Design and Technical Study of Neutrino Detector Spacecraft

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A neutrino detector is proposed to be developed for use on a space probe in close orbit of the Sun. The detector will also be protected from radiation by a tungsten shield Sun shade, active veto array and passive cosmic shielding. With the intensity of solar neutrinos substantially greater in a close solar orbit than on the Earth only a small 250 kg detector is needed. It is expected that this detector and space probe studying the core of the Sun, its nuclear furnace and particle physics basic properties will bring new knowledge beyond what is currently possible for Earth bound solar neutrino detectors.

1. Introduction

The Sun provides all of the energy that our planet needs for life and has been doing so for five billion years. Understanding our Sun and its interior is one goal of the NASA Heliophysics program. This is a very difficult task because very little makes it out of the Sun's interior. Never-the-less within the last ten years neutrino detectors on Earth have started to make reliable detection of neutrinos from the fusion reactions in the interior of the Sun and have started to use this information to investigate the Sun's nuclear furnace processes. Using a small detector in close solar orbit is a possible next step to expand this study, one which can provide more information that cannot be obtained by detectors situated on Earth. The Sun is located 150 billion meters from the Earth, even at this distance it is still a major source of neutrinos, as shown in the solar neutrino flux plot in Figure 1 [1]. This plot has many interesting features and includes both a broad spectrum and a few sharp lines.

Changes in solar flux make it advantageous to take a neutrino detector into space since the solar neutrino intensity changes dramatically as the inverse square of the distance from the Sun, by five orders of magnitude when going from the Earth to the Sun or from the Earth to the current position of the Voyager 1 space craft (Table 1). Launch of a neutrino detector into space toward the Sun will: a) aim to significantly reduce the detector size and experimental cost while allowing for improved detector energy resolution and performance, b) attempt to completely eliminate background terrestrial neutrino sources for improved measurement accuracy, and c) conduct unique science experiments near the sun.

NASA's interest in deep space exploration has been a key factor in its unmanned space-craft development and launch. In addition to this, NASA also has done experiments in space where the science benefits from the unique platform of a space-craft can provide unprecedented results. The Hubble Space telescope [2] is really a small and very common instrument, but when it is put into an orbit high above the Earth, it becomes one of the most powerful optical observatories in the world, as it returns impressive science results. Similar to these examples science returns from a small orbiting neutrino detector experiment close to the Sun will be studied; the study falls within the same classification as these experiments and is clearly part of the Heliophysics central mission in Appendix B of the NASA science programs.

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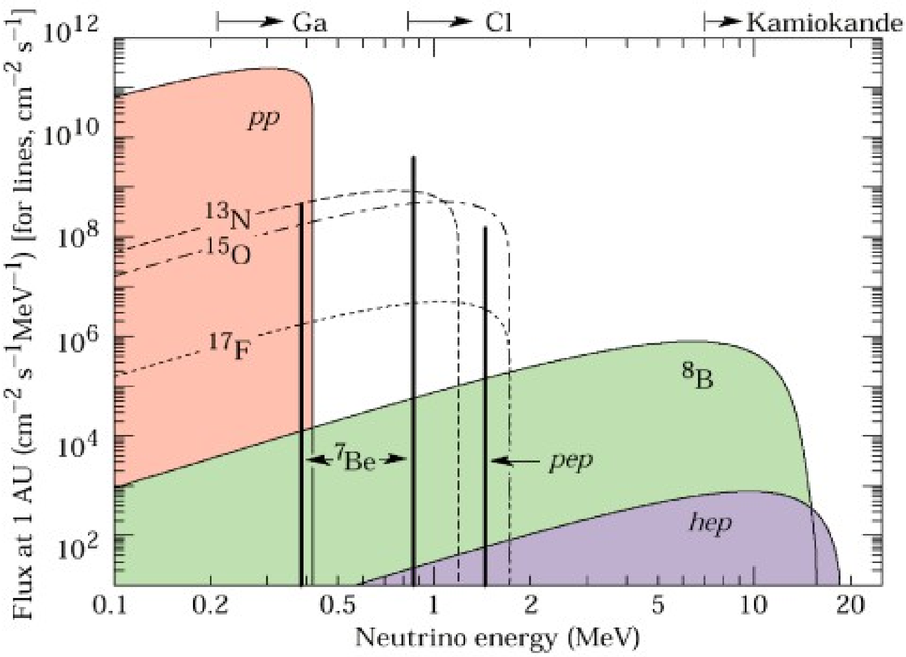

Figure 1: Solar Neutrino Spectrum, with intensity at the mean distance of the Earth, and the neutrino detection regions of a few experiments are shown as bars at the top [1].

