MONTE CARLO SIMULATIONS OF A NEAR-SOLAR ORBIT NEUTRINO DETECTOR

A Thesis by

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MONTE CARLO SIMULATIONS OF A NEAR-SOLAR ORBIT NEUTRINO DETECTOR

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Physics.

Nickolas Solomey, Committee Chair

Holger Meyer, Committee Member

Atri Dutta, Committee Member

Hyuck Kwon, Committee Member
I dedicate this thesis to my family, friends, and WSU faculty who provided help and encouragement along the way.
“It is difficult to say what is impossible, for the dream of yesterday is the hope of today and the reality of tomorrow.” - Robert H. Goddard
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Last but not least, a thank you to my parents for encouraging me to proceed with my graduate studies when difficulties seemed overwhelming.
ABSTRACT

Neutrinos—weakly interacting subatomic particles often resultant of nuclear processes, including hydrogen fusion—are the only direct insight into the core of the Sun. Previously constructed neutrino detection experiments have successfully detected solar-origin neutrinos, proving hydrogen fusion to be the Sun’s energy production mechanism; however, these experiments’ large size and Earth-based location limit their capabilities. A solar neutrino detection satellite orbiting the sun with a close approach distance of 7 to 3 solar radii could revolutionize solar interior studies. At such proximity, the neutrino flux increases by several orders of magnitude allowing for a much smaller detector design than Earth-based devices. An off-ecliptic orbital location also allows for fusion core geometry studies. To pursue these improvements, a scintillation detector using gallium-doped liquid scintillator and veto array methods has been devised. Interactions between neutrinos and gallium nuclei can result in a sequentially released electron and gamma-ray/X-ray, giving distinct double-pulse signals in the detector. The veto array is a secondary detection assembly to filter external-source charged particles. Presented here are the methods and results from Monte Carlo simulations of particle events visible to the detector. This code incorporates background event rates obtained from Geant4 simulations of the detector assembly, and neutrino interaction rates based on scaling of similar, Earth-based experiments’ performance to the detector’s parameters. The code output is examined to find the number of true double-pulse signals versus those of false signals. Establishing experiment parameters necessary for a false event detection rate less than 20% is a primary goal of these simulations.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1</strong> INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Solar Neutrinos</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Solar Neutrino Detection Experiments and their Methods</td>
<td>6</td>
</tr>
<tr>
<td>1.3 Summary of the Motivations for a Solar Neutrino Detection Spacecraft</td>
<td>12</td>
</tr>
<tr>
<td><strong>2</strong> SPACE-BASED DETECTOR DESIGN CONSIDERATIONS</td>
<td>14</td>
</tr>
<tr>
<td>2.1 Benefits and Challenges of a Near-Solar Orbit</td>
<td>14</td>
</tr>
<tr>
<td>2.2 General Detector and Spacecraft Design Overview</td>
<td>16</td>
</tr>
<tr>
<td>2.3 Double Signaling via Gallium Interactions and Cross-Section Considerations</td>
<td>18</td>
</tr>
<tr>
<td>2.4 Background Rates and the Application of Veto Array Methods</td>
<td>20</td>
</tr>
<tr>
<td>2.5 A Note on Tungsten Shielding</td>
<td>21</td>
</tr>
<tr>
<td>2.6 Summary of the Detection Method</td>
<td>22</td>
</tr>
<tr>
<td><strong>3</strong> SIMULATION METHODS</td>
<td>24</td>
</tr>
<tr>
<td>3.1 Application of the MIXMAX Random Number Generator Family</td>
<td>24</td>
</tr>
<tr>
<td>3.2 Program Structure and Output</td>
<td>25</td>
</tr>
<tr>
<td>3.3 Geant4 Simulations of Veto Array Performance</td>
<td>27</td>
