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SOLAR NEUTRINO EXPERIMENTS AND A TEST FOR NEUTRINO OSCILLATIONS WITH RADIOACTIVE SOURCES

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ABSTRACT

The results of the Brookhaven solar neutrino experiment are given and compared to the most recent standard solar model calculations. The observations are about a factor of 4 below theoretical expectations. In view of the uncertainties involved in the theoretical models of the sun we do not consider the discrepancy to be evidence for neutrino oscillations. The status of the development of a gallium solar neutrino detector is described.

Radiochemical neutrino detectors can be used to search for ν_e oscillations by using megacurie sources of monoenergetic neutrinos like ^{65}Zn. A quantitative evaluation of possible experiments using the Brookhaven chlorine solar neutrino detector and a gallium detector is given.

INTRODUCTION

In this report we will give the results of the Brookhaven solar neutrino experiment that has been operating for 12 years. This experiment has always observed a solar neutrino capture rate in ^{37}Cl below the rate expected from standard solar models. In recent years the observed rate has been approximately a factor of four below theoretical expectation. Among the various explanations advanced for the low solar neutrino (ν_e) flux is neutrino oscillation. We will discuss this question briefly and point out that the dominant solar neutrino flux signal expected to be observed by the ^{37}Cl experiment according to the standard solar model arises from ^{8}B decays in the sun, and that the flux of these neutrinos may not be reliably calculated. Therefore one should exercise great caution in using results of the ^{37}Cl solar neutrino experiment as evidence for ν_e oscillations. Since the flux of low energy neutrinos from the chain initiating proton-proton reaction can be reliably calculated, observing the flux of this component of the solar neutrino spectrum could give more direct information on the question of neutrino oscillations. A radiochemical solar neutrino detector based upon the neutrino capture reaction ^{71}Ga(ν_e,e$^-$)^{71}Ge has a sufficiently low energy threshold to observe p-p neutrinos. A gallium solar neutrino experiment can search for oscillations of electron neutrinos with an average energy of 300 keV over distances of one astronomical unit (1.5 x 10^{11} m). Progress on and the status of the development of a gallium solar neutrino detector will be described.

Radiochemical solar neutrino detectors can also be used to search for ν_e oscillations by using a source of neutrinos of well-defined energy such as ^{65}Zn. Plans for carrying out experiments along these lines using the Homestake chlorine detector and a small gallium detector will be described in a later section.

THE BROOKHAVEN SOLAR NEUTRINO EXPERIMENT

An experiment designed to observe the neutrinos from the sun has been operating since 1967 in the Homestake Gold Mine (depth 4400 hg/cm^2). A radiochemical technique is used that depends upon observing radioactive ^{37}Ar recovered from 615 tons of perchloroethylene (C_2Cl_4).[1] Neutrino detection depends upon the neutrino capture reaction $^{37}Cl(\nu_e,e^-)^{37}Ar$ and the calculated neutrino capture cross-sections.[2] The results from a series of 40 measurements over the period 1971 through 1979 are given in Figure 1. The values for the individual runs were obtained from argon gas samples removed from the liquid and counted for periods of 150 to 250 days, a sufficient time to distinguish a component decaying with the 35 day half-life of ^{37}Ar from the counter background. The counting data was treated by a maximum likelihood statistical method. The ^{37}Ar production rates are given for 40 individual experiments. The periods of exposure are indicated by the horizontal bars, and the errors given correspond to the 67 percent confidence level. The errors shown are statistical, and the fluctuations are in accordance with expected fluctuations obtained by Monte Carlo simulations.