II Science Goals

The Science goals fall into three parts, solar physics the study of the nuclear furnace in the interior of the Sun, Particle physics that can be done with the solar neutrinos generated, Nuclear Physics matter effects on neutrino propagation and Dark Matter studies.

Distance from Sun	Solar Neutrino intensity relative to Earth
696342 km	46400
1500000 km (~3 Sun R)	10000
4700000 km (~7 Sun R)	1000
15000000 km	100
474340000 km	10
Mercury	6.7
Venus	1.9
Earth	1

Table 1: Intensity of Solar neutrinos at various distances from the Sun.

See **Figure 2** for current theories on the location radius of nuclear fusion in the Sun's core. It is known that all of the Sun's energy comes from nuclear fusion reactions in the Sun's core, but there remain many unanswered questions in stellar evolution and astrophysics that can be addressed with a close solar orbiting spacecraft equipped with a neutrino detector. These are: a) solar fusion reaction neutrino spectrum, b) size and shape of the nuclear fusion reaction core in 3D, c) nuclear fusion rates, and d) changes of the nuclear fusion reactions over time and regions within the Sun. With a close orbiting satellite, the studies could be expanded due to the larger event rate. For a satellite out of the ecliptic plane, views of the nuclear fusion core from various solar latitudes could allow for a 3D image of the fusion core.

There are two categories of nuclear physics studies that can be performed with solar neutrinos and a spacecraft detector in near orbit of the Sun. These are studies of the matter effect on neutrino propagation through solar material and rare nuclear isotope fusion. Because the Sun is a rotating ball of gas, the Sun itself has an equatorial bulge much the like the Earth. The amount of matter that neutrinos produced in nuclear fusion processes within the solar core propagate through is different for the equatorial view and polar view. Theoretically, it should be possible to study this effect by placing a satellite in an orbit around the Sun that is not in the ecliptic plane. Also, due to the near solar orbit of the satellite, the detector will be more sensitive to the higher mass fusion processes of heavy isotopes that reside in the solar core than solar neutrino detectors located on the Earth. Both of these studies are specific only to a space-based neutrino detector and cannot be performed by experiments located on the Earth. Particle Physics can use this for the study of neutrino oscillations, and inside the 35 solar Radii limit the neutrinos are de-coherent and this would tell us unique science on particle physics oscillation.

An indirect search for Dark Matter in the core of the Sun can also be a result of such an experiment. Imagine that Dark Matter has accumulated in the gravitational well formed by the large mass of the Sun. This would distort the observed nuclear fusion region, see Fig. 2, displacing the neutrino source from the current calculations without any dark matter and making for a way to not only identify if Dark Matter is in the core of the Sun, but also would allow for a way to measure how much Dark Matter has accumulated in the Sun's core.

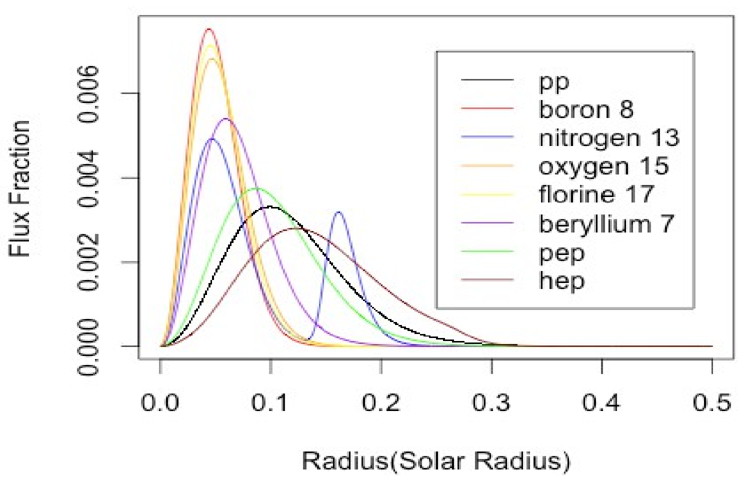

Figure 2**:** Predicted flux and radius of production from the standard solar model, see Ref. [3].