</tr>
<tr>
<td>3.4 Methods of Analysis and Interpretation</td>
<td>30</td>
</tr>
<tr>
<td><strong>4</strong> DISCUSSION OF RESULTS</td>
<td>31</td>
</tr>
<tr>
<td>4.1 Decay Profile Reproduction Capability</td>
<td>31</td>
</tr>
<tr>
<td>4.2 Performance Optimization through Closer Orbital Perihelion</td>
<td>33</td>
</tr>
<tr>
<td>4.3 Effects of Dopant Concentration</td>
<td>34</td>
</tr>
<tr>
<td>4.4 Conversion-Electron Energy Spectrum and Isotopic Optimization</td>
<td>35</td>
</tr>
<tr>
<td>4.5 Expectation of Neutrino Counts and Resolution of Neutrino Spectrum Features</td>
<td>37</td>
</tr>
<tr>
<td><strong>5</strong> CONCLUSION</td>
<td>39</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>40</td>
</tr>
</tbody>
</table>
## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar Neutrino Flux Relative to Earth at Selected Distances</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Spacecraft Mass Contributions</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>Neutrino-Gallium Interactions and Germanium Excited State Characteristics</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>Estimated Interaction Cross-Sections for $\nu_{\frac{71}{31}}$Ga Interactions</td>
<td>20</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>P-P Chain Schematic</td>
</tr>
<tr>
<td>2</td>
<td>Solar Neutrino Energy Spectrum</td>
</tr>
<tr>
<td>3</td>
<td>Neutrino Fluxes vs. Solar Radius</td>
</tr>
<tr>
<td>4</td>
<td>Neutrino-Electron Scattering Feynman Diagram</td>
</tr>
<tr>
<td>5</td>
<td>Results from Borexino</td>
</tr>
<tr>
<td>6</td>
<td>Previous and Current Solar Neutrino Experiments</td>
</tr>
<tr>
<td>7</td>
<td>Detector Layout Schematic</td>
</tr>
<tr>
<td>8</td>
<td>Detection Method Concept Illustration</td>
</tr>
<tr>
<td>9</td>
<td>Monte Carlo Program Output Samples</td>
</tr>
<tr>
<td>10</td>
<td>Geant4 Visual Output Examples</td>
</tr>
<tr>
<td>11</td>
<td>Geant4 Simulation Results for Veto Array Performance</td>
</tr>
<tr>
<td>12</td>
<td>Comparison Plots for Decays in Monte Carlo Simulation Output</td>
</tr>
<tr>
<td>13</td>
<td>Decay Timing Plot for Simulated Ge Decays</td>
</tr>
<tr>
<td>14</td>
<td>Effect of Perihelion Distance on Detection Efficiency in Simulation</td>
</tr>
<tr>
<td>15</td>
<td>Plot of Conversion-Electron Count per Energy Bin in Simulation</td>
</tr>
<tr>
<td>16</td>
<td>Comparison of Gallium Isotope Content Effect on Simulated Observed Energies</td>
</tr>
</tbody>
</table>
## LIST OF SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e^-$</td>
<td>Electron</td>
</tr>
<tr>
<td>$\bar{\nu}_e$</td>
<td>Electron Antineutrino</td>
</tr>
<tr>
<td>$\nu_e$</td>
<td>Electron Neutrino</td>
</tr>
<tr>
<td>$n$</td>
<td>Neutron</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Photon/Gamma-Ray/X-ray</td>
</tr>
<tr>
<td>$e^+$</td>
<td>Positron</td>
</tr>
<tr>
<td>$p$</td>
<td>Proton</td>
</tr>
<tr>
<td>$R_\odot$</td>
<td>Solar Radius</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION

Like all stars, our Sun is essentially an astrophysical laboratory where the laws of physics are put to the test in a highly visible way. Just through visible light observations alone, astrophysicists have observed wide ranging phenomena including convection currents below the Sun’s surface and magnetic anomalies revealed through spectroscopic studies of the so-called sunspots. Yet energy production processes within the Sun are still poorly understood, hidden in the solar interior where visible light observations are of little utility. To date, multiple ground-based experiments have provided evidence of hydrogen fusion in the solar furnace through the detection of resultant neutrinos; however, the instrumentation utilized is gargantuan in physical and economic scale. If any further progress is to be made toward understanding solar nuclear processes, smaller detection devices of greater scientific output must be designed.