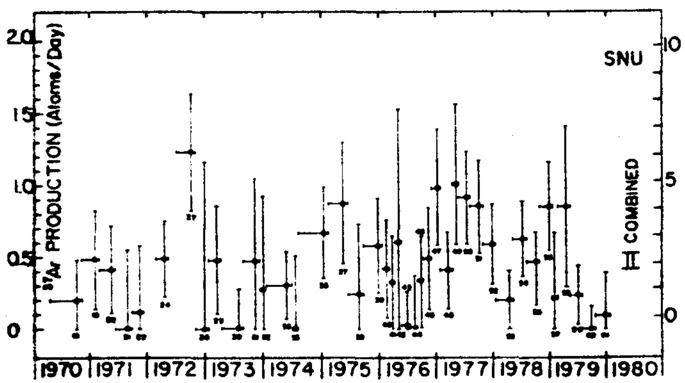


Figure 1

Combining the data for all runs gives a most likely ^{37}Ar production rate of 0.47 ±0.05 atoms per day. There is a background production of ^{37}Ar in the liquid resulting from cosmic ray muon interactions. This muon background is evaluated by measuring the ^{37}Ar production rate in perchloroethylene at shallow depths (300-1100 m.w.e.) and extrapolating these measured values to determine the rate in the solar neutrino detector (4400 m.w.e). We will use a background of 0.08 ± 0.03 ^{37}Ar atoms/day estimated by this method.[3] Experiments are in progress by E. L. Fireman[4] to evaluate this critical background by measuring the depth dependence of muon photonuclear interactions in potassium by the process $^{39}K(\mu^{\pm},\mu^{\pm}n,p)^{37}Ar$. Subtracting the muon background we obtain the following result:

Average ^{37}Ar production rate	= 0.47 ± 0.05 atoms/day
Background from muons	= 0.08 ± 0.03
^{37}Ar production possibly attributable to solar neutrinos	= 0.39 ± 0.06 atoms/day

Possible solar neutrino rate = 5.31 x (0.39±0.06) = 2.1±0.3 SNU

where 5.31 is the appropriate factor for converting the rate in atoms per day in a detector containing 2.18 x 10^{30} atoms ^{37}Cl to SNU (SNU = solar neutrino unit = neutrino captures per second per ^{37}Cl atom x 10^{36}).

The above rate is to be compared to the neutrino capture rate of 7.8 SNU predicted using the standard solar model.[5] This model will be discussed by John Bahcall at this conference. The calculated rate depends upon a number of assumptions associated with the standard solar model. For example, it is assumed that the sun was initially homogeneous with the composition presently observed in its photosphere, and that the sun is non-rotating, spherically symmetrical, and constant in mass. This calculation uses a mixing length theory for turbulent convective energy transport and a modified ideal gas equation of state.[6] A large amount of input data is used in the calculations, some of which is well known and accurately determined (mass, age, and luminosity of the sun), some that is not as well measured or requires extrapolation to obtain relevant values (solar composition, and nuclear reaction rates) and other information that must be calculated or assumed (opacities, turbulent mixing processes). Because of the diverse nature of the input data alone it is difficult to assess the errors involved in the calculated neutrino fluxes. The stated error is 1.5 SNU for this most recent model with a total ^{37}Cl capture rate of 7.8 SNU. Another very important consideration in interpreting the ^{37}Cl solar neutrino experiment is that the major contribution to the rate is from the ^{8}B neutrinos, and this source of neutrinos is very sensitive to various parameters and assumptions used in the solar model. Table 1 lists the neutrino sources in the sun, the calculated cross sections and standard solar model fluxes. It can be noticed that 6.3 SNU is attributed to the ^{8}B neutrino flux alone.

Table 1

SOLAR NEUTRINO FLUXES* AND CROSS SECTIONS**

$\nu + {}^{37}Cl \rightarrow e^- + {}^{37}Ar^* \rightarrow {}^{37}Ar$

Neutrino Sources & Energies	Flux on Earth ϕ in cm^{-2} sec^{-1}	Cross Section σ in cm^2	Capture Rate ${}^{37}Ar$ $\phi\sigma \times 10^{36}$ sec^{-1} SNU
$H + H \rightarrow D + e^+ + \nu$ (0-0.42)	6.1×10^{10}	0	0
$H + H + e^- \rightarrow D + \nu$ (1.44)	1.5×10^{8}	1.56×10^{-45}	0.23
${}^{7}Be$ decay	4.1×10^{9}	2.38×10^{-46}	0.98
${}^{8}B$ decay	5.85×10^{6}	1.08×10^{-42}	6.31
${}^{15}O$ decay	3.7×10^{8}	6.61×10^{-46}	0.24
${}^{13}N$ decay	2.6×10^{8}	1.66×10^{-46}	0.04

$\Sigma\phi\sigma = 7.8$ SNU

* J. N. Bahcall, W. F. Heubner, S. H. Lubow, N. H. Magee, A. L. Mertz, P. D. Parker, B. Rozsnyai and R. K. Ulrich