III Technical Development

Development of detector technology suitable for space flight is of major importance since none of the techniques currently used in ground-based solar neutrino detectors have been certified for space flight. Given that the potential science returns as reviewed in Section 2, laboratory-based testing and development of detector technology for these missions are needed. Detector technology for neutrinos detectors are well established and would be classified as a TRL3 (Technical Readiness Level) detector; however, none of this technology is certified for space flight. This summer aimed to study the science and detector technology using simulations. The technical readiness levels for these will not change, but the end goal of this study will advance the technical readiness level by determining which of the many possible detector should be pursued to get them ready for the space flight technical readiness based upon which detector technology preforms the best in simulation studies, lab tests and accelerator/reactor tests for the best science needs.

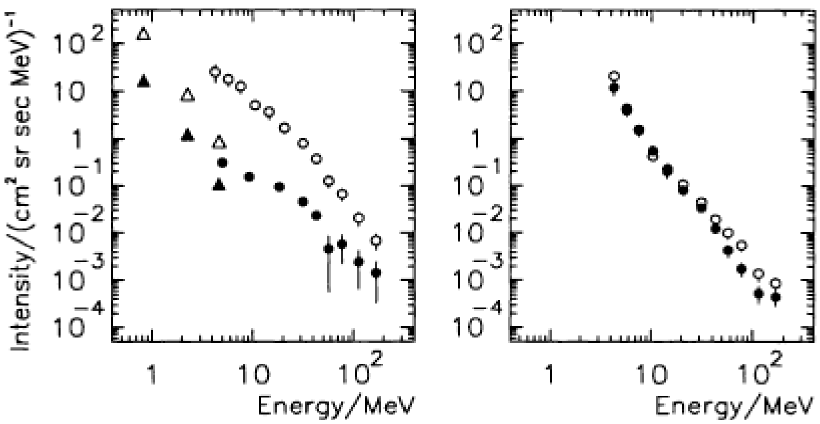

Figure 3: Spectrum of electrons and protons close to the Sun from the Helios Space Probe [4].

Interaction Mode	2nd signature	Timing	Energy	ν energy threshold
$^{12}C + \nu$ into $e^- + {}^{12}N$	^{12}N decays into ^{12}C + e+	11 ms	e+e- annihilation 2.2 MeV signature	15 MeV
Cl + ν into e- + Ar	Chemical sniffing			0.85 MeV
$^{18}O + \nu$ into e- ^{18}F m1	^{18}F m1 decays into ^{18}F and gamma	162 ns	1121 keV	7 MeV
$^{69}Ga + \nu$ into e- ^{69}Ge m1 or m2	^{69}Ge m1 decays X-ray ^{69}Ge m2 decay gamma	5 us 2.8 us	86 keV 397 keV	0.4 MeV 0.45 MeV
$^{71}Ga + \nu$ into e- ^{71}Ge m1	^{71}Ge m1 decay gama	20 ms	175 keV	0.4 MeV
D + ν into e- ^{2}He	^{2}He decays to proton proton Topology of event	<1 ns	back to back protons depends on neutrino energy	2.2 MeV

Table 2: Solar Neutrino interaction mode, subsequent decays, timing and energy threshold for reaction.

