not support continuation of data collection

by the ^{37}Cl experiment. A minority of the Subcommittee felt that the Cl facility should be maintained, as it might be useful if it is decided at some future time that a commitment to a ^{81}Br experiment should be made, and that a modest program of ^{37}Cl data collection should continue until another neutrino detector is operational, both to provide an overlap of flux measurements and as a monitor of a possible future cataclysmic event.

A related investigation aimed at a better determination of the cosmic ray background at the site of the ^{37}Cl detector should be continued. This ongoing experiment, based on a KOH detector, will allow one to place better limits on the flux of the ^{8}B neutrinos observed in the ^{37}Cl detector. Establishing both lower and upper bounds on this flux is important for interpreting the results of the ^{37}Cl experiment and for the design of other experiments that are sensitive only to ^{8}B neutrinos.

For example, a new background determination giving a ^{37}Cl result of <1 SNU would place stronger constraints on explanations of the discrepancy. With regard to the planning of future experiments, if the actual flux were a factor of ten smaller than standard model predictions (rather than the factor of three implied by the ^{37}Cl experiment with the background presently assumed), other experiments searching for ^{8}B neutrinos might be marginal. For these reasons it is an important part of any program of solar neutrino physics that measurements of background relevant to the ^{37}Cl experiment be pursued.

B. Other Radiochemical Experiments

1. A ^{81}Br Experiment

A detector based on ^{81}Br would have an effective threshold for neutrino capture such that it would be primarily sensitive to neutrinos from the ^{7}Be + $e^- \rightarrow {}^7$Li + ν reaction in the sun. When the ^{81}Kr detection techniques have been shown to be quantitatively reliable, this experiment may well become useful to help unfold the spectral distribution of neutrinos. Its value, however, is dependent on the results of the ^{71}Ga experiment and the establishment that the counting rate observed in the ^{37}Cl experiment is not due to backgrounds. Long range research and development might be appropriate but a major commitment of funds at this time would be premature.

2. A ^{98}Mo Experiment

The principle behind this detector (which is primarily sensitive to the ^{8}B neutrinos) involves the extraction and counting of ^{98}Tc atoms produced in the ^{98}Mo(ν,e^-)^{98}Tc reaction. The long 4.6 million year half life of ^{98}Tc, and geologic deposits of Mo in a long-shielded ore body, enable one to integrate the flux of ^{8}B neutrinos over the past few million years in order to determine if the lack of the expected ^{8}B flux in the ^{37}Cl detector may be due to temporal variations in the central temperature of the sun. The first attempt at the extraction of ^{98}Tc from sizeable amounts of Mo ore is expected to take place later this year. Before this detector can yield useful information,

this extraction process and an adequate mass-spectrometer sensitivity must be successfully demonstrated. The quantitative interpretation of any result ·from this technique will be substantially compromised unless an improvement is made in the present ±30% uncertainty in the rate for the ^{98}Mo(ν,e^-)^{98}Tc reaction.

3. A ^{205}Tl Experiment

The principle behind the proposed ^{205}Tl solar-neutrino detector is similar to the principle behind the ^{98}Mo detector with the significant difference that the ^{205}Tl detector, with a Q-value of only 43 keV, is sensitive primarily to the p-p neutrinos while the ^{98}Mo detector is sensitive only to the ^{8}B neutrinos. Substantial practical problems still exist for this solar neutrino detector, especially the largely unknown rate for the (ν,e^-) reaction transition leading to the 2.3-keV first excited state of ^{205}Pb, but also the ion-source efficiency that limits the minimum sample size that must be used, and the uncertain geological history of the ore body.

C. Direct Detection Approaches

In addition to the radiochemical experiments, several other approaches under active development deserve encouragement. They include as future experimental goals: identification of each of the major neutrino producing reactions in the sun (by determining the energy spectrum of solar neutrinos), real time detection, directional sensitivity, and total (flavor independent) neutrino flux measurements by measuring neutral-current interactions. No single experimental technique has yet demonstrated the capability to achieve all of these goals; however, active research and development is in progress on techniques based upon indium (normal and superconducting), and silicon (cryogenic bolometry) detectors and on the applicable technology of proton decay detectors.

1. Proton-Decay-Type Detectors

The first generation of detectors constructed to search for proton decay has been in operation for several years. To date, these detectors have set lower limits which are larger than the proton half-life expected from leading unification theories. ·They have also demonstrated their ability to detect and analyze high energy neutrino-induced reactions from neutrinos produced in the earth's atmosphere by cosmic rays. These first-generation detectors are principally based upon two technologies: detection of Cherenkov radiation in water, and a variety of segmented, fine-grained solid detectors with suitable readout. Much larger, second generation detectors based on these technologies and new technologies (such as cryogenic liquids with electrostatic drift readout) are in the advanced proposal stage.