** J. N. Bahcall, Rev. Mod. Phys. 50, 881 (1978)

A number of non-standard models have been calculated that give solar neutrino capture rates in ${}^{37}Cl$ in the range 1 to 2 SNU. Various features are introduced in these models that lead to lower internal temperatures and thereby yield lower ${}^{8}B$ and ${}^{7}Be$ production rates.[7] Although most of these models do agree with the results of the chlorine experiment, they are not generally accepted because some of the mechanisms invoked do not seem to be reasonable or they lead to consequences that are in conflict with observations. Of these various models one of the most reasonable simply assumes that the heavy element composition in the interior of the sun is a factor of ten below the accepted photospheric value. The lower heavy element composition reduces the opacity, which gives lower internal temperatures, and leads to a capture rate in ${}^{37}Cl$ of about 1.5 SNU.

There are many uncertainties in the theoretical calculations of the solar neutrino spectrum and the errors are difficult to evaluate properly. Therefore, the difference between our result of 2.1 ± 0.3 SNU and the rate of $7.8 \pm (\sim 1.5)$ estimated from the standard model could easily be ascribed to our incomplete or incorrect knowledge of the solar interior. Neutrino oscillations could of course account for the discrepancy, a factor of 3.6 ± 0.9, or a part of it, depending upon the value of the mixing angle and oscillation length.

NEW SOLAR NEUTRINO EXPERIMENTS

There is great interest in performing additional experiments directed toward observing the solar neutrino spectrum. At this conference there will be a report by R. S. Raghavan on the development of a direct counting neutrino detector based upon the ${}^{115}In(\nu,e^-){}^{115}Sn^* \rightarrow {}^{115}Sn$ reaction. Another approach to observation of the solar neutrino spectrum is to perform a set of measurements with radiochemical detectors having different threshold energies and sensitivities to the neutrino flux.[2] The radiochemical detectors considered for this purpose are based upon the following reactions: ${}^{71}Ga(\nu,e^-){}^{71}Ge$, ${}^{7}Li(\nu,e^-){}^{7}Be$, ${}^{81}Br(\nu,e^-){}^{81}Kr$, and ${}^{37}Cl(\nu,e^-){}^{37}Ar$. Table 2 compares these

Table 2

COMPARISON OF RADIOCHEMICAL SOLAR NEUTRINO DETECTORS

Percent of signal from various solar neutrino sources, standard model.

Neutrino Source	${}^{37}Cl-{}^{37}Ar$	${}^{7}Li-{}^{7}Be$	${}^{71}Ga-{}^{71}Ge$	${}^{81}Br-{}^{81}Kr$
$H + H \rightarrow D + e^+ + \nu$	0	0	65	0
$H + H + e^- \rightarrow D + \nu$	3	22	2	8
${}^{7}Be$ decay	12	10	27	69
${}^{13}N$ decay	1	3	1	4
${}^{15}O$ decay	3	21	3	10
${}^{8}B$ decay	81	44	2	9
$\Sigma\phi\sigma$	7.8	41	100	6.3
Tons Element for 1 ν-capture/day	356	3.5	34	495

detectors. It shows the $\sum\phi\sigma$ and the tons of the element required for one ν-capture per day according to the standard solar model.[5] The main body of the table gives the percent of the signal contributed by the various neutrino sources in the sun. The pp reaction rate in the sun is very well calculated and is essentially independent of the usual input data. The major energy producing reactions in the sun are those of the predominant p-p I chain, $H(H,e^+,\nu)D(H,\gamma)^3He(^3He,2p)^4He$, that includes only this one neutrino producing reaction. Therefore, the p-p reaction rate is related very directly to the solar luminosity and, if the sun is indeed producing energy by hydrogen fusion, the p-p rate is established. If a measurement of the total capture rate in ^{71}Ga is made, it should be between 67 and 100 SNU, the lower limit being the p-p flux contribution alone. If we have confidence in this argument, then a signal lower than 67 SNU could be evidence for neutrino oscillations. A gallium solar neutrino experiment has great potential for testing whether the lower than expected solar neutrino capture rate in ^{37}Cl is a result of incorrect solar structure or input data or is a consequence of a property of the neutrino such as oscillation or decay.