Our present method of detection is to consider a multiple method, shown in Table 2, one is the neutrino capture on C12 into N12 and a ms secondary decay process. Another method is to replace the H in Liquid Scintillaotr with D using a 100% complete catalytic process and have the Neutrino capture on D into He2 which decays into two signals and another third simultaneous method is to dope with Ga to look for the neutrino capture into Ge m1 or m2 excited state that decays 2 to 5 micro-seconds into the Ge ground state emitting signature X-rays. All three of these methods would cover a broad range of neutrino energies and have a double signal to separate out the signal from background. Simulations of this detector have been done and show the rates for Galactic Cosmic rays and Solar Electromagnetic radiation very acceptable.

Measurements from the Helios 1 Probe that the charged protons went up to 200 MeV but had an extremely small rate of 10^{-2} (cm^2 sr s MeV)$^{-1}$ and Helios 2 electron spectrum went up to only 20 MeV [4] shown in Figure 3. A simple first detector idea is shown in Figure 4. Cosmic ray rates seen on Earth would be smaller due to the Solar Modulation Theory, this expectations is supported by observations close to the Sun made by Helios 1 and 2 space-crafts. Between the two factors, of the exceptional quiet Sun in Cycle 23/24 and the assumption of a smooth cosmic-ray intensity gradient as a function of distance, it was seen that the expected 'upper limit' of cosmic-ray intensity at a nominal distance of 10 solar radii are well within the error bars of PAMELA's 1-AU data [5]. Galactic gamma ray rates as seen by Egret and Fermi satellite are reasonable low at 10^{-4}/s cm^2 sr [5]. Solar neutrino rates are expected to be ten per hour, and through the double coincident in time will be identified in subsequent data analysis. Keeping the background low by both shielding and active veto will be the two ways to reduce these rates.

The main source of count rate in the detector will be that from solar electromagnetic radiation emission. This is expected to be in the region of 0.5 to 10 MeV and at 10 down to 10^{-1}/s cm^2 sr, again as seen by the Helios space craft and shown in Figure 4. We have been able to do a detailed study of the shielding needed for such a spec craft. The final optimized shielding was determined to be 9 cm of Tungsten and a shield that completely shields a 25 kg detector would need to be 900 kg and less than a meter in diameter. This is very reasonable and the rates from electromagnetic solar radiation would be low. This is shown in figure 5 and is from an internal study conducted in the summer of 2016 by Prof. Solomey and Schmidt.

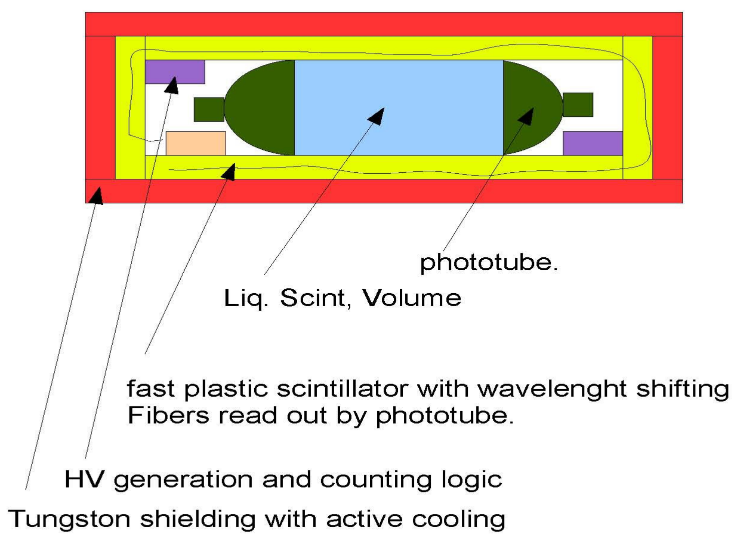

Figure 4: Test detector of a compact neutrino detector that is suitable for space flight.

