An Alternate Resolution of the Solar Neutrino Problem

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The solar neutrino problem for the various neutrino detectors appears to lie in not understanding and analyzing adequately how the neutrinos interact with the various detector materials. The measured data were not properly interpreted, resulting in miscalculation of the neutrino fluxes measured. This gave the appearance of the detectors not seeing fractions of the neutrinos expected. By modeling nucleons as collections of electron-like and positron-like particles, I show that the ^{37}Cl, ^{71}Ga, H_2O and D_2O detectors all saw the electron neutrino flux predicted by the Standard Solar Model.

1 Introduction

For nearly 40 years a problem plagued physicists and astronomers. Based on models of what occurs at the core of the Sun, physicists determined that a substantial number of neutrinos should be produced. Using data about the Sun's energy production, they calculated how many neutrinos the Sun should produce and what neutrino flux should reach the Earth. Subsequently, several experiments were performed to measure and verify the flux calculations.

However, the early experiments found that only a fraction of the predicted flux appeared to reach the Earth. This discrepancy became known as the solar neutrino problem. It was not resolved until one experiment claimed to show that the neutrinos produced by the Sun changed flavors as they traveled to Earth, causing only a fraction to be measured by detectors that could only see one flavor.

1.1 Discovery of the Problem

In 1964, John Bahcall did a calculation to predict how many of the neutrinos created by the Sun should reach Earth.[1] The calculation was based on a model of the thermonuclear fusion proposed to be taking place at the core of the Sun by Hans Bethe. Bethe proposed that, initiated by the proton-proton reaction, the reactions in Table 1 should produce electron neutrinos with the energy thresholds listed.[2] Bahcall determined that each of the neutrinos should produce the flux shown.

Table 1. Neutrino producing reactions in the Sun's core

No.	Label	Reaction	ϕ_ν ($cm^{-2}s^{-1}$)	E_ν (MeV)
1	*pp*	$p + p \rightarrow {}^2H + e^+ + \nu_e$	5.95×10^{10}	≤ 0.42
2	*pep*	$p + e^- + p \rightarrow {}^2H + \nu_e$	1.40×10^8	1.44
3	*hep*	${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	9.30×10^3	≤ 18.77
4	^7Be	${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	4.77×10^9	0.86
5	^8B	${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	5.05×10^6	< 15
6	^{13}N	${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	5.48×10^8	≤ 2.22
7	^{15}O	${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	4.80×10^8	≤ 2.75
8	^{17}F	${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$	5.63×10^6	≤ 2.76

In 1965, Raymond Davis began constructing an experiment to detect solar neutrinos.[3] The detector was built deep underground in the Homestake Gold Mine in South Dakota.[4] It was a tank filled with 380,000 liters of the dry-cleaning fluid perchloroethylene (C_2Cl_4). The detector relied on the neutrinos to react with ^{37}Cl in C_2Cl_4 to form radioactive ^{37}Ar per the reaction $^{37}Cl + \nu_e \rightarrow {}^{37}Ar + e^-$. After an exposure period of up to 200 days, the ^{37}Ar was extracted from the tank and counted to see how much the neutrinos produced.

The neutrino reaction with ^{37}Cl only occurred for neutrinos with energies greater than 0.81 MeV. Therefore, as Table 1 indicates, it could not see the bulk of the neutrinos, thought to be produced by the *pp* reaction. Initially, Bahcall calculated that the ^{37}Cl detector should see a flux of 5.8 solar neutrino units (SNU), where 1 SNU = 10^{-36} neutrinos per target atom per second, while Davis measured only 1.8 SNU.[5] In the end, with some calculation and data analysis refinements, the calculated flux rose to 7.6 SNU, while the measurement increased to 2.56 SNU.[6] This suggested that the detector was seeing only ⅓ of the neutrinos the calculation predicted. So, was the calculation right and the measurement wrong? Was the measurement right and the calculation wrong? Or, were they both wrong?

1.2 Resolution of the Problem

According to the latest experiments, they were both right. Fast-forward about 30 years and enters the Sudbury Neutrino Observatory (SNO). The SNO neutrino detector was another tank buried underground, but in Canada.[7] Instead of C_2Cl_4, it was filled with deuterium (D_2O). By then, it had been determined that three types or "flavors" of neutrinos existed: electron, ν_e, muon, ν_μ, and tau, ν_τ. While the ^{37}Cl in the Homestake detector could only see electron neutrinos, the D_2O in the SNO detector could detect and measure all three flavors of neutrinos.

