A POSSIBLE EXPERIMENTAL METHOD FOR MEASUREMENT OF THE NEUTRINO FLUX FROM THE REACTION $e + {}^7Be \rightarrow {}^7Li + \nu_e$ IN THE SUN

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Abstract

The merits and principal limitations of an experiment to detect the solar neutrinos from the electron capture reaction $e^- + {}^7Be \rightarrow \nu^e + {}^7Li$ are discussed quantitatively, and proposals are made for a series of direct tests to determine the feasibility of the experiment.

Introduction

It has been apparent for several years that additional observations of neutrinos originating from various nuclear reactions in the sun would significantly improve our understanding of the sun, and possibly give rise to new information concerning the intrinsic properties of neutrinos, e.g., mass, degree of rigor with which they conserve separate lepton number, and stability against decay.

Promising proposals and plans for such observations, on which appreciable action is being taken, indicate that the concentration of present effort is aimed principally in two directions. *(i)* Several experiments seek to detect the energetic (0-14 MeV) neutrinos from the relatively rare decay ${}^8B \rightarrow {}^8Be + e^+ + \nu_e$, either by repeating[1] the pioneering radiochemical experiment of R. Davis, Jr. and his collaborators,[2] or by utilizing massive imaging water Cherenkov detectors[3] or a liquid argon detector[4] to observe the reaction $\nu_e + e \rightarrow \nu_e + e$ produced in real time by the neutrinos from ${}^8B$ decay.[3] *(ii)* Several other experiments seek to detect by radiochemical methods the abundant, low energy (0-0.42 MeV) neutrinos from the initial solar fusion reaction[5] $p + p \rightarrow d + e^+ + \nu_e$.

In this note we discuss (and repeat) arguments in favor of a solar neutrino experiment directed at a different solar reaction, namely, observation of neutrinos from the electron capture reaction $e + {}^7Be \rightarrow \nu_e + {}^7Li, (E(\nu_e) = 0.86\ MeV)$, and suggest an experimental method to observe those neutrinos. If the method is feasible, it would succeed also in detecting a fraction of the neutrino fluxes from the reactions $p + e^- + p \rightarrow d + \nu_e(E(\nu_e) = 1.44 MeV)$, ${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e(0 < E(\nu_e) < 1.19\ MeV)$,and ${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e(0 < E(\nu_e) < 1.70\ MeV)$. The expected total count rate, calculated as described below, would be approximately 0.45 cts per day per metric ton of detector, assuming the neutrino fluxes to be as predicted by the standard solar model.[6] If the reduction observed in the rate of ${}^8B$ neutrinos is assumed for all solar neutrino rates, the total count rate in the proposed experiment would be reduced by the factor 0.36.

In what follows we discuss the merits of the experiment, outline the experimental method and the possible limitation due to backgrounds, and propose a series of direct, relatively inexpensive tests to determine the feasibility of the method.

Merits of the Experiment

In the disposition of ${}^7Be$ in the sun, the electron capture reaction $e + {}^7Be \rightarrow \nu_e + {}^7Li$ is the alternate path to the proton capture reaction $p + {}^7Be \rightarrow \gamma + {}^8B$. This suggests that decisive information might be obtained from comparison of the total neutrinos fluxes $\phi_\nu(e7)$ and $\phi_\nu(p7)$ from the two reactions. Here $\phi_\nu(e7)$ and $\phi_\nu(p7)$ are the total neutrino fluxes in $\nu_e/(\mathrm{cm}^2 - sec)$ observed on earth from electron and proton capture, respectively, by ${}^7Be$.

In the standard solar model (SSM),[7] the rate of electron capture by ${}^7Be$ $(1/\tau(e7))$ is weakly dependent on the value of the temperature in the core ($r \leq 0.1\ R_\odot$) of the sun. The temperature dependence of $(1/\tau(e7))$ is $T_6^{-\frac{1}{2}}$ (with $T_6 = T/10^6\ {}^oK$), which arises from the coulomb wave functions that describe the electrons in the continuum states from which most ($\sim 80\%$) of the electron captures take place. As a result, measurement of $\phi_\nu(e7)$ would yield directly the product $n_e n_7$ in the core with small uncertainty due to the uncertainty in T_6. Here n_e and n_7 are the number densities of electrons and ${}^7Be$ nuclei, respectively.

