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BNL 29440

CONF-810135--3

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SOLAR NEUTRINO EXPERIMENTS AND NEUTRINO OSCILLATIONS

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ABSTRACT

This report will give the results of the Brookhaven solar neutrino experiment that is based upon the neutrino capture reaction, $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$. The experiment was built in 1967 to test the theory of solar energy production, and it is well known that the neutrino capture rate in the detector is lower than that expected from theoretical models of the sun. The results will be compared to the current solar model calculations. One possible explanation of the low solar neutrino capture rate is that the neutrinos oscillate between two or more neutrino states, a topic of particular interest to this conference. We will discuss this question in relation to the ^{37}Cl experiment, and to other solar neutrino detectors that are capable of observing the lower energy neutrinos from the sun. A radiochemical solar neutrino detector located deep underground has a very low background and is capable of detecting the monoenergetic neutrinos from megacurie sources of radioisotopes that decay by electron capture. Experiments of this nature will be described that are capable of testing for neutrino oscillations with a δm^2 as low as 0.2 eV^2 if there is maximum mixing between two neutrino states.

THE ^{37}Cl EXPERIMENT

The operation and results of this experiment have been reported many times¹. The ^{37}Ar produced in 615 metric tons of C_2Cl_4 after exposing for 1 to 4 months is removed by a helium purge, purified, placed in a small proportional counter and counted for 100 to 300 days. The pulse height and pulse rise-time are measured to differentiate ^{37}Ar decay events from most events produced by background processes. The events having the correct pulse rise-time and pulse height for ^{37}Ar decays are resolved into a decaying component and a uniform background component (approximately 0.5 to 1 counts per month) by a maximum likelihood statistical method. The ^{37}Ar production rate observed in the detector over the period 1972-1979 is given in figure 1.

*Research carried out under the auspices of the United States Department of Energy under contract no. DE-AC02-76CH00016.

Backgrounds. To obtain the residual rate that could be attributed to neutrinos from the sun, the rate of ^{37}Ar production by cosmic-ray muons and by cosmic ray associated neutrinos must be determined and subtracted. This cosmic ray rate was estimated by exposing smaller tanks of C_2Cl_4 (11.2 m tons) at various levels in the mine from 25 to 1080 hg/cm^2 and extrapolating the observed rates to the full depth of the solar neutrino detector tank at 4400 hg/cm^2 .² This extrapolation of the measured values with depth is guided by the known variations of total muon intensity and average muon energy with depth, and the variation of the photonuclear cross-section with muon energy. The background ^{37}Ar production rate so derived in 615 m tons of C_2Cl_4 is 0.08 ± 0.03 atoms per day. Upon subtracting this background from the average ^{37}Ar production rate of 0.47 ± 0.05 atoms per day observed, one obtains the ^{37}Ar production rate that could be ascribed to solar neutrinos of 0.39 ± 0.06 per day. This rate corresponds to a solar neutrino rate of 2.1 ± 0.3 SNU (where SNU = solar neutrino unit 10^{-36} captures sec^{-1} target atom $^{-1}$). The cosmic ray background is presently the major uncertainty in determining the solar neutrino signal. E. L. Fireman (Smithsonian Astrophysical Observatory) is currently studying the photonuclear interactions of energetic muons as a function of the depth by a radiochemical method based upon the process $^{39}\text{K}(\mu^{\pm}, \mu^{\pm}\text{np})^{37}\text{Ar}$. His current results scaled to the ^{37}Ar production rate in C_2Cl_4 yield a background rate of 0.09 ^{37}Ar atoms per day for 615 m tons of C_2Cl_4 .³ Backgrounds from internal alpha contamination, and fast neutrons from the rock wall are negligibly small. The ^{37}Ar produced by cosmic ray produced neutrinos is calculated to be small, 0.0065 SNU².