In 1957, Bruno Pontecorvo had floated the idea that neutrinos could change flavor while traveling through the vacuum of space.[8] The solar neutrino problem caused it to gain traction. By the time of SNO, so-called "neutrino oscillations" were thought to be causing the problem. The thinking was that by the time the neutrinos from the Sun reached Earth, ⅔ of them had changed into either muon or tau neutrinos, leaving only ⅓ as electron neutrinos for the ^{37}Cl detector to see.[9]

The solar neutrinos can react with the D_2O in SNO in three ways.[10] An electron neutrino, ν_e, can react with a deuteron causing it to split into two protons and an electron ($\nu_e + d \rightarrow p + p + e^-$). This is called a charged current (CC) reaction. Any neutrino, ν_x, can cause an electron in the D_2O to scatter and give off Cerenkov radiation ($\nu_x + e^- \rightarrow \nu_x + e^-$), the so-called elastic scatter (ES) reaction. Finally, any neutrino can react with a deuteron, causing it to break up into a neutron and a proton ($\nu_x + d \rightarrow n + p + \nu_x$). This is the neutral current (NC) reaction. The SNO experiments found that the NC reaction, which can see all neutrinos, saw a flux of 5.44 x 10^6 $cm^{-2}s^{-1}$, while the CC reaction, which sees only electron neutrinos, saw 1.75 x 10^6 $cm^{-2}s^{-1}$, about ⅓ of what the NC reaction saw.[11] This seems to show both Bahcall's calculation and Davis' measurement were right. It appears ⅔ of the neutrinos changed flavor before reaching Earth.

1.3 There's Still a Problem

Between the time of the Homestake experiments and the SNO experiments a couple of other experiments attempted to measure the solar neutrino flux using gallium. Initially, the Gallium Experiment (GALLEX),[12] and later the Gallium Neutrino Observatory (GNO),[13] built in Italy, used gallium chloride ($GaCl_2$) to exploit the reaction $^{71}Ga + \nu_e \rightarrow {}^{71}Ge + e^-$, where neutrinos interact with ^{71}Ga to produce ^{71}Ge. Like ^{37}Ar, ^{71}Ge is radioactive and can be chemically extracted and counted to determine how many neutrinos the detector saw during the exposure period. Unlike ^{37}Cl, the ^{71}Ga can see neutrinos with energies down to 0.233 MeV, allowing it to see the neutrinos from the *pp* reaction. Bahcall's calculation for the flux the ^{71}Ga detectors should see came to 129 SNU.[14] After 123 runs, the measured fluxes from the GALLEX/GNO detectors averaged 69.3 SNU, 54% of the predicted value.[15]

The other gallium experiment was the Soviet-American Gallium Experiment (SAGE) built in Russia.[16] SAGE used a gallium-germanium telescope made of liquid gallium metal. After 92 runs, it measured an average solar neutrino flux of 70.8 SNU, about 55% of the predicted value, but in good agreement with the GALLEX/GNO measurement.[17] The two, being completely independent, validate the fluxes they measured.

This creates a problem. Table 2 compares the ^{37}Cl and ^{71}Ga predictions and results. Like the ^{37}Cl reaction, the ^{71}Ga reaction can only see electron neutrinos. So, if the ^{71}Ga can see 54% of the solar neutrinos arriving at Earth, why is it that the ^{37}Cl and CC reaction in D_2O can only see 33%? This seems to suggest that something other than neutrinos changing their flavor is causing the discrepancies between the calculated and measured flux values. If only ⅓ of the solar neutrinos are making it to Earth as electron neutrinos, then the ^{71}Ga should see only about 43 SNU.

Table 2. Neutrino fluxes predicted for ^{37}Cl and ^{71}Ga

Label	E_ν (MeV)	ϕ_ν ($cm^{-2}s^{-1}$)	ϕ_{Cl} (SNU)	ϕ_{Ga} (SNU)
pp	≤ 0.42	5.95 x 10^{10}	0.0	69.6
pep	1.44	1.40 x 10^8	0.2	2.8
hep	≤ 18.77	9.30 x 10^3	0.0	0.0
^7Be	0.86, 0.38	4.77 x 10^9	1.15	34.4
^8B	< 15	5.05 x 10^6	5.9	12.4
^{13}N	≤ 2.22	5.48 x 10^8	0.1	3.7
^{15}O	≤ 2.75	4.80 x 10^8	0.4	6.0
^{17}F	≤ 2.76	5.63x 10^6	0.0	0.1
Total			7.75	129.0
Measured			2.56	70.0
Fraction			0.33	0.54