This study focuses on a novel approach to making such an improved device for solar neutrino studies. As is the case with any other emitted radiation from a source, the solar neutrino flux will increase exponentially as the distance to the Sun decreases; hence, a neutrino detection device situated very close to the Sun could provide increased observations over Earth-based experiments while utilizing more compact equipment [1]. Affecting the design of a satellite-based experiment is the lack of natural shielding against non-neutrino space radiation sources. To properly configure a potential detection satellite’s design parameters, a series of Monte Carlo simulations have been performed with the intention of addressing the “needle in a haystack” challenge of finding neutrino-related particle signals amongst far more numerous background events.
1.1 Solar Neutrinos

Although popular literature gives a simple picture of hydrogen fusion in the solar interior, the full picture of these processes is much more complex than generally described (see Figure 1 and Figure 2). What is called the Standard Solar Model (SSM) incorporates a diverse series of nuclear interactions which can take place in the solar interior, leading to multiple paths of neutrino production. The most predominant path—ppI—involves the initial fusion of two protons, followed by the fusion of resultant deuterons with protons, then a final fusion of resultant $^3$He nuclei [2]. Of all solar neutrinos, those produced in this process constitute the lowest exclusive energy range emitted, spanning from sub-0.1 MeV energies to 0.42 MeV [3]. Another possible initial path is the p-e-p process which emits neutrinos at a specific 1.44 MeV [3]. The fusion of $^3$He and a single proton can emit neutrinos over a range from 0.55 MeV to nearly 11 MeV; however, this path is exceptionally rare and the neutrinos attributable accordingly few [2, 3]. The ppII path includes a $^7$Be and electron fusion step with emits neutrinos at 0.384 MeV and 0.862 MeV exclusively; though not as numerous as the proton fusion neutrinos, these beryllium fusion neutrinos are the second most numerous solar neutrino source [2,3]. Looking to the ppIII path, the widest energy range of neutrinos results from the decay of $^8$B, spanning from at least 0.1 MeV to nearly 13 MeV [2,3].
Figure 1: Schematic representation of the proton-proton chain [2].

Figure 2: Neutrino flux per energy range at Earth for specific pp chain and CNO processes. The wide ranges are per MeV energy width while the spikes are to be read directly [3].
These fusion paths were originally postulated by Hans Bethe in 1939, and subsequent studies by John Bahcall and others have produced the Standard Solar Model as we know it today [4]. In regard to the proton-proton chain as described, experimental observations have largely confirmed this picture of nucleosynthesis to be true [4]. There also exists a possibility of carbon-nitrogen-oxygen (CNO) fusion processes in the Sun, where the production of helium is catalyzed by the small amount of carbon present [2]. Though this is thought to be more predominant in very massive stars, the Sun is rich enough in carbon to allow for the CNO process to be a minority contribution in solar energy production; however, none of the solar neutrino experiments to date have provided conclusive evidence of this [5].