In the standard solar model, the T_6- dependence of $1/(\tau(p7))$ is $T_6^{-\frac{2}{3}}\ exp(-102.7\ T_6^{-\frac{1}{3}})$, so that the uncertainty in T_6 dominates the uncertainty in the prediction of $\phi_\nu(p7)$, which depends also on the product $n_p n_7$, where n_p is the number density of protons.

It follows that the ratio $\tau(p7)/\tau(e7)$ depends on $(n_e/n_p)T_6^{\frac{1}{6}}$ $exp(-102.7\ T_6^{-\frac{1}{3}})$. The ratio n_e/n_p is of order unity, and not especially sensitive to variations in other parameters of the sun. Hence comparison of the measured values of $\phi_\nu(e7)$ and $\phi_\nu(p7)$ would yield directly T_6 with small uncertainty, since $\Delta T_6/T_6 \cong 0.07\Delta R/R$, where $R = \phi_\nu(e7)/\phi_\nu(p7)$.

Accordingly, in the absence of anomalous properties of neutrinos, measurement of $\phi_\nu(e7)$ and $\phi_\nu(p7)$ would accurately determine the quantities $n_e n_7$ and T_6. Accurate knowledge of $n_e n_7$ and T_6 should severely constrain the solar model. At present, the prediction of $\phi_\nu(p7)$ from the standard solar model is thought to be accurate within $\pm$ 40% (the effective 3σ-limit).[6] This implies either the same percentage uncertainty in the product $n_p n_7$ if T_6 is assumed perfectly known, or an uncertainty in T_6 of less than 1% if the uncertainty in the predicted value of $\phi_\nu(p7)$ is attributed to an uncertainty in T_6 .

It is unnecessary to elaborate here on the importance of a measurement of the neutrino flux $\phi_\nu(pp)$ from the reaction $p + p \rightarrow d + e^+ + \nu_e$. The rate of that reaction is closely related to the rate at which the sun is losing energy by photon emission from its surface, i.e., its luminosity, which is directly observed. The flux $\phi_\nu(pp)$ is only weakly dependent on possible errors in the SSM. Measurement of $\phi_\nu(pp)$, which hopefully might be accomplished in the next few years, would determine T_6 and n_p within narrow limits. A closely related reaction is $p + e + p \rightarrow d + \nu_e$, mentioned earlier.

If, therefore, $\phi_\nu(e7)$ and $\phi_\nu(pp)$ or $\phi_\nu(pep)$ were measured and $\phi_\nu(p7)$ remeasured, the possible general conclusions that might ensue appear to be three-fold. *(i)* The earlier measurement of $\phi_\nu(p7)$ was in error, and the new values of $\phi_\nu(e7)$, $\phi_\nu(pp)$, $\phi_\nu(pep)$, and $\phi_\nu(p7)$ agree well with the SSM. *(ii)* The earlier measurement of $\phi_\nu(p7)$ was correct, but relatively minor modification of the SSM suggested by the newly measured values of $n_e n_7$, n_p, and T_6 would be sufficient to obtain reasonable agreement between the SSM and experiment. *(iii)* The new measurements in conjunction with the older measurement yield values of $n_e n_7$, n_p, and T_6 that are incompatible with the SSM, which would suggest either major modification of the model or the presence of anomalous intrinsic properties of neutrinos.

In connection with (iii) above, there has been recent work[8] reviving and quantifying the possibility of neutrino oscillations in the sun as the source of the discrepancy between the SSM and the existing measurement of $\phi_\nu(p7)$. One feature of this work of particular relevance to the experimental proposal described here is the sensitive dependence on neutrino energy of the resonant vacuum-matter oscillation phenomenon. Stated briefly, it is suggested that lower energy ν_e, e.g., $\phi_\nu(e7)$, may not be subject to attenuation while higher energy ν_e, e.g., the upper end of the $\phi_\nu(p7)$ spectrum, may be completely converted into ν_μ. A second possible theoretical solution satisfying the resonance

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condition involves loss of the low energy ν_e and transmission of the higher energy ν_e. Accordingly, in the calculations that follow we have not automatically reduced all reaction rates by the factor (0.36) representing the discrepancy between the SSM and the measured value of $\phi_\nu(p7)$.