To further compound the problem, another experiment, Super-Kamiokande, used ultra-pure water buried in the mountains of Japan to detect the solar neutrinos using an H_2O version of SNO's ES reaction ($\nu_x + e^- \rightarrow \nu_x + e^-$).[18] Because the neutrinos scatter off electrons in the atom's electron orbitals, the ES reactions for D_2O and H_2O are essentially the same. They should see the same solar neutrino flux. And, indeed they do. Super-Kamiokande measured a solar neutrino flux of 2.32 x 10^6 $cm^{-2}s^{-1}$ compared to the SNO ES reaction flux of 2.39 x 10^6 $cm^{-2}s^{-1}$. Both are about 46% of the total neutrino flux determined by the SNO NC reaction.

Super-Kamiokande attributes all the measured neutrinos to electron neutrinos from the ^8B reaction in the Sun, while SNO claims that some of the neutrinos are muon and tau neutrinos. If all the neutrinos Super-Kamiokande sees are electron neutrinos, then it seeing only 46% of the predicted solar neutrino flux is the third different fraction of solar neutrinos seen arriving at Earth. Three different detectors see three different fractions of solar neutrinos from the Sun.

According to SNO, the ES reaction can see all flavors of neutrinos but is six times more sensitive to electron neutrinos. Since the ES reaction can see all flavors of neutrinos, it was assumed the SNO value is the sum of the electron neutrino flux measured in the CC reaction, plus a small number of muon and tau neutrinos. In light of the SNO measurements, the Super-Kamiokande measurement may, too, be the 33% of solar neutrinos to reach the Earth as electron neutrinos plus some muon and tau neutrinos. However, before the SNO experiments, the Super-Kamiokande flux was thought to be all electron neutrinos.

There is a given flux of neutrinos arriving at Earth from the Sun. The fact that the three different detectors measure three different values of the flux appears to indicate that there is something wrong with the measurements – all the measurements. Therefore, before asserting that there is something unknown about the neutrino flux, efforts should be made to reconcile the differences between the detectors.

2 What Did Sudbury Really See?

From the Sudbury experiment, when an electron neutrino interacts with a deuteron, two things can happen. It can be absorbed and reemitted, causing the deuteron to split into a proton and a neutron – the NC reaction; or it can be absorbed and reemitted as an electron, causing the deuteron to split into two protons – the CC reaction. In both cases, the deuteron absorbs the electron neutrino. The question is, what cause the reaction to go charged or neutral? The answer may be found by using a model of the nucleons different from that of the Standard Model.

2.1 Alternate Particle Models

The Standard Model of Particle Physics models protons and neutrons as three quarks. However, electron-proton deep inelastic scattering can be interpreted to show that protons and neutrons are made of either nine muons[19,20] or eight pions[21,22]. In turn, the muons and pions are made of particles resembling free electrons and free positrons that can be called beta electrons and beta positrons. The proton appears to contain 918 beta positrons and 917 beta electrons, while the neutron contains 919 beta positrons and 919 beta electrons.

The difference between a free electron and a beta electron is that the free electron is a beta electron coupled with an electron neutrino. This is what makes the magnetic moment of the free electron slightly greater than the Bohr magneton. The free electron is a beta electron in a high-frequency orbit around an electron neutrino.[23,24] Likewise, a free positron is a beta positron in a high-frequency orbit around an electron antineutrino. These models set up an interesting situation.

2.2 The $\nu_e + d$ Reaction

From Table 1, the *pp* reaction that forms a deuteron in the core of the Sun is $p + p \rightarrow {}^2H + e^+ + \nu_e$. This reaction proceeds very slowly within the Sun's core. What appears to happen is that when the two protons fuse into a diproton, one of the beta positrons in the nucleus must be emitted for the deuteron to form. However, the appearance of the electron neutrino signals that, during the collision of the two protons, an electron neutrino – antineutrino pair was formed.

One of the beta positrons captured the antineutrino to become the free positron. This left the electron neutrino to exit the reaction along with the newly formed positron. When the beta positron is removed from the proton, it leaves it with the same number of beta positrons as beta electrons, rendering it neutral. This makes what was a diproton, a deuteron. It has one charged nucleon and one neutral one.