Each particular path of the proton-proton chain and the CNO cycle happens under specific temperature, pressure, and density conditions [2]. The Sun itself has a continuous variance of these conditions moving from the core to the surface, therefore the fusion processes described should originate in definite regions some distance from the center rather than at at $R/R_\odot = 0$, as shown in Figure 3 [6]. The initial steps of the pp fusion process proceed most efficiently at conditions found near 0.10 solar radii from the center, while the ppII path $^7$Be to $^7$Li and ppIII path $^7$Be to $^8$B processes require greater temperatures and pressures, pushing their regions to roughly 0.06 and 0.04 solar radii respectively [6]. The CNO cycle, like the ppIII path, requires more extreme environments; thus, the $^{13}$N, $^{15}$O, and $^{17}$F beta decay neutrinos should originate in a region approximately 0.045 solar radii from the center [2, 6]. No Earth-based experiments presently in operation can confirm these regional distributions precisely: only a few helioseismology observations have revealed enough information for rough constraints [2, 7]. A spacecraft-based solar neutrino experiment in a variable location around the Sun with the ability to determine detected neutrino energies may provide a better insight into the spatial location of certain fusion processes.
Aside from lacking exact confirmation of aforementioned solar neutrino flux distributions, there remains an incomplete understanding of heavy-element abundance in the solar interior. Most specifically, the solar interior sound speed profile obtained from helioseismological studies is not in agreement with the SSM when accounting for current estimates of metallic content [2, 5]. Though still unresolved, future experiments (e.g. further studies using Borexino) may measure the neutrino flux from the CNO cycle.
precisely enough to inform revisions to the SSM [8]. Already, the expected rates of electron
capture by $^7\text{Be}$ in the ppII process have been revisited in light of recent $^7\text{Be}$ neutrino flux
measurements by Borexino [9].

The discovery of so-called “dark matter” has introduced another area of uncertainty
in solar modeling [10]. Because of a star’s massive and compact nature, its core region
should be a significant gravitational well for concentrated quantities of dark matter. It has
been postulated that as yet unconfirmed weakly interacting particles constitute dark matter,
opening the possibility of unforeseen weak interactions between these dark matter particles
and solar neutrinos [10]. The $^8\text{B}$ neutrino energy curve is shown to be significantly affected by
the introduction of such dark matter particles; thus, any solar neutrino detection experiment
which can adequately characterize the $^8\text{B}$ curve will give invaluable insight into the nature
of dark matter [11]. Determining any properties of this dark matter through its physical
distribution in the core is another kind of investigation which can benefit from a space-based
experiment.

1.2 Solar Neutrino Detection Experiments and their Methods

Detection of neutrinos of any origin, because of being near-massless and only weakly
interacting, has required extraordinary experimental designs and apparatus to accomplish.
The earliest such experiments focused on antineutrinos emitted from various nuclear decay
processes, in part since the neutrino was originally hypothesized by Wolfgang Pauli and
Enrico Fermi as a solution to the peculiar energy spectrum of beta decay electrons [4]. The
first experiments to successfully detect neutrinos were conducted by Fred Reines and Clyde
Cowan between 1953 and 1956, where the antineutrinos produced from beta decay events
in nuclear fission reactors were observed indirectly through inverse beta decay interactions
[12, 13]. Although this experiment was not meant for solar neutrino
observation (none of the solar neutrinos are antineutrinos), its innovative approach to
neutrino detection is quite informative for the construction of detection experiments.
Because of the need for proximity to a nuclear fission reactor, many of the neutrons and gamma-rays resultant of fission could not be blocked effectively; however, the neutron and positron from the interaction in Equation 1 can be used in further interactions to produce a distinct double signal [13].

\[ \bar{\nu}_e + p = e^+ + n \]  

(1)

For the Cowan-Reines experiments, a large volume of water provided the target protons and contained a concentration of cadmium chloride (CdCl\textsubscript{2}) for a secondary interaction with the neutrons produced [13]. The positron and an electron would annihilate, producing an initial gamma-ray signal in an adjacent liquid scintillator volume [13]. Following the positron-electron annihilation, the neutron would be captured by a cadmium nucleus, resulting in another gamma-ray emission within a distinct time range [13]. Using this unique double-signal of gamma rays associated with the antineutrino interaction, Cowan and Reines became the first scientists to conclusively detect the neutrino [12]. For the purposes of this study, the double-signal method utilized by this experiment demonstrates an effective method which could be modified for use in an improved solar neutrino detection device.