Experimental Method

Elementary considerations indicate that observation on earth of ν_e from the electron capture reaction in ^7Be may be possible in a detector designed to observe the reaction $\nu_e + e \rightarrow \nu_e + e$ in real time, provided that very serious background associated problems can be resolved. The SSM[6] gives $\phi_\nu(e7) = 0.42 \times 10^{10}\text{cm}^{-2}sec^{-1}$ at earth. The cross section for $\nu_e + e \rightarrow \nu_e + e$ at $E(\nu_e) = 0.86\ MeV$, the ν_e energy from $^7Be + e \rightarrow {}^7Li + \nu_e$, is $0.62 \times 10^{-44}\text{cm}^2$/electron. In liquid scintillator, the material of the proposed detector, there are $N_e \approx 3.4 \times 10^{29}$ electrons/metric ton. Hence $N_e\sigma(\nu_e e)\ \phi_\nu(e7) = 8.9 \times 10^{-6}\nu_e e$ reactions per metric ton per second or 0.77 $\nu_e e$ reactions per metric ton per day. The distribution in energy of the final state electrons is approximately flat in the interval $0 < E_e < 0.66\ MeV$. Assuming zero detection efficiency for events with $E_e < 0.25\ MeV$, and 80% detection efficiency for events with $0.25 < E_e < 0.66\ MeV$, yields an overall detection efficiency of approximately 50% for the electrons ($\overline{E}_e = 0.45\ MeV$) from $\nu_e + e \rightarrow \nu_e + e$. Consequently, 0.38 $\nu_e + e \rightarrow \nu_e + e$ reactions initiated by the ν_e from $\phi_\nu(e7)$ would be observed per day per metric ton of detector.

A similar calculation indicates that 0.031 cts per day per metric ton would be produced by $\phi_\nu(pep)$, 0.014 cts per day per metric ton by $\phi_\nu(^{13}N)$, and 0.023 cts per day per metric ton by $\phi_\nu(^{15}0)$, all in the absence of any corrections arising from the discrepancy between the measured and predicted values of $\phi_\nu(p7)$ or from the loss of neutrinos in transit from the sun's core to the earth. Hence the fluxes $\phi_\nu(pep), \phi_\nu(^{13}N)$, and $\phi_\nu(^{15}0)$ would contribute 15% of the expected total event rate.

Consider a detector consisting of a central sphere of liquid scintillator, say, 6m in diam (98 metric tons) enclosed in an hermetic water shield 5m thick. Let the central sphere be surrounded by 1000 photomultiplier tubes (PMT), each 0.50m in diameter, located on the surface of a concentric sphere 12m in diameter. The area of the outer spherical surface is $452m^2$, and the photocathode area of a single PMT is $0.2m^2$, so that a single PMT subtends 4.4×10^{-4} of the total area of the outer sphere.

Apart from the central scintillator sphere, the 3 metric kiloton imaging water cherenkov detector (Kamiokande II) in Japan, initially designed to search for nucleon instability, would serve as a model for the detector described above.[9] Kamiokande II has 1000 PMT of $0.50m$ diameter arranged over the entire surface of a cylinder at a distance of $7m$ from the geometrical center. The response of the PMT in Kamiokande II and the possible use of that detector for an *in situ* test of the experimental method proposed here are discussed below.

An electron of 0.45 MeV kinetic energy is a point source of $0.45 \times 10^6 eV/150eV$ /photon = 3000 photons of scintillation light in liquid scintillator. Thus, a single PMT would intercept about 0.48 photon of scintillation light from a 0.45 MeV electron in the inner sphere, when light absorption ($\lambda_{abs} \cong 3m$) of the liquid scintillator is taken into account. The PMT have on average a photocathode efficiency of 0.2 photoelectron/incident photon. Hence it follows that (0.48 photon/PMT x 0.2 photoelectron/photon $\times$ 1000 PMT =) 96 photoelectrons would be randomly distributed among 96 PMT of the detector, each with an output signal corresponding to 1 photoelectron, for every 0.45 MeV deposited in the liquid scintillator. With 53 and 138 photoelectrons expected from depositions of 0.25 and 0.65 MeV, respectively, it should be possible with a few hundred events (1 to 2 months of data) to confirm that the shape of the energy distribution of the electrons from $\nu_e + e \rightarrow \nu_e + e$ is approximately flat as expected theoretically.