An electron neutrino with enough energy can interact with a deuteron, causing its two nucleons to separate. The neutrino can interact with either a beta electron or beta positron in either nucleon. This sets up four possible scenarios for the interaction: the neutrino can interact with a beta positron in the charged nucleon; it can interact with a beta electron in the charged nucleon; it can interact with a beta positron in the neutral nucleon; or the neutrino can interact with a beta electron in the neutral nucleon. Fig. 1 shows the reactions.

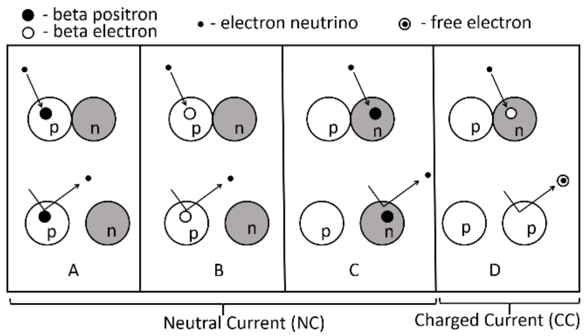

Fig. 1: The ν_e + *d* reaction in SNO
Four frames showing how the electron neutrino interacts with the deuteron. In frame A, the neutrino interacts with a beta positron in the positive nucleon of the deuteron, breaking it into a proton and a neutron as it scatters off. In frame B, the neutrino scatters off a beta electron, breaking the deuteron into a proton and a neutron. In frame C, the neutrino scatters off a beta positron in the neutral nucleon of the deuteron, again breaking it into a proton and a neutron. In frame D, the neutrino collides with a beta electron in the neutral nucleon and couples with it to form a free electron, converting the neutral nucleon into a positive one. The collision breaks the nucleus up into two protons. The first three reactions are the neutral current (NC) reactions and the fourth reaction is the charged current (CC) reaction in SNO.

Since electron neutrinos only couple with beta electrons to form free electrons, interactions with the beta positrons only cause the neutrinos to scatter after separating the positive and neutral nucleons. If the electron neutrinos interact with beta electrons in the deuteron, they can form the free electrons seen emanating from the CC reactions. However, the free electron is only emitted when the deuteron separates into two protons. This indicates that the neutrino can only couple with a beta electron in the neutral nucleon to form the free electron. Apparently, the neutral nucleon will give up a beta electron to become a +1 nucleon, but the +1 nucleon will not give up one to become a +2 nucleon, which does not occur in nature.

2.3 The Sudbury ν_e Flux

Of the four possible scenarios the neutrino interaction with the deuteron can take, only one can produce a free electron. Assuming all four scenarios have an equal probability of occurring, one would expect the one with the neutrino forming the free electron to occur ⅓ as many times as the ones just scattering the neutrino. This explains why the Sudbury NC reaction saw three times as many neutrinos as its CC reaction.

The NC reaction was not seeing all the neutrinos, it was only seeing the electron neutrinos that interacted with either the beta positrons in the deuterons or beta electrons in the charged nucleons of the deuterons. Consequently, both the CC and the NC reactions are seeing only electron neutrinos and the total number of electron neutrinos Sudbury saw is the sum of the CC and NC fluxes. The fact that the NC reaction saw only three times the neutrinos the CC reaction did indicates that the neutrinos it saw were electron neutrinos.

3 What Did the Gallium Detectors See?

In light of the reanalysis of the Sudbury data, it is useful to revisit the results of the other neutrino detectors. The two gallium detectors, GALLEX/GNO and SAGE, both reported about 55% of the expected neutrino flux from the Sun. Those detectors relied on the neutrinos interacting with ^{71}Ga to form radioactive ^{71}Ge via the reaction $^{71}\text{Ga} + \nu_e \rightarrow {}^{71}\text{Ge} + e^-$.

The ^{71}Ga nucleus has 71 nucleons, of which, 31 are positive and 40 are neutral. The ^{71}Ge nucleus also has 71 nucleons, but 32 of them are positive. From the reaction, like the $\nu_e + d$ reaction in SNO, it appears the neutrino interacts with a beta electron in the ^{71}Ga nucleus to form a free electron. Once the free electron exits the nucleus, it leaves it with 32 positive nucleons, making it ^{71}Ge. However, unlike the deuteron, where its two nucleons are held together by one bond, the nucleons in the ^{71}Ga nucleus are all held in the nucleus by multiple bonds. Because of this, the neutrino cannot separate a nucleon from the nucleus when it interacts with the nucleus.