Comparison with solar theory. The observed solar neutrino rate of 2.1 ± 0.3 can be compared to the rate of 7.8 ± 1.5 expected from the most recent standard model calculations.⁴ These results differ from earlier standard solar model calculations that gave an expected rate of about 5 SNU⁵ because improved opacities, solar composition and nuclear reaction cross-sections were used. Table 1 lists the neutrino capture cross-sections and the neutrino fluxes predicted by the most recent standard model calculation. Note that 6.3 SNU out of a total of 7.8 SNU arise from the low flux of energetic neutrinos from ^8B decay. This high capture rate results from the fact that ^8B decay

neutrinos have sufficient energy (0 to 14 Mev) to feed the analog state in ^{37}Ar at 5.2 Mev, a super allowed transition.

The production of ^8B in the sun is very sensitive to the internal temperatures. To account for the low neutrino capture rate observed in the chlorine experiment a number of solar models have been proposed in which various mechanisms are invoked to reduce the internal temperatures. These mechanisms include internal convection, periodic mixing, a fast rotating core, high internal magnetic fields, a helium rich core, and a depleted heavy element composition. The resulting models give a total neutrino capture rate in the range of 1-2 SNU⁶. However, none of these models has gained general acceptance because the mechanisms are considered unreasonable. Some have features that conflict with observations of the sun, or of other main sequence stars. One of the more attractive models with a low ^8B flux presumes that the proto-sun had a heavy element content (mostly C, N and O) a factor of ten lower than that presently observed in the sun's photosphere. This model gives a ^8B flux diminished by a factor of 10, and a total neutrino capture rate of 1.5 SNU.⁷

Neutrino oscillations. Of direct interest to this conference is the possibility that the low solar neutrino capture rate observed by the chlorine experiment is a result of neutrino oscillations as first suggested by Pontecorvo.⁸ The rate reported here is a factor of 3.9 ± 0.9 below the rate expected from the most recent standard solar model. This reduction factor could conceivably be explained by maximum mixing between three neutrino types. Because of the large distances involved a solar neutrino experiment is sensitive to very small neutrino mass differences ($\delta m^2 \sim 10^{-10} \text{ eV}^2$). A recent analysis by Barger, Whisnant and Phillips⁹ suggests that reduction factors of as much as 0.1 are possible. A recent analysis of the Zee model involving extra Higgs bosons leads to reduction in solar neutrino fluxes by a factor of 1/2 to 1/3.¹⁰ However, in view of the sensitivity of the ^{37}Cl experiment to the flux of ^8B neutrinos and of the strong dependence of the flux of these neutrinos on various solar processes, one should be very cautious in attributing the low observed rate to neutrino oscillations. On the other hand, the flux of the low energy neutrinos from the chain initiating

proton-proton reaction, is predicted with great certainty, and a measurement of the flux of these neutrinos could permit a valid test for neutrino mixing or oscillations.

NEW SOLAR NEUTRINO EXPERIMENTS AND NEUTRINO OSCILLATIONS

The proton-proton chain of reactions is almost certainly the primary source of the sun's energy. The indicated neutrino

sources in this chain of reactions are the $\text{H} + \text{H} \rightarrow \text{D} + \text{e}^+ + \nu$ reaction, ${}^7\text{Be}$ decay and ${}^8\text{B}$ decay. The fluxes of these neutrinos are listed in Table 1. A direct measurement of the solar neutrino spectrum would verify our present understanding of these processes. Unfortunately, observing low fluxes of low energy neutrinos is beyond our present capability. A method has been proposed based upon the ${}^{115}\text{In}(\nu, \text{e}^-){}^{115}\text{Sn}^* \rightarrow {}^{115}\text{Sn}$ reaction that is, in principle, capable of giving this information. A pilot indium detector with a $\sim 35\%$ resolution is being developed.¹¹ Another approach toward resolving the solar neutrino spectrum is a set of measurements with radiochemical detectors each having a dominant sensitivity to a particular neutrino source. Table 2 lists four radiochemical detectors that could be used. The table gives the total neutrino capture rates in SNU, the tons of the element needed to obtain a capture rate of 1 per day according to the standard model and the percent of the total signal that is produced by each neutrino source in the sun. Detectors based upon three of these inverse- beta processes would be capable

of resolving the solar neutrino spectrum: $^{71}\text{Ga}(\nu, e^-)^{71}\text{Ge}$ for the very low energy neutrinos from the H-H reaction, $^{71}\text{Br}(\nu, e^-)^{81}\text{Kr}^* \rightarrow ^{81}\text{Kr}$ for the monoenergetic ^7Be decay neutrinos, and $^{37}\text{Cl}(\nu, e^-)^{37}\text{Ar}$ for the energetic ^8B decay neutrinos.