With confirmation of the neutrino’s existence, attention turned to the detection of solar-origin neutrinos. In 1967, Raymond Davis Jr. led an effort to construct a solar neutrino detection device capable of finding a few higher-energy solar neutrinos [14]. This device, placed nearly 1,478 meters below ground to shield from the effects of charged cosmic ray particles and other backgrounds, contained a 615-ton mass of perchloroethylene (dry cleaning fluid) as a source of chlorine for the interaction in Equation 2 [14].

\[ \nu_e + ^{37}_{17}Cl = e^- + ^{37}_{18}Ar \]  

(2)

Chemical methods were used to extract the argon produced for counting. Because of its location in an abandoned mine, the experiment is commonly referred to as the Homestake mine experiment. Although the expected rate of neutrino detections ranged between 6 and
9 SNU\textsuperscript{1}, the actual rate was nearly 2.56 SNU [14]. This roughly one-third deficit in neutrino count became known as the “solar neutrino problem” and continued to be observed in many solar neutrino experiments [4].

Another radiochemical detection method uses gallium as the interaction nucleus instead of chlorine (Equation 3) with the advantage of detecting lower energy neutrinos. The Homestake mine experiment could only detect neutrinos above 0.814 MeV and with greatest efficiency above 5.8 MeV (mostly in the $^8\text{B}$ neutrino range), whereas a gallium experiment can detect neutrinos down to nearly 0.232 MeV allowing for measurement of the numerous pp neutrinos [14, 15].

\[ \nu_e + ^{71}_{31}\text{Ga} = e^- + ^{71}_{32}\text{Ge} \]  \hspace{1cm} (3)

Two experiments commissioned in the early 1990s, GALLEX/GNO and the Soviet-American Gallium Experiment (SAGE), utilized this interaction scheme [16, 17]. Again, these experiments came up short of expectations: GALLEX/GNO measured 69.3 SNU and SAGE measured 66.9 SNU compared to an expectation between 122 SNU and 131 SNU [16]. Despite the observed deficit, these experiments made the first confirmed observations of the pp process neutrinos [16]. It should also be noted that these experiments, like the Homestake mine experiment, were extremely large (50 tons of liquid gallium was used in SAGE) and did not observe the neutrino interactions directly; however, the success of the gallium interaction scheme at low neutrino energies can be applicable to new solar neutrino detection concepts as presented here [18].

For the ultimate resolution of the solar neutrino problem, detection methods able to directly observe the neutrino interaction events (and different kinds of neutrinos) were required. According to a theory developed by Bruno Pontecorvo and others, the neutrino comes in three “flavors” of differing mass: electron neutrino, muon neutrino, and tau neutrino. SNU stands for Solar Neutrino Unit, which is equivalent to one neutrino interaction per $10^{36}$ target atoms per second.
neutrino in order of increasing mass [4]. Each of these can oscillate between the different mass flavors while propagating through space, so if a neutrino is emitted as an electron neutrino, there is only a one out of three chance that it is detected as such after traversing enough distance [4]. In short, the electron neutrinos produced in the Sun can be detected as muon or tau neutrinos once they reach Earth. Two astrophysical neutrino detection experiments commissioned near the turn of the millennium, the Super-Kamiokande experiment and the Sudbury Neutrino Observatory (SNO), contributed to the confirmation of neutrino oscillations and the phenomenon’s responsibility for the solar neutrino problem [4, 19]. Both experiments were of the Cherenkov type, taking advantage of light emitted in the path of charged particles as their velocity exceeded the light velocity limit within the media of propagation [19, 20]. A detailed description of the interaction schemes used in these experiments is saved for other treatments of neutrino detection technology. In general, Cherenkov detection methods are relegated to very high-energy neutrinos above 6.2 MeV and tend to be extremely large even compared to the previously mentioned radiochemical experiments [19]. Super-Kamiokande itself is a prime example of the enormity of Earth-based neutrino detectors, containing 50,000 tons of purified water and 13,000 photomultiplier tube (PMT) assemblies [20].