As is the case with the deuteron, the electron neutrino can interact with a beta electron or beta positron in the ^{71}Ga nucleus. When it interacts with a beta positron, it just scatters off it because it cannot couple with it to form a free positron. Only the electron antineutrino can do that. Since the neutrino cannot breakup the ^{71}Ga nucleus, there is no indication that it scattered off it, as was the case with the deuteron. It cannot be seen. When the neutrino interacts with a beta electron in ^{71}Ga, it can create a free electron and form radioactive ^{71}Ge. This interaction can be seen.

Assuming the neutrino can interact with any nucleon in the ^{71}Ga with equal probability, it can interact with 31 positive nucleons and 40 neutral nucleons. If, like in the deuteron, only the neutral nucleon will give up a beta electron to the electron neutrino to form a free electron, then the neutrinos will also scatter off the beta electrons in the positive nucleons, leaving no sign of the interaction. Consequently, only 40 of the 71 possible interactions can be registered by the detector, 56%. This is essentially the same fraction of the predicted electron neutrino flux the two gallium detectors saw. So, it seems the gallium detectors were seeing the full flux but could only show 56% of it.

4 What Did the Chlorine Detector See?

Like the gallium detectors, the chlorine detector relies on the electron neutrino to convert a stable isotope, ^{37}Cl, into radioactive ^{37}Ar by coupling with a beta electron. Since the reaction, $^{37}\text{Cl} + \nu_e \rightarrow {}^{37}\text{Ar} + e^-$, is similar to the ^{71}Ga reaction, one might expect a similar measurement result. There are 37 nucleons in ^{37}Cl and 20 of them are neutral. Therefore, the detector should see 20 out of every 37 interactions, or 54% of the predicted solar neutrino flux. However, the Homestake detector only measured about 33% of the predicted flux. What is causing the discrepancy between the two?

4.1 Interpreting the ^{37}Cl Detector Data

The electron neutrino flux the detector saw during the exposure period is related to how much ^{37}Ar was produced in the detector. This is determined by collecting the ^{37}Ar gas from the detector and counting the radioactive disintegrations it produces in a counter. The general expression used to determine the ^{37}Ar production rate, p, from the number of ^{37}Ar decays the counter counts, N_c, is

$$p = \frac{N_c \lambda}{1 - e^{-\lambda t_{exp}}} = N_c \lambda' , \qquad (1)$$

where λ is the ^{37}Ar decay constant and t_{exp} is the exposure time of the ^{37}Cl to the neutrinos. This indicates that the number of ^{37}Ar nuclei produced is essentially proportional to the ^{37}Ar decay constant, which is inversely proportional to its half-life. Therefore, if the half-life for the neutrino-induced ^{37}Ar nuclei is shorter than that of the proton/deuteron induced ^{37}Ar nuclei; then its decay constant would be larger, and the calculated ^{37}Ar production rate would be greater.

4.2 The Same, But Different

The ^{37}Ar is created in the laboratory by bombarding ^{37}Cl with either a proton or a deuteron, $^{37}\text{Cl} + p \rightarrow {}^{37}\text{Ar} + n$, or $^{37}\text{Cl} + d \rightarrow {}^{37}\text{Ar} + 2n$. The mass of the resulting ^{37}Ar nucleus, at 36.956690 u, is greater than the ^{37}Cl nucleus mass of 36.956577 u. The collision increases the mass of the nucleus.

This likely happens because during the collision, the proton or deuteron transfers one of its beta positrons to one of the neutral nucleons in the ^{37}Cl. This makes it a positive nucleon, and the nucleus ^{37}Ar. This ^{37}Ar nucleus has a half-life of about 35 days.

When ^{37}Ar is created by with an electron neutrino interacting with ^{37}Cl, the neutrino apparently couples with one of the beta electrons in a neutral nucleon in the nucleus. This results in the formation of a free electron, which exits the nucleus. Now, the nucleus has 18 positive nucleons, making it ^{37}Ar.

The loss of the beta electron should make the mass of the resulting ^{37}Ar nucleus less than that of the ^{37}Cl nucleus. This means the ^{37}Ar nucleus from neutrino interaction is different from that created in the lab.

This begs the question, do the different configurations of ^{37}Ar decay at different rates? Does the nuclear configuration determine the half-life? If so, then the neutrino flux value determined using the laboratory ^{37}Ar half-life of 35 days is probably incorrect.