A gallium solar neutrino detector is being developed through a joint program of several laboratories: the Max-Planck Institute at Heidelberg, the Weizmann Institute, Institute for Advanced Study, the University of Pennsylvania, and Brookhaven National Laboratory.[8] The product, ^{71}Ge, is separated from the target, a water solution of $GaCl_3$ with added hydrochloric acid, as $^{71}GeCl_4$ by a helium purge. A pilot detector that uses 1.3 metric tons of gallium is now in operation. Extraction of ^{71}Ge is essentially quantitative, and it is clear that a 50 ton solar neutrino experiment is indeed feasible. The next step in development is the calibration of a gallium detector with a megacurie radioactive source of monoenergetic neutrinos. This source calibration can serve as a test for neutrino oscillations, as will be described in the next section.

OBSERVING NEUTRINO OSCILLATIONS WITH MEGACURIE RADIOACTIVE SOURCES

This section deals with possible radiochemical experiments that can test for the existence of short range neutrino oscillations. This type of experiment follows the original suggestion of L. W. Alvarez to use a ^{65}Zn source to measure the neutrino absorption cross-section of ^{37}Cl.[9]

The general principles of an oscillation experiment are quite straightforward: a strong source of a radioactive isotope that decays primarily by electron capture is prepared. The shielded source is placed deep underground within or near to a target material that is able to capture the emitted neutrinos by an inverse beta decay process that leads to a moderately long-lived product isotope. This product is extracted from the target by chemical means and then counted by detecting the beta decay back to the original target isotope. Possible sources include ^{51}Cr and ^{65}Zn; possible target isotopes are ^{7}Li, ^{37}Cl, ^{71}Ga, ^{81}Br, etc.

Some of the advantages of radiochemical neutrino oscillation experiments are:

1. The neutrinos are monochromatic
2. The neutrinos are of the electron type for which oscillations have been reported by Reines et al.[10]
3. The source can be made quite compact
4. The source strength can be accurately calibrated
5. The neutrino absorption cross-section is well-known
6. Background production rates due to α-particles, neutrons, and muons can be made negligibly small. There is only a minor residual background effect from solar neutrinos.
7. Different neutrino oscillation lengths can be sampled by placing concentric detectors about the source.

The principal difficulaty in experiments of this type is that very large source strengths are required. With the strongest available reactor flux an irradiation time of approximately one year is needed. Even then, large targets are required (1-10 m in diameter) and the neutrino capture rates are low (less than 5 per day).

We shall now outline the procedures used in the calculation of the expected capture rate and then present two radiochemical experiments that are feasible at the present time.

Consider a point source that emits s neutrinos per second and an extended absorber that contains n atoms/cm^3 of a neutrino absorbing isotope. From the definition of the cross-section σ, the neutrino capture rate R is given by $R = A\cdot G$ where $A = ns\sigma$ depends on the physical properties of the source and absorber and

$$G = \frac{1}{4\pi}\int_{\text{absorber}}\frac{dV}{r^2} \qquad (1)$$

depends only on the source and absorber geometry (r here is the distance from the source to an arbitrary point in the absorber). The factor A is given in Table 3 for cross-sections calculated by Bahcall.[2] The geometrical factor G can be expressed in closed form for simple geometries such as a sphere or a cylinder, and can be easily evaluated for more complex geometries or for an extended source by Monte Carlo techniques.

Table 3

Absorber	Source	Detected Isotope	A (cm^{-1} Mc^{-1})
C_2Cl_4	^{65}Zn	^{37}Ar	0.0112
7.1 M $GaCl_3$	^{51}Cr	^{71}Ge	0.0284
7.1 M $GaCl_3$	^{65}Zn	^{71}Ge	0.0367