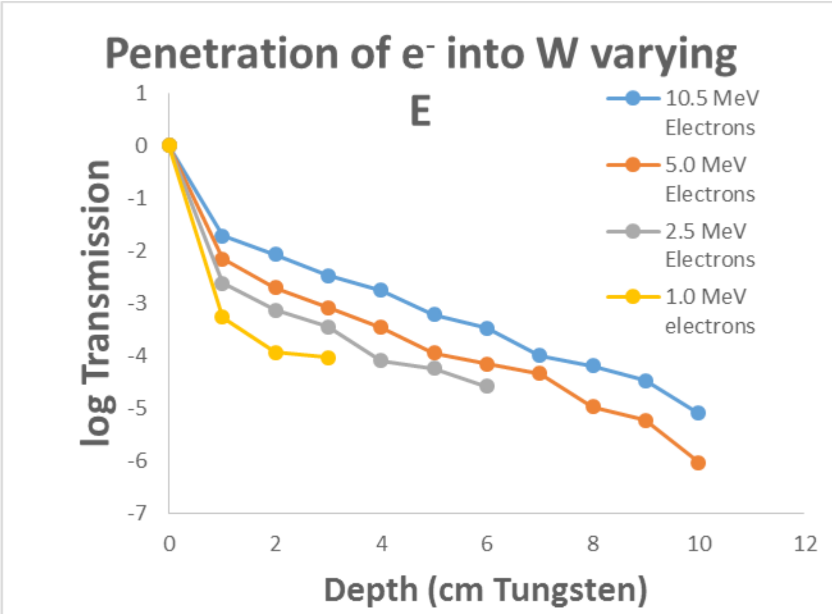

Figure 5: Electromagnetic Radiation penetration through depths of Tungsten for shield studies.

IV Technology Development of Heavy Liquid Scintillator

One of the best methods for solar neutrino detection is the conversion of solar neutrinos on Deuterium. Often used by having a sack of heavy water. However, the process of making "heavy liquid Scintillator" is a known process from the fusion bomb production, where 73 years ago the idea was created where Deuterium gas is infused into any Oil compound and with the help of a catalysts it is possible to have a 100% complete replacement of all the Hydrogen into Deuterium. Although such a detector has never been made for neutrino or particle physics, the process is relatively simple and 100% complete.

Although a large detector might have problems with large amounts of Deuterium because of the 1% contamination of Tritium in the gas, and the old Deuterium bubble chambers had a large radiation dose from that much Tritium, but in a small detector likes what we are planning for a "Neutrino Solar Orbiting Laboratory" this is not a problem since the largest planned active volume of liquid scintillator is 250 to 350 kg. Plus with a small volume like this then the Deuterium gas can be purified making it free of Tritium or at least much better than was possible when liquid Deuterium bubble chambers were used.

The solar neutrino interaction off of Deuterium would produce and electron ionizing track and the production of a He-2 nucleus. This gives the threshold for neutrino sensitivity all the way down to 2.2 MeV solar neutrinos. The He-2 decays with a nanosecond half-life into proton-proton or Deuterium and a positron track (<1%). The space flight detector\ being designed for the "Neutrino Solar Orbiting Laboratory" would have two photo-tubes looking on each side of the cylinder detector volume, see Figure 4. This would be used to our advantage where the timing is very short to measure a double pulse, but the first produced electron track could go into on photo-tube and the recoiling proton-proton emission can go into the photo-tube on the other end, giving a topology signature instead of a timing signature. If we measure just the prompt light then we would have a signature for the events specific to this interaction and decay process.

V Electronics Signal Processing and Trigger Board Technical Requirements

The base design of the neutrino detector has a volume of liquid scintillator contained by a baggy and viewed by photo-tubes on one or both ends, and these photo-tubes might even become multi-anode segmented devices in future revisions. The baggy is contained by a solid plastic scintillator veto cylinder with end-caps. This veto array could be read out by a single wavelength shifting fiber that wraps around the inside or outside of the cylinder and end caps to a photo-tube, but it could also eventually be a multi-anode photo-tube with multiple segments from an array of sections of the veto. See the sketch of the detector in the Figure 4.