4.3 Revised ^{37}Cl Analysis

All the analyses of the Homestake detector data was done using the lab ^{37}Ar half-life of about 35 days. There was no reason for those running the experiment and analyzing the data to believe that the half-life would be anything but 35 days. The Standard Model of Particle Physics does not indicate that the formation of a ^{37}Ar nucleus from ^{37}Cl could produce more than one configuration of the ^{37}Ar nucleus. The only way to have known that the half-life was different would have been to analyze the ^{37}Ar decay data with the intent of determining its half-life.

The Homestake team did consider analyzing the decay data to determine if it indicated a 35-day half-life, but not to acknowledge that the ^{37}Ar was decaying at a different rate. Instead, the analysis was to confirm that they were analyzing ^{37}Ar. If the analysis had shown a different half-life, then the sample would have been considered either contaminated or just not ^{37}Ar. They would not have considered gas extracted from the detector with a half-life other than 35 days to be ^{37}Ar.

The count rates were so low for the ^{37}Ar samples extracted from the detector after ^{37}Cl exposure, that they were generally not useful for determining the ^{37}Ar half-life. However, there may be enough information in them to determine if the half-life of ^{37}Ar extracted from the detector was 35 day, or if it was greater than or less than that value. If the indication is that the half-life is less than the 35-day half-life of lab ^{37}Ar, it will be a validation of the ^{37}Ar formation models suggested above for proton/deuteron collision with the ^{37}Cl nucleus and neutrino interaction with the ^{37}Cl.

Table 3 gives a summary of the useful data taken from the Homestake detector from 1970 through 1975. There are 19 runs listed, with ^{37}Cl exposure times ranging from 33 to 216 days. After the ^{37}Ar gas was extracted from the detector, it would be counted for up to as many as seven times for a duration of about 35 days each time (one half-life).

The number of counts recorded in the first period after ^{37}Ar extraction are very low, with only runs 19 and 27 making it to 10 and 11, respectively. Most of them are less than six, and there appears to be no correlation between number of counts and exposure time.

Of the two runs with the highest counts, the source document indicated that run 27 may be contaminated. Therefore, run 19 will be used here to try to get a sense of what the half-life is of the neutrino induced ^{37}Ar. Its exposure time is t_{exp} = 112 days.

Table 3: Homestake ^{37}Cl neutrino detector counting results from 1970 – 1975 [25]

	Exposure period		Counts (~ 35-day periods)						
Run no.	Start date	Time (days)	1	2	3	4	5	6	7
18	4/12/70	216	5	3	2	1	1		
19	11/14/70	112	10	5	4	4	3	3	
20	3/6/71	103	3	1	3	0	1		
21	6/17/71	107	1	3					
22	10/2/71	72	2	2	3				
23	12/13/71	80	4	0	1				
24	3/2/72	77	2	1	1	0	0	1	0
27	7/7/72	121	11	6	4	3	1	2	
28	11/5/72	82	4						
29	1/26/73	78	6	1	6	2	3		
30	4/14/73	139	1	5	1	3	4	1	2
31	8/31/73	104	1	0	1	1			
32	12/13/73	43	1	1	1	1			
33	1/25/74	152	3	2	2	1			
35	7/1/74	33	0	4	2				
36	8/3/74	194	4	6	3	2	0	0	1
37	2/13/75	121	6	3	3	0	0	1	
38	6/14/75	102	7	3	4				
39	9/24/75	121	6	2	3	2			

In run 19, there is a dramatic drop in counts from the first to the second counting periods. However, the number of counts in periods 3 through 6 are essentially constant. In fact, in most of the runs, the counts appear to level off above zero starting at period 3. This seems to suggest that, at least by counting period 3, there is a source producing ^{37}Ar within the counter to keep the counts constant.

The likely culprit is the ^{37}Cl gas that the ^{37}Ar decays back into. Apparently, muons from cosmic rays can produce proton that could interact with the ^{37}Cl from the ^{37}Ar decay, converting it back into ^{37}Ar. Clearly, something is making up the ^{37}Ar as it decays away beyond period 2.

4.4 Getting It Right

There is, perhaps, one way to reconcile the difference between the apparent adjustment needed and the measurement. The graph in Fig. 2 is a plot of the run 19 data broken into two segments. The first segment shows an exponential fit to the counts from periods 1 and 2. The second segment is a linear fit of the counts from periods 3, 4, 5, 6 and 7.

The first fit shows that, initially, the ^{37}Ar is decaying exponentially with a decay constant of $\lambda = 0.02\ s^{-1}$, corresponding to a half-life of about 34 days and $\lambda' = 0.022\ s^{-1}$. However, after 70 days, the counts stay constant at an average of four counts per counting period. Therefore, four ^{37}Ar atoms are being produced in the counter to replace the four decaying during the counting period.