Another feature of the detector that would provide useful information on the signal and aid in discriminating against background which penetrates the water shield and produces light in the scintillator is the fast timing possible with the large diameter PMT and the fast response of the scintillator. The PMT have a spread in time of different trajectories from the photocathode to first dynode given by a σ of $4ns$ at 1 photoelectron level. With this as the limiting factor in a timing measurement, it should be possible to locate a low energy ($\leq 1MeV$) electron in the scintillator within a sphere of radius $0.3m$. That uncertainty follows from the flight path of the light and the average index of refraction of the detector material. One has $1/v = 4.5ns/m$, so that two light paths originating in the central sphere and differing in path length by $0.3m$ would arrive at PMT separated in time by $2.8ns$. Many pairs of diametrically opposite PMT will receive signals from an event, and thus a path difference of $\pm$ 0.3 m can on average be measured. It follows that low energy (point) sources of light would be located in the central sphere with a precision of about 0.1 the radius of the sphere by the timing measurement.

In addition, the location of an event in the central sphere can be checked independently by the areal density of PMT that receive light. The areal density is particularly sensitive to events close to the periphery of the central sphere. It appears likely, therefore, that a radial distribution (of 10 bins of $0.3m$ width) of events observed in the central sphere would indicate the presence of background entering the sphere from outside, and yield an estimate of its magnitude.

Backgrounds

Background events, e.g., throughgoing or stopping muons, that deposit large amounts of energy ($\geq 100\ MeV$) in the central sphere or in the water shield would be recognized directly and vetoed. Medium energy events ($\geq 10\ MeV$) in the scintillator would be recognized by the large number and random pattern of struck PMT; such events in the water shield would involve a small number of struck PMT exhibiting a pattern appropriate to a cherenkov cone of light production.

The background emanating from the walls of the underground cavity in which the detector would be located will interact and be largely absorbed or vetoed in the $5m$ water shield as indicated by direct calculation. This conclusion, amongst others below, needs empirical confirmation.

The sources of background that will be most severe are *(i)* radioactivity in the water shield and the PMT, and *(ii)* radioactivity in the liquid scintillator and its container.

(i) The uranium (thorium) content of the water in the shield might be expected to about $5 \times 10^{-10}\text{gm/cm}^3$, which is the measured value for most water in the absence of effort to remove the heavy metal ions. In the water shield there would be $1.0gm$ or $2.5 \times 10^{21}U$ nuclei which would decay at the rate of $1.2 \times 10^4 sec^{-1}$. The thorium series would increase this rate by a factor of 1.35, if the mass of thorium were equal to the mass of uranium. All electrons will range out before entering the liquid scintillator, and the low energy photons that do enter the central sphere will exhibit an exponential decrease in intensity with penetration distance. Finally, a reduction in the U and (Th) content of the water by a factor of 10^3 can be achieved by ion exchange. These factors would reduce the background counting rate in the central sphere due to radioactivity in the water shield to less than one count per day. This rate limit must be confirmed by direct measurement in a prototype detector, as described below.

The contribution to the background of radioactivity in the PMT should be absorbed by the water shield. It also has been observed to have an unique signature consisting of a large pulse height (> 5 photoelectrons) in a single PMT which would serve as an efficient veto signal.

(ii) Radioactivity in the scintillator material itself is the most serious potential source of background. If the contribution to the count rate in the interval $0.25 < E_e < 0.65$ Mev in the scintillator sphere is to be less than 10 per day from the possible major radio isotope contaminants, ^{40}K and ^{238}U, their limiting levels are approximately : for ^{40}K(beta spectrum endpoint 1.35 MeV, $T_{\frac{1}{2}} = 1.3 \times 10^9$yr), 1.3×10^5 ^{40}K nuclei/cm^3, or equivalently 1.3×10^9 K nuclei/cm^3 corresponding to 5×10^{-14}gm

of K per cm^3 of scintillator; for ^{238}U, the number density is 0.3×10^6/cm^3 or 10^{-16}gm of ^{238}U per cm^3 of scintillator.