Because of the low energies carried by the solar neutrinos those detectors based upon water Cherenkov radiation and cryogenic liquids are most suitable. If it is possible to reduce the rate of background events that deposit energies greater than about 5 MeV in the detector to less than

approximately five/day, then a detector containing a few thousand tons might detect one or two events/day due to the important reaction $\nu_e + e^- \rightarrow \nu_e + e^-$ if the Davis flux for ^{8}B electron neutrinos is correct. Such detectors would be limited to the ^{8}B neutrinos because of the threshold restrictions inherent in the technology. However, because of their strikingly characteristic signature they could provide a first measurement of the direction and location of the neutrino source, thus checking the solar origin. The principal backgrounds are believed to come from natural radioactivity both within and without the detector and from hadronic debris resulting from cosmic ray muons interacting in the detector and in the surrounding rock; thus both the depth and the environment are important. While a sufficiently low background rate has not yet been achieved, the question is currently being actively addressed at the Kamioka (Japan) proton decay detector by a Japan-USA collaboration.

A particularly interesting extension of the water Cherenkov technique has been suggested and is under active study by a Canada- USA- UK collaboration. It would involve the use of heavy water (D_2O) in a detector and might permit the acquisition of qualitatively new information. This new capability is brought about by the use of two additional reactions; the neutrino disintegration of the deuteron by the neutral current, and the charged-current inverse beta decay of the deuteron. Because the reactions in the sun are expected to produce purely electron-type neutrinos, proof of oscillations independent of flux calculations requires the measurement of the ratio of electron neutrinos to other types of neutrinos. In a D_2O detector the neutral-current reaction would provide a measure of the total ^{8}B neutrino flux independent of neutrino type while the inverse beta decay and neutrino-electron scattering reactions sample the electron-type neutrino flux and give directional information. A comparison of rates for the neutral-current interactions (sensitive to all neutrino types) and charged-current interaction (sensitive to electron neutrinos) then provides an unambiguous signature for neutrino oscillation phenomena. Studies of the various sources of background have established that the direct counting of ^{8}B solar neutrinos is feasible. Some background questions concerning the neutral current interactions are not yet answered but are under active study.

2. Other Direct Counting Approaches

^{115}In has been suggested as a detector for determining the neutrino energy spectrum. The neutrino energy would be deduced from the electron energy in the reaction, ^{115}In $+ \nu_e \rightarrow \,^{115}Sn^* + e^-$. This reaction would be uniquely identified by a delayed coincidence between the original electron and the two gammas (or one gamma and one conversion electron from the subsequent decay of excited ^{115}Sn$^*(\tau=4.7\ \mu sec)$. Exploitation has been hampered due to the large background of random coincidence events from the decay of ^{115}In. Recently emphasis has shifted from developing a detector capable of seeing the low-energy neutrinos from the p+p reaction to the perhaps more reachable goal

of detecting those neutrinos above the 485 keV endpoint of the ^{115}In beta-decay background. The latter approach's lack of sensitivity to p-p neutrinos is a serious limitation. Some work aimed at p-p neutrinos is continuing in Europe on superconducting ^{115}In; however, both this and the non-cryogenic approach need considerable work before viability of these detectors can be established.

A new approach for determining the solar neutrino spectrum has recently been put forward based on a bolometric detector, in which neutrinos would scatter off electrons in a large volume of Si cooled to about 1 mK. Due to the high Debye temperature of Si and the corresponding small heat capacity at low temperatures, the electron recoil energy of 100 keV would lead to a temperature rise from 1 mK to 4 mK for a mass of about 1 kg. It is proposed to exploit the transition temperature of a superconducting thin-film ring as the temperature-rise sensor. A small prototype detector is under development. If successful the next step would be development of a larger detector for use in a possible reactor-based neutrino-oscillation experiment. The final stage for a solar neutrino detector would be the careful study of backgrounds and the construction of an array of detectors. It will be necessary to deal with high event rates due to radioactive ^{32}Si produced by cosmic-ray muons, or to produce the detector from material that has been not only geologically well shielded but also kept in shielded (deep underground) areas during the refinement and manufacturing process. A number of years will be needed to acquire sufficient information to predict the usefulness of Si bolometry as a solar neutrino detector.

VII. Findings and Recommendation

The solar neutrino problem is a major anomaly in the understanding of the physical world in the 1980's, cutting across the disciplines of astronomy and astrophysics, elementary particle physics, nuclear physics, and the interface between high temperature atomic physics and plasma physics. Because our present understanding of the production and possible oscillatory nature of solar neutrinos is inadequate, calling into question our beliefs about the environment in which energy production takes place in our sun, the ages of stars and galaxies, and the nature and stability of fundamental particles, at least one new experiment would help resolve the present impasse in finding the source of the solar neutrino problem. The only experiment presently feasible and sensitive to the crucial p-p neutrino flux is a ^{71}Ga radiochemical experiment.

Therefore, we make the following recommendations:

The scientific questions currently surrounding the solar neutrino problem can best be addressed by a detector using 30 metric tons of gallium. The technical feasibility of a ^{71}Ga detector for measuring the p-p neutrino flux has been demonstrated. A gallium experiment should be initiated

immediately with sufficient funding to acquire a practical fraction of the 30 tons of gallium which we deem necessary to complete this experiment.

It is important that systematic development work on detector backgrounds commence very soon in the U.S., and that substantial experience and statistical information on detector backgrounds be available by the time gallium is being procured.