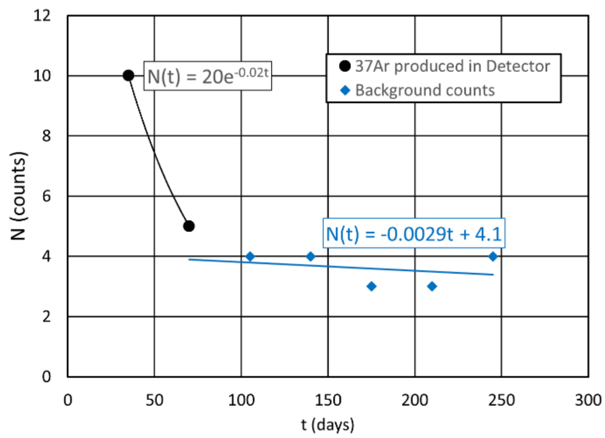

Fig. 2: Homestake ^{37}Cl neutrino detector run 19
The data from run 19 is broken into two segments. The first plots data from the first two counting periods and the second from the remaining five periods.

The graph in Fig. 3 plots the cumulative number of ^{37}Ar decays as a function of the time since the ^{37}Ar was extracted from the neutrino detector. The fit shows that the ^{37}Ar decays at about 0.1 nuclei per day after the first counting period. This equates to about four decays each counting period. These counts are from ^{37}Ar made within the counter from ^{37}Cl built up in it. The count for the first counting period falls below the fit line. This likely indicates that, because the ^{37}Cl was building in the first period, less than four decays occurred.

Assume that only enough ^{37}Cl built up during the first counting period to produce two counts from the ^{37}Ar produced in the counter. In the count of 10 recorded in the first period, two of the counts came from the ^{37}Ar created in the counter, leaving eight counts from detector ^{37}Ar.

In the second counting period, the ^{37}Cl in the counter had apparently built up to the point that three counts from that period were from new ^{37}Ar created from decay ^{37}Cl. That means there were only two counts produced by the original ^{37}Ar from the neutrino detector during that period.

After the second counting period, there was no ^{37}Ar left from the original sample. All the counts registered were from new ^{37}Ar made from proton bombardment. This suggests that the original ^{37}Ar had experienced many more than two half-lives.

The graph in Fig. 4 shows the fit of the first two counting periods if the counts in the first period is eight and the counts in the second period is two. The decay constant for the original ^{37}Ar from the neutrino detector becomes $\lambda = 0.0400\ s^{-1}$, which is a half-life of about 17 days and $\lambda' = 0.0404\ s^{-1}$. The decay constant for a 35-day half-life is $\lambda = 0.0198\ s^{-1}$, with $\lambda' = 0.0222\ s^{-1}$. This indicates that the neutrino-induced ^{37}Ar is different from the proton/deuteron – induced ^{37}Ar, and decays at a faster rate.

If this λ' is for the ^{37}Ar produced from ^{37}Cl interacting with neutrinos, then it is about 1.82 times that of the ^{37}Ar made from bombarding ^{37}Cl with protons. That means the solar neutrino flux measured by the Homestake detector is actually about 1.82 times the value calculated using the lab ^{37}Ar decay constant.

Adjusting the ^{37}Cl measured flux calculation by a factor of 1.82 would increase the flux value from 2.56 SNU to about 4.66 SNU. This is about 61% the calculated expected value of 7.6 SNU. This crude adjustment is reasonably consistent with the ^{37}Cl detector seeing 20 out of every 37 neutrino interactions or 54% of the predicted neutrino flux.

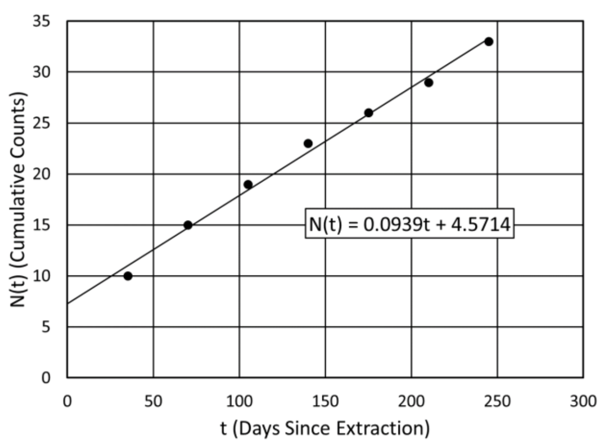

Fig. 3: Cumulative counts from Homestake run 19
The graph shows the total counts over time in run 19. The slope indicates there is about 0.1 counts per day. This is generated by the decay of ^{37}Ar resulting from the buildup of new ^{37}Ar from conversion of the ^{37}Cl from the original ^{37}Ar decay.