The liquid scintillator will be sensitive to neutrinos though multiple process each having the possibility of a double timed pulse. The basic ones currently considered are using heavy liquid scintillator Deuterium conversion into He-2, which then decays in 5 ns to a signature X-ray, second is a Ga doping where the neutrino iterations converts the Ga to Ge m1 or m2 excited nuclear state that then decays to a 40 keV X-ray or 300 keV gamma in 2.5 micro-seconds or 5 micro-seconds half-life. The third process is capture on C-12 into N-12 that decays with a 10 milli-second half-life with a 2 MeV gamma. Each of these process use a nuclear to capture the solar neutrino and produces an electron with a track segment up to 5 cm in length, a time decay of the second pulse and then a signature second pulse which has a well defined energy level for triggering on. All of this allows for great reduction of background.

The detector must live with a high rate of Galactic Cosmic Rays, High Energy Gamma Ray, and solar EM and protons some of which is shielded by the heat shield and outer container. In the simplest idea of the electronics each channel is stored in a time delay buffer. If a background event goes through after the first neutrino interaction signal is observed and before the second energy signature event then this event may be kept alive because the buffer streams of the photo-tube on the liquid scintillator can identify the background event with the same timing from the veto array observed event of either a GCR entering and exiting the liquid scintillator or a High Energy Photon starting a shower in either the veto array or the liquid scintillator and then the shower exits the liquid scintillator producing a signal in the veto array. For the long lived processes of C-12 where the half-life of the processes is milli-seconds then this is essential to keep the live time high and may even need to reject multi cosmic-ray background events, but it is also helpful for the micro-second decays of the Ga dopant options. For the timing signature see Figure 6. The electronics can also be improved by being sensitive to the 2^{nd} decay which should have a characteristic pulse height of their respective decays.

It is expected that the electronics board would then provide all the signal process of the photo-tube signals of the detector volume and veto array and produce candidate events for neutrino interactions and background event readout converted to digital format and sent to the spacecraft's main computer for data storage and transmission. It is necessary for this board to also monitor live-time and different characteristic rates of backgrounds although the background trigger rate might be to hard to read out all of the events but we need to monitor the number of these different types of background events and to provide some scaled down events for readout and later analysis. The electronics board needs to be able to be programmed by the spacecraft computer during flight if changes are necessary and in the event that different neutrino processes are used and the ability to set the decay half-life the pulse height of the signature signal events and to be able to handle multiple processes during the testing and flight of the detector.

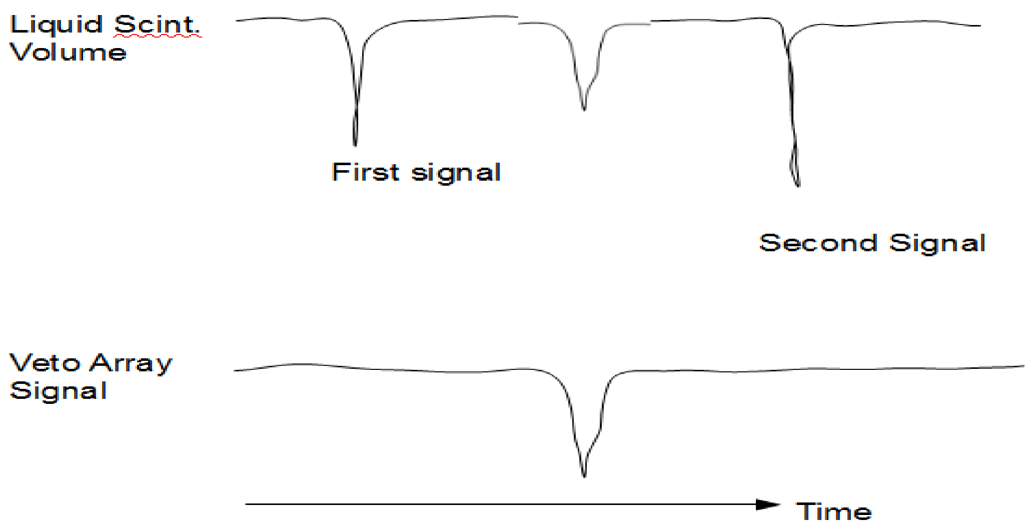

Figure 6: Top trace is the photo-tube pulse height of a neutrino interaction event in the Liquid Scintillator two pulses with a event inserted between the two signals from a background event. The bottom trace is the pulse height from the veto array photo-tube.