Between the low-energy sensitivity of gallium radiochemical experiments and the remarkable observational capabilities of Cherenkov experiments at high energy existed a technical gulf bridged by the Borexino experiment. In this detector, electron-neutrino scattering (Equation 4 and the included Feynman diagram in Figure 4) was observed through the luminescing of liquid scintillator by recoil electrons [21].

\[ \nu_e + e^- = \nu_e + e^- \]  

(4)

Although it did not rely upon the Cherenkov effect, Borexino utilized a large array of PMTs to detect the faint liquid scintillator light in a way very similar to the
aforementioned Cherenkov-based experiments [21]. A key advantage of this design is its ability to detect neutrinos down to 0.165 MeV, allowing for an exceptional coverage of the pp neutrinos [22]. Additionally, the large number of target electrons in the 100-ton fiducial scintillator mass—$3.307 \times 10^{31}$ electrons—guarantees numerous detections compared to previous methods [21]. Through Monte Carlo fitting to the observed electron spectrum from Borexino, a remarkable pp neutrino rate of 144 counts per day and a $^{7}\text{Be}$ neutrino rate of 46 counts per day were successfully observed [22]! In regard to its truly revolutionary capabilities, the techniques used in Borexino will be of much importance in this design study.

Figure 4: Feynman diagram for the charged-current neutrino-electron scattering. The “W” represents the W boson which intermediates this weak interaction [4].
Figure 5: Spectrum of observed electron events in the Borexino experiment. The interaction count from pp, $^7$Be, pep, and CNO (upper limit) neutrinos have been deduced through fitting of possible flux curves to the data. All other contributions listed are from various known background events [22].

Despite the great progress which has been accomplished with these and many other neutrino detection experiments, the still limited capabilities of these devices has left a series of questions still unanswered. In some cases, more questions have been opened by the findings of these experiments than complete answerers. Of immediate note is the exceptional size of the examples previously given (see Figure 6) and their equally exceptional financial expense. Though even larger follow-up experiments are planned for the coming decades, it is very likely that we are reaching a critical juncture where such large-volume detectors become technically and monetarily infeasible. This is not to mention the limitations of being Earth-based.
1.3 Summary of the Motivations for a Solar Neutrino Detection Spacecraft

In the previous sections, a context has been established for the development of a space-based neutrino detection experiment. An orbital vantage point can allow for a variable position in reference to the solar equator and a variable distance from the solar interior. In
terms of the scientific motivations of such an experiment, this can allow for studies including but not limited to solar interior geometry mapping, heavy-element abundance studies in correlation with existing ground-based experiments, and solar interior dark matter searches [1, 23, 24]. Considering the increasing size of Earth-based experiments, a detector placed in an extremely close perihelion orbit will cross a region of greatly increased solar neutrino flux, inviting a greatly reduced detector size for performance similar to much larger Earth-based experiments. This engineering and economic motivation will be extended upon in the next chapter of this thesis, in addition to the specific technical requirements for such a detector.
CHAPTER 2

SPACE-BASED DETECTOR DESIGN CONSIDERATIONS

Though a spacecraft-based solar neutrino experiment offers the promise of several key improvements over existing projects, the space environment and the practical limits of rocket payloads introduces a series of specific design challenges which must be addressed. As this thesis mainly examines the feasibility of the detection method being used, other aspects of the design (orbital parameters, heat shield development, spacecraft electronic system requirements, etc.) will only be mentioned briefly and mostly in regard to their implications for affecting neutrino detection. The proposed design takes advantage of increased neutrino flux near the Sun, veto-array methods, and potential double-signal techniques to observe solar neutrinos.