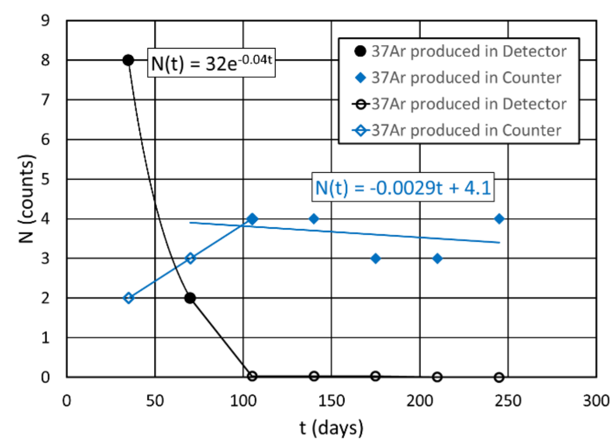

Fig. 4: Homestake detector run 19 with modified data
The count from the first counting period in run 19 is changed from 10 to 8 and the second period, from 5 to 2 to reflect the decay of ^{37}Ar resulting from the buildup of new ^{37}Ar from conversion of the ^{37}Cl from the original ^{37}Ar decay.

This all suggests that there is nothing happening to the neutrinos coming from the Sun. The problem for the ^{37}Cl detector was in interpreting the measurements. The problem was subtle and aided in its elusiveness by the inaccuracy of the Standard Model depiction of the ^{37}Cl – ν_e reaction, which it assumes produces the same ^{37}Ar configuration as the ^{37}Cl – *p* or ^{37}Cl – *d* reactions.

5 What Did the ES Reactions See?

The two ES reactions, H_2O and D_2O, claim to see a mixture of mostly electron neutrinos but also muon and tau neutrinos arriving at Earth from the Sun. Both SNO, seeing 2.39 x 10^6 cm^{-2}s^{-1}, and Super-Kamiokande, seeing 2.32 x 10^6 cm^{-2}s^{-1}, see the same flux. However, section 2 showed that the NC flux seen by SNO, 5.09 x 10^6 cm^{-2}s^{-1}, is all electron neutrinos. When combined with the CC flux, 1.76 x 10^6 cm^{-2}s^{-1}, always considered to be electron neutrinos, the total electron neutrino flux SNO sees is 6.85 x 10^6 cm^{-2}s^{-1}.

When the NC flux is considered the total neutrino flux from the Sun, the ES flux is about 45% of the total neutrino flux. However, if the total flux is actually 6.85 x 10^6 cm^{-2}s^{-1}, then the ES flux is only 35% of the total flux. Since all the neutrinos appear to be electron neutrinos, what is causing the ES reactions to record only 35% of them? It may be that not all the electrons in the water molecule can respond in a way that the detector can measure their interaction.

In the H_2O and D_2O molecules, there are 10 orbital electrons available for the neutrino to interact with, eight from the oxygen atom and one from each of the hydrogen atoms. Two of the oxygen electrons are in the inner 1s orbital. If the neutrino interacts with one of them, they may not be able to escape the molecule with enough energy to produce the Cerenkov radiation.

Four more of the electrons are involved in bonding the two hydrogen atoms to the oxygen atom. Again, they may not be able to achieve Cerenkov velocities if hit by a neutrino. That leaves four electrons that are out in the open and free. These are the electrons that likely produce the Cerenkov radiation that the detectors see. This means that only four out of ten possible neutrino-electron interactions, 40%, may be detectable. This is consistent with the 35% the two ES reactions see.

6 Conclusion

Based on the conjecture and analyses of the previous sections, it seems the solar neutrino problem for the various neutrino detectors lie in not understanding and analyzing adequately how the neutrinos interact with the various detector materials. Consequently, the measured data were not properly interpreted, resulting in misidentification of the neutrino fluxes measured. This gave the appearance of the detectors not seeing a fraction of the neutrinos expected. In fact, it appears they were seeing all the solar neutrinos predicted.

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