VI Rates of Neutrino Signals and Backgrounds from Galactic Cosmic and Gamma Rays

Count rates in the detector will be from Solar Electromagnetic particles that will be blocked and reduced by the EM shield function of the solar shade and Galactic Cosmic and Gamma Rays. These Galactic sources have known rates and the design of the detector outlined in this report has both a passive shield around the whole neutrino detector as well as a active veto array. The passive shield was taken as 0.5 cm of W and the active shield 1.5 cm or polystyrene Scintillator. Fellow NASA summer faculty fellow, Robert McTaggart wrote a detailed Geant-4 Monte-Carlo package for this design and gamma and cosmic rays where simulated. The summary of the rejection and shielding provided for Gamma rays is in Figure 7, and Cosmic Rays Figure 8.

A 1 ton (1000 kg) detector at sever Solar Radii from the Sun would have a neutrino flux 1000x higher, making a 1 kg detector equal to a 1 ton detector on Earth. A small detector has much better light collection and current experiments such as Kamland and Borexino lose about a fourth of the events due to insufficient light collection. If an idealized small detector can be 100% perfect in collecting the light then this 1 kg detector would need to be only 0.25 kg. The Ga isotope needed for neutrino detection is only 50% the concentration in nature, but with a small detector needing only a small amount of doppant, then a single isotope of Ga can be ordered and that yields another factor of two making the 1 ton detector only 0.125 kg. Likewise using D instead of Hydrogen with the idea of a Heavy Liquid Scintillator, yields another factor of 1.5 giving 0.83 kg of mass for a 1 ton detector. In addition to this most solar neutrino experiment use only 1% doping of Ga so as not to make the light collection harder, but with a smaller detector this number could be increase up to the 19% limit, exactly how much would be the subject of a technical study, not used in this estimate.

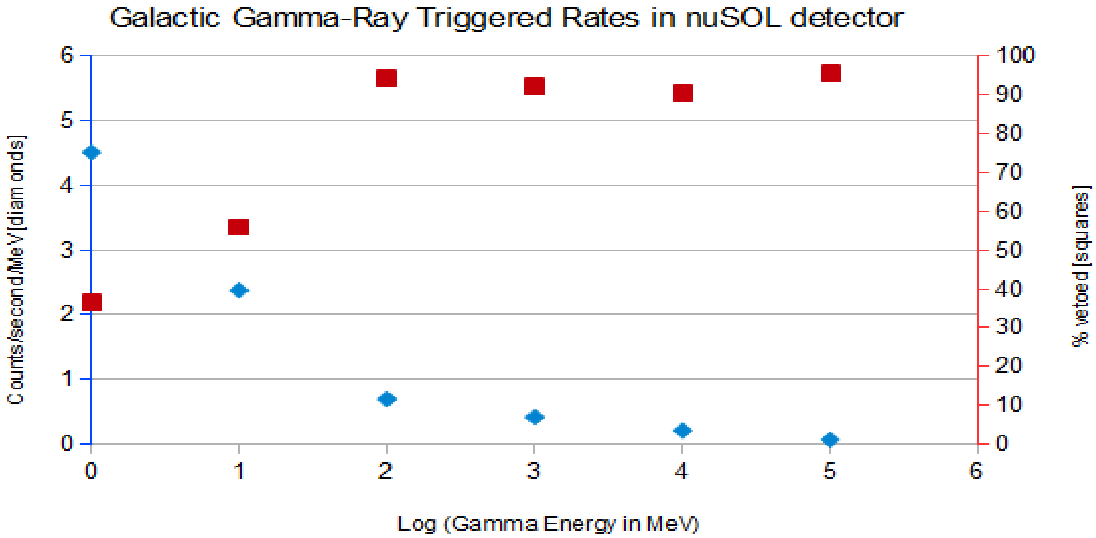

Figure 7: Galactic Gamma-Ray simulated in the detector design, the diamond points associated with the left vertical axis are triggered rates in the neutrino detector volume, and the square points associated with the right vertical access on the rejection rate of the veto design.