2.1 Benefits and Challenges of a Near-Solar Orbit

Like any radiation emitted from a point source, solar neutrinos obey the inverse-square law of intensity where the intensity $I$ is proportional to the inverse of the distance $r$ from the source (Equation 5).

$$I \propto \frac{1}{r^2}$$

(5)

If the point of observation is placed significantly closer to the source, in this case the Sun, the radiation flux will increase by many orders of magnitude over that observed initially. Table 1 shows these increases in flux for solar neutrinos at selected distances from the Sun. During the course of this design study, it was immediately determined that an orbital perihelion of 7 solar radii or closer would be desirable for the factor of 1,000 improvement in flux [1]. This means that for a detector of a certain volume on Earth, the same detector could be 1,000 times smaller when placed at the 7 $R_\odot$ distance to accomplish the same performance.
Operating in close proximity of the Sun (even the 7 \text{ R}_\odot \text{ is within the Sun’s outer atmosphere}) leads to a series of design concerns, most obviously the intense heat of the Sun’s corona. Fortunately for this development project, a precedent has already been established for spacecraft operation in the solar corona. Technology development for the Parker Solar Probe, a spacecraft currently in operation for solar corona studies, has already surmounted many engineering hurdles associated with the intense temperature and radiation environment [25]. Parker Solar Probe (named Solar Probe Plus for a time before launch) is designed to make a solar close approach of 8.86 \text{ R}_\odot from the surface, utilizing a thick reinforced carbon-composite shield to maintain a 300 K instrument temperature opposed to the outside 1,640 K environment [25]. The spacecraft power systems, reliant upon retractable photovoltaic panels, have also been successfully designed for operation in this environment [25]. Although the spacecraft concept presented here would ideally travel closer to the Sun, an overall mission profile similar to that of Parker Solar Probe with some slight modifications can be envisioned for the solar neutrino spacecraft.

Another concern, to be addressed in further sections, is the ionizing radiation environment of near-solar space. The Sun produces a constant stream of charged particles in the form of the solar wind, mostly protons and some electrons which are steadily ejected through the solar system [26]. Other space radiation sources, mainly galactic gamma-rays
and cosmic-rays, must be considered as well; however, this neutrino experiment does not have to contend with the population of cosmic-ray muons which are produced in the Earth’s atmosphere from cosmic-ray interactions and problematic for all ground-based solar neutrino experiments.

2.2 General Detector and Spacecraft Design Overview

An initial assessment of mission requirements has led to the detector layout diagramed in Figure 7 [1]. The core of this instrument is a 250 kg mass of mineral-oil type liquid scintillator doped with gallium, where the gallium serves as the interaction nuclei for neutrino interactions. This scintillator mass is sandwiched between two photo-detection assemblies, which in the given diagram are represented as PMTs; however, the use of PMTs as the photodetectors is not a firm design requirement and it is likely that the final design will incorporate solid-state photodetectors instead. Immediately surrounding the main scintillator volume is a polystyrene-based solid scintillator shell which serves as the veto array [27]. Optical fibers are placed throughout the solid scintillator as a means of collecting the scintillation light for detection by the veto array electronics, as illustrated in the diagram. Alternating layers of thin metal and plastic, not illustrated in the diagram directly, separate the detection components from a 0.5 cm thick tungsten shell which serves as the passive background radiation shield [27].
Figure 7: Diagram of the proposed detector design showing the arrangement of the main detection scintillator volume, the veto array system, and the surrounding tungsten shielding [1].

Not shown in the accompanying diagram is the solar radiation shielding; however, this is clearly shown in the examples of Geant4 simulations given later. Like the Parker Solar Probe, a large carbon-composite heat shield is required for temperature control. In this design, there is an additional 9 cm thick layer of tungsten placed behind the heat shield to act as a barrier to solar electromagnetic radiation [1,27]. Altogether, this shield should be approximately 1 meter in diameter and 900 kg in mass, making the overall spacecraft design just over 1 ton [1]. The following table lists each of the known spacecraft mass contributions (Table 2).