Due to the interdisciplinary nature of the problem a special funding initiative from a governmental level above the normal ones appropriate for the standard compartmentalization of science is required.

In order to avoid further delays in these crucial measurements it is important that consideration of this project should proceed, for the present, on the assumption that its funding must come from within the United States, but at the same time the question of resuming collaboration with the European GALLEX group should be kept open. It is not likely to be a sensible or practical allocation of resources to have two gallium experiments carried out in parallel.

We further point out that complementary experiments are likely to be important and recommend that development of new detection methods should be encouraged. Direct counting experiments capable of providing spectral information, directional information, or sensitivity to neutral-current interactions (e.g. an experiment employing a D_2O Cherenkov detector) are particularly important.

Department of Energy
Washington, D.C. 20585

April 11, 1985

Dr. John Schiffer
Chairman, Nuclear Science
 Advisory Committee
Physics Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL   60439

Dear Dr. Schiffer:

Background: Energy production in our sun is essential to life on earth. The study of solar neutrinos associated with this energy production has been an intriguing one, especially for physicists and astronomers. Such studies provide an important link between our detailed understanding of the interior of the sun on one hand (indeed, neutrinos are the only direct link with the interior of the sun), and of fundamental questions regarding our description of solar nuclear processes and the nature of the neutrino, on the other hand.

The bulk of solar energy is believed to come from fusion burning of hydrogen. Only one experiment to measure the flux of neutrinos has been carried out over the past two decades and it has yielded a lower flux than that predicted by the best available theoretical models of solar processes. However, the measurement was sensitive to only a small fraction of the solar neutrinos, i.e., those with sufficient energy to trigger the detection scheme. The low energy neutrinos associated with the first stage of hydrogen burning were invisible to the experiment which has been carried out.

It has been proposed that a new experiment, sensitive to this critical low energy part of the solar neutrino spectrum be carried out. This new experiment should be able to resolve whether the discrepancy is related to the measurement of the higher energy solar neutrinos, of nuclear reaction processes, or possibly of the fundamental nature of the neutrino.

Charge: Please establish an ad hoc review panel that includes representatives from the various disciplines interested in the scientific and technical aspects of the solar neutrino discrepancy. This panel would be expected to review the scientific importance of new solar neutrino experiments without regard to how they might be funded or where they might be done. If the panel concludes that new solar neutrino experiments are scientifically justified, then they should recommend the best and most cost-effective way to do the experiments and obtain

sufficient information to answer the principal questions. For instance, there has been an on-going debate on the mass of gallium required to conduct the experiment as well as on the type of detector material and experimental scheme to be used. The relative merits of these various approaches need to be reviewed. Comments on the practicality of collaboration with groups outside the United States and on complementary projects elsewhere would also be appreciated.
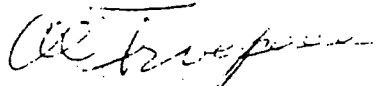
The chairman for this ad hoc panel should be a member of the Nuclear Science Advisory Committee (NSAC). Any report that is generated by the panel must be reviewed at a full NSAC public meeting before submission.

We would like to receive the report of the ad hoc panel and any NSAC recommendations, comments, and endorsements by August 1985.

Sincerely,

Marcel Bardon
Director, Division of Physics and
Acting Assistant Director for
 Mathematical and Physical Sciences
National Science Foundation

Alvin W. Trivelpiece
Director, Office of
 Energy Research
U.S. Department of Energy

June 6, 1985

AGENDA

Solar Neutrino Subcommittee Meeting

(DOE/NSF Nuclear Science Advisory Committee)

June 12-13, 1985

Department of Energy
Forrestal Building
Room 1E-245
1000 Independence Avenue
Washington, DC 20545

(a few blocks from L'Enfant Plaza Subway Station)

Wednesday, June 12, 1985

9:00am	Opening Remarks
9:15am	Discussion
10:30am	Coffee Break
11:00am	Molybdenum Experiment; Status and Prospect (G. Cowan, LANL)
11:40am	Bromine Experiment; Status and Prospect (S. Hurst, ORNL)
12:20pm	Lunch
1:30pm	Nuclear Cross Sections Relevant to Solar Model Calculations (S. Austin, MSU)
2:10pm	Solar Model; Predictions and Uncertainties (J. Bahcall, Princeton)
3:00pm	Neutrino Physics, (P. Rosen, Los Alamos)
	Coffee Break
4:00pm	Proposed Ga Experiment (T. Bowles or H. Robertson, LANL)
5:00pm	Chemical Aspects of Ga Experiment (L. Remsberg, BNL)

Thursday, June 13, 1985

9:00am	Bolometric Detection of Neutrinos (B. Cabrera, Stanford)
9:40am	Sudbury D_2O Neutrino Detector (H. Chen, Irvine)
10:20am	Coffee Break
10:40am	Prospect and Goal of Future Cl Experiments (R. Davis, Penn)
11:20am	Neutrino Spectroscopy Using an In Detector (R. Raghavan, Bell Labs)
12:00	Lunch
1:00pm	Executive Session
4:00pm	Adjourn