The detector could be 83 kg or smaller and our base design of a 250 kg detector would be equal to a 3 kton detector on earth. Table 3 summarizes the expected rates for the Standard Solar Model in the 300 ton Borexino experiment compared to the 250 kg νSOL baseline detector. The number of neutrino events per day would be around 200 neutrino interactions observed per day. The Borexino rates come from the paper in ref. [6].

VII Conclusion

This summer advanced furthered the idea of a neutrino detector close to the Sun for Solar Interior Physics studies, Particle and Nuclear Physics plus the added advantage of a Dark-Matter Search in the Sun. We reached the conclusion that the rates of particles in the detector from the Solar and Galactic backgrounds from Cosmic-ray and Gamma-rays are reasonable. In addition to this these rate studies which were achieved, we also showed how a new technical method of detecting solar neutrinos can be done with "Heavy Liquid Scintillator" where a 100% complete method of changing the hydrogen to Deuterium is possible. We layed out the design specifications for a signal and veto processing board for neutrino event selection, and how it would be used for background rejection and live time monitoring.

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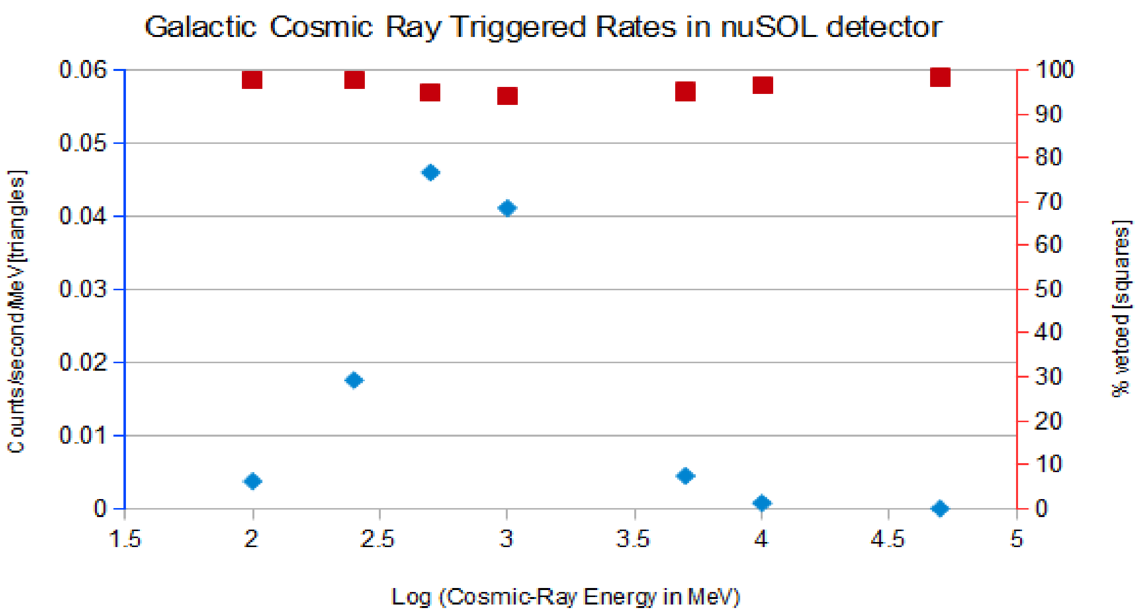

Figure 8: Galactic Cosmic-Ray simulated in the detector design, the diamond points associated with the left vertical axis are triggered rates of un-vetoed events in the neutrino detector volume, and the square points associated with the right vertical access is the rejection rate of the veto design.

Neutrino Energy	300 ton Borexino	250 kg νSOL at 7 $R_\odot$
0.4 – 0.8 MeV	15 ν/day	150 ν/day
0.8 – 1.5 MeV	3.5 ν/day	35 ν/day
>1.5 MeV	0.5 ν/day	5 ν/day

Table 3: Neutrino rates observed in the 300 ton Borexino detector on Earth and a 250 kg νSOL detector at 7 solar Radii, for three intervals of neutrino energy.

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