Gallium. A solar neutrino detector based upon the ^{71}Ga isotope is the best choice to test the question of neutrino oscillations. The flux of the H-H reaction neutrinos is essentially independent of many of the parameters used in the model calculations such as opacities and solar composition, and within broad limits, internal structure. The rate of the H-H reaction is closely related to the solar luminosity, and the neutrinos from this reaction provide 67 SNU. If neutrinos oscillate between 2 or 3 states and the mixing is near to the maximum allowed, a rate below 30 SNU would result, and this could be observed with a 35-50 ton gallium detector. A pilot experiment is now in operation that uses 1.3 tons of gallium. The gallium is in the form of a water solution of gallium chloride and hydrochloric acid. The ^{71}Ge is removed from this solution as GeCl_4 by purging with gas. The extracted ^{71}Ge is converted to germane, GeH_4 , and counted in proportional counter. The next stage of development will be to build a similar system using 10 tons of gallium. With this 10 ton system a measurement will be made of the neutrino capture cross-reaction with a 2.5 M curie source of ^{51}Cr . This measurement will also serve as a test for neutrino oscillations over short distances. The project is a joint effort of the Max Planck Institute for Nuclear Physics, Heidelberg, the Weizmann Institute, the Institute for Advanced Study, Oak Ridge National Laboratory, the University of Pennsylvania and Brookhaven National Laboratory.

Bromine. The ^{81}Br - ^{81}Kr experiment was originally proposed as a test for variations in the solar neutrino luminosity over the last 10^5 years by measuring the ^{81}Kr (half-life 2.1×10^5 years) that would accumulate in a natural salt deposit.¹² Some recent developments have led us to consider using this reaction to observe the present ^7Be neutrino flux from the sun. Techniques have been developed at Oak Ridge National Laboratory that make it possible to measure a few hundred atoms of ^{81}Kr .¹³ It now appears feasible to fill the Homestake chlorine detector tank with a bromine compound ($\text{CH}_2\text{BrCH}_2\text{Br}$

or $C_2Cl_4Br_2$) and to measure the ^{81}Kr atoms that accumulate in a year (~ 300). Another important development is that Bennett and his colleagues have measured the electron-capture partial lifetime of the 13 second isomeric state in ^{81}Kr that is produced by neutrino capture.¹⁴ Their measurement allows the calculation of the neutrino capture cross-section, which in the past had to be estimated.¹⁵ A ^{81}Br solar neutrino detector has a high sensitivity to 7Be decay neutrinos and would serve to measure this important neutrino flux. The 7Be neutrinos are monoenergetic, an important consideration for studying neutrino oscillations.⁹ Ehrlich has already considered the possibility that the signal presently being observed by the ^{37}Cl experiment is perhaps mainly from 7Be decay neutrinos and it is possible that a change in the rate has been observed as an annual variation in earth-sun distance.¹⁶

Summary. The possibility of neutrino oscillations is obviously of great importance in the general field of neutrino astronomy and, more particularly, in the field of solar neutrino astronomy. Although the question raised by the results of the chlorine experiments can be answered by electron neutrino oscillations, these experimental results alone do not constitute conclusive evidence for neutrino oscillations. Many other explanations are possible. A logical step on the way to a full-scale gallium solar neutrino experiment is to calibrate a smaller gallium detector using a source of neutrinos with a known flux and energy. A similar source calibration of the present chlorine experiment is highly desirable. Although our principal objective is to study solar neutrinos, either of these calibrations could also easily serve as a neutrino oscillation experiment. A detailed consideration of such experiments is the topic of 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 .¹⁷

The general principles of a radiochemical 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 ^7Li , ^{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.¹⁸
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 difficulty in experiments of this type is that very large source strengths are required. With the strongest available reactor flux (the HFIR reactor at Oak Ridge) 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 (no more 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/cm³ of a neutrino absorbing isotope. From the definition of the cross-section σ , the neutrino capture rate R is given by $R = A G$ where $A = ns\tau$ depends on the physical properties of the source and absorber and

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

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.¹⁵ 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.