The difficulty posed by the need for these low concentrations may be intractable. We have, however, verified that no appreciably quantities of radioactive materials are present in the liquid scintillator intended for the central sphere. Radioactivity from ^{14}C, ^{40}K, ^{208}Tl, and ^{238}U in small scintillator samples is below the sensitivity of carbon dating[10] and double beta decay counting systems.[11] Note also that the scintillator is 85 to 90% by weight refined mineral oil, which has been measured[12] to contain less than 5×10^{-10}gm/cm^3 of uranium. The organic fluor and solvent in the scintillator can be manufactured to be free of any but small amounts of induced short-lived radioactivity.

The measured limit quoted above on the uranium contamination in the liquid scintillator was obtained by mass spectrometry, and will soon be inproved by a factor of 10^3 or more. It may also be possible to reduce the limit further by slow neutron activation and subsequent counting of the short lived activity of one of the fission products. Similarly, a search will soon be made for the presence of potassium in the scintillator by mass spectrometry and, if necessary, by slow neutron activation of ^{41}K. Depending on the magnitude and chemical nature of any radioactive compound that is found, it is possible to consider purification, e.g., by ion exchange and distillation, of the materials of the scintillator.

In Situ Test

Even if the results of the direct tests for radioactive contamination of the scintillator are encouraging, it is unlikely that they will provide conclusive evidence for the feasibility of the experimental method proposed here. An *in situ* conclusive test can be made as follows. A small scintillator sphere ($\sim$ 1.0m diameter, 0.46 metric ton) can be constructed and suspended at the center of, say a 6m diameter spherical water shield equipped with 10^2 PMT (0.5m diam.) following the Kamioka design, which would allow a direct measurement of the background level at the center of the water shield at relatively low cost. This test would be sensitive to radioactive contamination in the liquid scintillator at the following levels: for 1 count/day from ^{40}K/cm^3 or 10^{-12}gm K/cm^3; for 1 count/day from ^{238}U, the level would be 2×10^{-15}gm/cm^3. Hence a test of one month duration would yield the contamination limits necessary to evaluate the full scale experiment. Furthermore, the test would provide a direct determination of the effect of a 3m water shield, and allow a more accurate extrapolation to a 5 or 6m radius shield. An alternative test arrangement might be to suspend the liquid scintillator sphere in Kamiokande II.

Summary

There exists the possibility of a real time measurement of the solar neutrino flux $\phi_\nu(e7)$ from the reaction $e^- + {}^7Be \rightarrow \nu_e + {}^7Li$. Additional contributions to the observed counting rate amounting to 18% of the rate from $e^- + {}^7Be \rightarrow \nu_e + {}^7Li$ would be made by $\phi_\nu(pep), \phi_\nu(^{13}N)$, and $\phi_\nu(^{15}0)$.

In an appropriately shielded, massive (98 metric ton) sphere of liquid scintillator the expected total count rate would be 45 per day, or 16 per day under the assumption that neutrinos from all reactions in the sun are reduced by the same factor (0.36) as the neutrinos from ^8B appear to be. The signal produced by the solar neutrinos through the reaction $\nu_e + e \rightarrow \nu_e + e$ in the scintillator would be clear and identifiable. The feasibility of the measurement depends critically on the radioactivity present in the shield and liquid scintillator, and on the degree of success in purifying those materials. Direct chemical measurements of the radioactive contamination are in progress. Furthermore, by making use of a scaled down version of the imaging water cherenkov detector in Kamiokande II, it is possible to determine empirically the background level crucial to the experiment in an experimental arrangement similar in all essentials to that which would be employed in a final experiment. Alternatively, Kamiokande II itself might be used for *in situ* testing.

The result of this experiment in conjunction with the results from the previous and planned measurements of the solar neutrinos from the reactions $p + {}^7Be \rightarrow {}^8B + \gamma$ (and the beta-decay of ^8B), and $p + p \rightarrow d + e^+ + \nu_e$ would significantly improve our understanding of the sun, and possibly cast new light on the intrinsic properties of neutrinos.

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