We suppose that the electron type neutrinos emitted by the source oscillate into one other type and that the probability of no oscillation at the distance r (cm) from the source is given by the standard formula,

$$P(r) = 1 - \sin^2(2\alpha_m)\sin^2(0.0127\ \delta m^2 r/E) , \qquad (2)$$

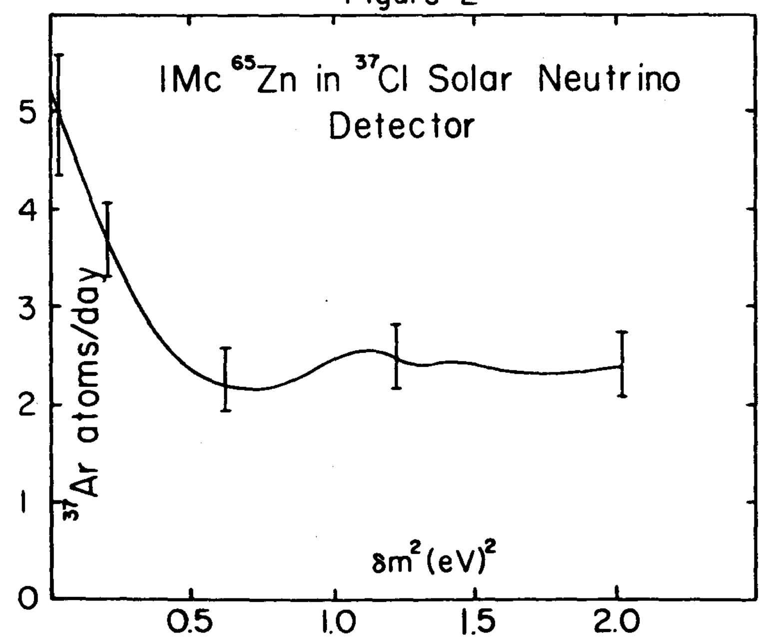
where α_m is the mixing angle, $\delta_m{}^2$ is the neutrino mass difference in eV^2, and E is the neutrino energy in MeV. The neutrino capture rate in the presence of oscillations is then easily calculated by including P(r) from eq (2) into the integrand of G in eq (1).

Two possible experiments will now be considered. The first involves placing a 1 Mc source of ^{65}Zn inside a tube that extends to the center of the 100,000 gallon C_2Cl_4 detector in the Homestake mine. Two obvious advantages of this experiment are that the detector presently exists and that the background has been well determined. The dependence of the capture rate on δm^2 for the case of maximal mixing is given in Figure 2. Without oscillations the capture rate of neutrinos from the source is 4.2 per day and there is also present a background production rate of 0.5 per day. The error bars indicated on this figure are at the 68% confidence level and are due only to random effects. These errors have been calculated by a simulation of the entire process of ^{37}Ar production, extraction, and counting for a set of experimental conditions that are believed to be realizable in practice. The production rate due to the neutrino source was extracted from the simulated counting times by a maximum likelihood method. It is evident from Figure 2 that for $\delta m^2 > 0.2\ eV^2$ the production rate at the 90% confidence level falls below the predicted rate in the absence of oscillations. The lower limit on δm^2 that is obtained for other choices of the mixing angle is presented in Figure 3.

Another possible experiment employs a target of a water solution of $GaCl_3$.[8] All of the procedures for extraction, purification, and counting of the ^{71}Ge that is produced by neutrino capture have been well developed. Background effects due to neutrons and α-particles are known and can be controlled by suitable choice of location and materials of construction. The muon produced background is much less severe than for C_2Cl_4 and is less than 0.1 per day for depths greater than 1800 hg/cm^2. The background effect due to solar neutrinos is believed to be 0.2 to 0.3 per day for the approximately 10 tons of Ga that is needed for a neutrino source experiment. In this case since an experiment can be designed specifically to search for neutrino oscillations, it can be made in two different zones. An experimental configuration that could be built consists of a central tank that forms the inner zone surrounded by six close-packed tanks as the outer zone. With a 2 Mc source of ^{65}Zn in a central annulus the capture rates in the inner and outer zones of a 10.6 ton Ga detector are given as a function of δm^2 in Figures 4 and 5, respectively. This again is for maximal mixing and the error bars are at the 68% confidence level for a reasonable schedule of experimental operations. A zero background has been assumed in both zones. If we compare these predicted rates in the two zones, there are two regions of δm^2 over which the rates differ by more than two standard deviations. These regions are plotted for this and for other mixing angles with a dashed line in Figure 6. These regions happen to overlap to a considerable extent with the regions suggested by the reactor ν_e experiment of Reines et al.[10] We can also look at only the rate in the outer zone, and, in a manner similar to that for the Cl experiment, obtain the lower bound for δm^2 given by the solid line in Figure 6.