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 (m) from the source is given by the standard formula,

$$P(r) = 1 - \sin^2(2\theta_m) \sin^2(1.27 \delta m^2 r/E), \quad (2)$$

where θ_m is the mixing angle, δm^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).

Chlorine. We have two radiochemical experiments to search for neutrino oscillations under active consideration. 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 4.7 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 $\delta m^2 > 0.2 \text{ eV}^2$ 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.

Gallium. Another attractive experiment employs a target of a water solution of GaCl_3 .¹⁹ 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 1500 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 2.5 Mc source of ^{51}Cr 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 Figure 3. 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 the inner zone and the background in the outer zone has been assumed to have been measured to an accuracy of ± 0.25 atoms/day. This rate given for the outer zone had this known background subtracted with the errors combined in quadrature. 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 5. These regions happen to overlap to a considerable extent with the regions suggested by the reactor ν_e experiment of Reines et al.¹⁸ 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 5.

It is apparent from these figures that interesting neutrino oscillation experiments can be performed with a strong radioactive 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.

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Table 1
SOLAR NEUTRINO FLUXES* AND CROSS SECTIONS**

Neutrino Sources (in the sun)	Energies (in MeV)	Flux on Earth ϕ in $\text{cm}^{-2} \text{sec}^{-1}$	Cross Section σ in cm^2	Capture Rate ${}^{37}\text{Ar}$ $\phi\sigma \times 10^{36} \text{sec}^{-1}$ SNU
$\text{H} + \text{H} \rightarrow \text{D} + e^{+} + \nu$	0-0.42	6.1×10^{10}	0	0
$\text{H} + \text{H} + e^{-} \rightarrow \text{D} + \nu$	1.44	1.5×10^8	1.56×10^{-45}	0.23
${}^7\text{Be}$ decay	0.861	4.1×10^9	2.38×10^{-46}	0.98
${}^8\text{B}$ decay	0-14	5.85×10^6	1.08×10^{-42}	6.31
${}^{15}\text{O}$ decay	0-1.73	3.7×10^8	6.61×10^{-46}	0.24
${}^{13}\text{N}$ decay	0-1.19	4.6×10^8	1.66×10^{-46}	0.08

$$\Sigma\phi\sigma = 7.8 \text{ SNU}$$

* J. N. Bahcall, W. F. Heubner, S. H. Lubow, N. H. Magee, A. L. Mertz, P. D. Parker, B. Rozsnyai and R. K. Ulrich, Phys. Rev. Lett. 45, 945 (1980).

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

Table 2

COMPARISON OF RADIOCHEMICAL SOLAR NEUTRINO DETECTORS

Percent of signal from various solar neutrino sources, standard model

Neutrino Source	$^{37}\text{Cl}-^{37}\text{Ar}$	$^7\text{Li}-^7\text{Be}$	$^{71}\text{Ga}-^{71}\text{Ge}$	$^{81}\text{Br}-^{81}\text{Kr}$
$\text{H} + \text{H} \rightarrow \text{D} + \text{e}^+ + \nu$	0	0	65	0
$\text{H} + \text{H} + \text{e}^- \rightarrow \text{D} + \nu$	3	22	2	8
^7Be decay	12	10	27	69
^{13}N decay	1	3	1	4
^{15}O decay	3	21	3	10
^8B decay	81	44	2	9
$\int \phi \sigma$		7.8	41	16.5
Tons Element for 1 ν -capture/day	356	3.5	34	189

Table 3

Absorber	Source	Detected Isotope	A ($\text{cm}^{-1} \text{Mc}^{-1}$)
C_2Cl_4	^{65}Zn	^{37}Ar	1.12
7.1 M GaCl_3	^{51}Cr	^{71}Ge	2.84
7.1 M GaCl_3	^{65}Zn	^{71}Ge	3.67

Figure 2

Figure 3

Figure 4

Figure 5