It is apparent from these figures that interesting neutrino oscillation experiments can be performed with a ^{65}Zn source and either a gallium or chlorine target. Such experiments, sensitive to oscillation lengths of the order of several meters, are logical steps to be taken on the way to a full-scale gallium solar neutrino experiment. They would settle the question of the possible oscillations suggested by the Reines experiment. In addition, if it is shown that such oscillations do not exist, the calculated neutrino capture cross sections of these targets can be confirmed. Then a full scale gallium solar neutrino experiment could be confidently undertaken which would yield critical information about the reason for the present discrepancy between the results of the chlorine experiment and the predictions made by the standard solar model.

Figure 2



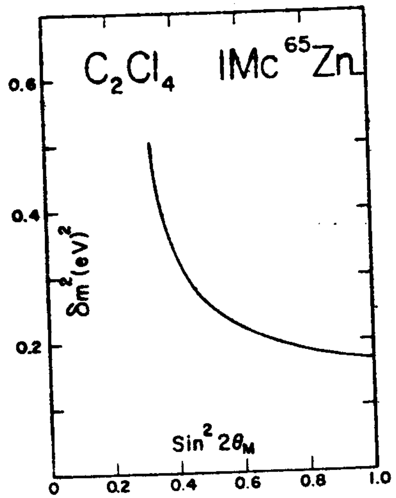


Figure 3

Figure 5

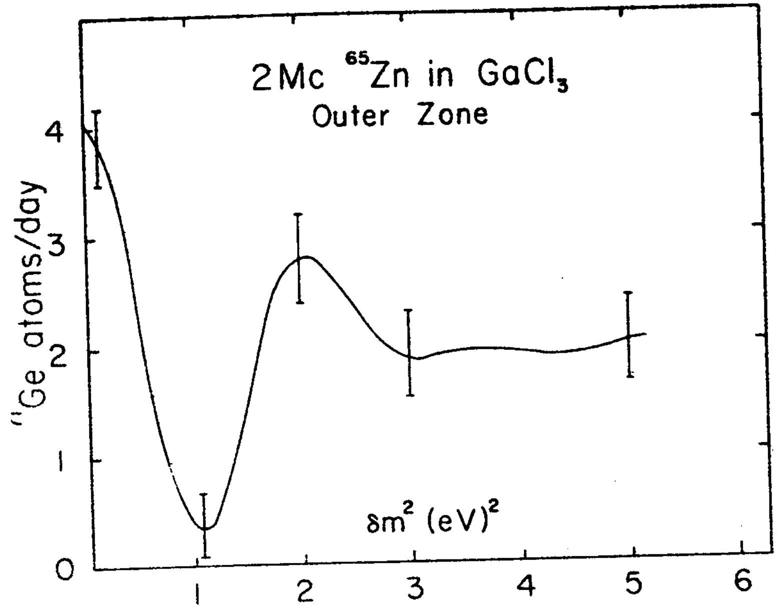
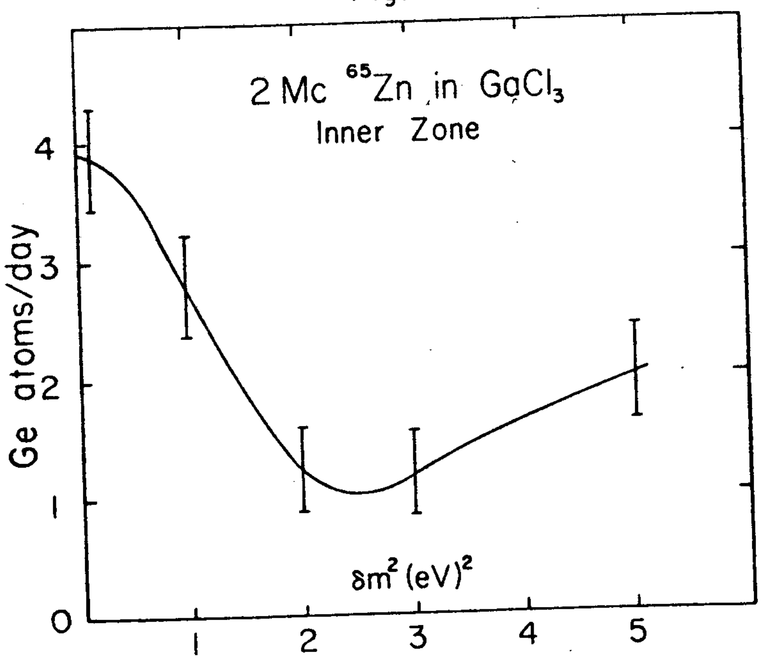


Figure 4



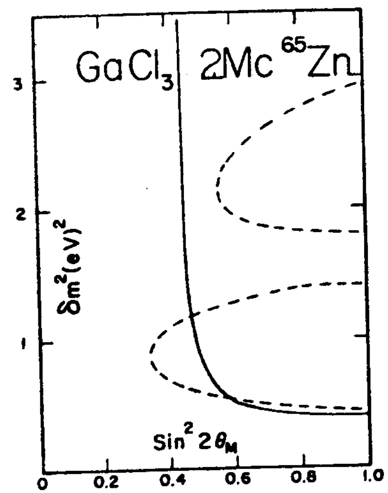


Figure 6

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DIRECT DETECTION AND SPECTROSCOPY OF SOLAR NEUTRINOS USING INDIUM

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ABSTRACT

The development of the Indium Solar Neutrino Spectrometer is reviewed. The importance of position sensitivity in this detector is emphasized. A novel concept for a "neutrino chamber" is advanced and being developed. A solar prototype chamber could be applied to reactor $\bar{\nu}$ experiments.

1. INTRODUCTION

Almost since the development of the ^{37}Cl radiochemical solar neutrino detector some 20 years ago, there has been a parallel but unsuccessful search for a physical technique by which solar neutrinos could be directly counted[1,2]. The desirability of such a method stems largely from the fact that this approach offers the only way to measure the energy of the detected neutrino. The energy spectrum of solar neutrinos constitutes the most complete experimental information on the solar interior that can possibly be obtained.

In 1976, a promising development occurred with the discovery of the possibility of inverse β-decay in ^{115}In[3]. This approach, with a threshold of 128 keV $\ll E_\nu^{max}(pp) = 420$ keV, a distinctive delayed coincidence signature and only a relatively small target mass of 4 tons of In (for 1 ν-capture/d) offers, in principle, most of the features long sought for in an ideal solar neutrino detector. In practice, however, the problems imposed by the weak ($\tau = 7 \times 10^{14}$y) β-radioactivity of In necessitate no less than the development of a new kind of counting instrument to realize the potential offered by this approach. Ideas underlying a novel "neutrino chamber" have been developed in this laboratory and experimental work to demonstrate 'proof of principle' of this device is in progress. The problem of electronic signal conversion in such classes of devices is being studied by a group at MIT led by Martin Deutsch as part of a Bell Labs-MIT collaboration[4] aimed at developing the In solar neutrino detector.

2. THE NEUTRINO CAPTURE REACTION IN ^{115}In

Fast Gamow-Teller β-decay is observed systematically between $9/2^+$ states of In isotopes and $7/2^+$ Sn nuclides throughout the mass range 111-131 (see Fig. 1). At the lighter end of this range Sn decays to In by electron capture, crossing over to In$\rightarrow$Sn β-decay at the heavier end. Near the crossover, at A = 115, the two levels are only 128 keV apart, the $9/2^+$ level being the ground state of ^{115}In while the $7/2^+$ level which lies above, is an excited metastable state ($\tau = 4.7$ μsec) of ^{115}Sn. These systematics and the nuclear structure data show that inverse β-decay induced by solar ν-capture in ^{115}In would populate only this $7/2^+$ metastable state in ^{115}Sn the matrix element for which can be inferred with confidence from the β-decays of the neighbouring members of this family[3]. With the cross section for ν-capture calculated[3,5] on this basis and the neutrino fluxes predicted by the standard solar model, the mass of In for an average ν-capture rate of 1/d is $\sim$4 tons. ^{115}In (isotopic abundance 96%) is a long-lived nuclide (see Fig. 2) decaying by a highly hindered β-transition (Q = 490 keV) to ^{115}Sn (stable). The ^{115}Sn $7/2^+$ isomeric state is depopulated by a cascade of a 116 keV transition which is 50% internally converted into a $\sim$94 keV electron (e_1) followed by a 498 keV γ-ray (γ_2).