Table 2: Various contributions to the mass of the neutrino detection spacecraft from known components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
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<tbody>
<tr>
<td>Liquid Scintillator and Veto Array Detector</td>
<td>250 kg</td>
</tr>
<tr>
<td>Tungsten Shielding and Heat Shield</td>
<td>900 kg</td>
</tr>
<tr>
<td>Total</td>
<td>1,150 kg</td>
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</table>
2.3 Double Signaling via Gallium Interactions and Cross-Section Considerations

Even with the most favorable shielding and veto array performance, the number of background particles which can evade these safeguards is considerable enough to preclude the kind of single-electron signal utilized for neutrino detection in Borexino, Super-Kamiokande, SNO, and other existing neutrino experiments. Looking back to the double-signaling technique used in the Cowan-Reines experiments has provided some inspiration for a potential solution to this problem; however, in this case the interaction method must be accommodative for neutrinos rather than antineutrinos.

For this design study, a method has been devised for the use of neutrino-gallium interactions as the source of an initial conversion electron signal and the possible de-excitation decay of the resultant germanium nucleus as a secondary gamma-ray signal [1]. As a gallium interaction, this has the added benefit of accessibility to very low-energy neutrinos. Natural gallium is composed of two isotopes, gallium-71 and gallium-69 in abundances of 39.892% and 60.108% respectively [28, 29]. The $^{71}_{31}$Ga interaction has been historically used (see Chapter 1) and can result in an excited $^{71}_{32}$Ge nucleus which decays via the emission of a 0.175 MeV gamma-ray, as outlined in Equation 6 and Equation 7 [15, 29].

$$\nu_e + ^{71}_{31}Ga = e^- + ^{71m1}_{32}Ge \quad (6)$$

$$^{71m1}_{32}Ge \rightarrow \gamma + ^{71}_{32}Ge \quad (7)$$

In the case of the $^{69}_{31}$Ga interaction, there are two excited state possibilities for the $^{69}_{32}$Ge nucleus depending on the total energy of the initial neutrino interaction [28]. The m1 state decays via a 0.086 MeV X-ray while the higher-energy m2 state decays via a 0.397 MeV gamma-ray, shown in Equation 8 through Equation 11 [28].

$$\nu_e + ^{69}_{31}Ga = e^- + ^{69m1}_{32}Ge \quad (8)$$
\[ {^{69m1}_{32}}Ge \rightarrow \gamma + {^{69}_{32}}Ge \] (9)

\[ \nu_e + {^{69}_{31}}Ga = e^- + {^{69m2}_{32}}Ge \] (10)

\[ {^{69m2}_{32}}Ge \rightarrow \gamma + {^{69}_{32}}Ge \] (11)

Emission of both an electron and photon in sequence—depending on the energy of the incoming neutrino, the interaction cross-section associated with each possible interaction, and the isotope of gallium involved—proves advantageous for solar neutrino detection amongst background particle events. The combination of the secondary photon’s specific energy value and the timing of the related decay allow for the associated signals to be pinpointed in comparison to dramatically uncharacteristic background signals. Table 3 outlines the important parameters for each of these interactions.

Table 3: Neutrino-gallium interactions with excited germanium state possibilities, including the neutrino energy thresholds for each interaction and the decay half-life for each excited state [28,29].

<table>
<thead>
<tr>
<th>Interaction</th>
<th>( \nu_e ) Energy Threshold</th>
<th>Decay Photon Energy</th>
<th>Half-Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_e + {^{71}<em>{31}}Ga = e^- + {^{71m1}</em>{32}}Ge )</td>
<td>0.405 MeV</td>
<td>0.175 MeV</td>
<td>20 ms</td>
</tr>
<tr>
<td>( \nu_e + {^{69}<em>{31}}Ga = e^- + {^{69m1}</em>{32}}Ge )</td>
<td>0.9 MeV</td>
<td>0.086 MeV</td>
<td>5 ( \mu )s</td>
</tr>
<tr>
<td>( \nu_e + {^{69}<em>{31}}Ga = e^- + {^{69m2}</em>{32}}Ge )</td>
<td>1.3 MeV</td>
<td>0.397 MeV</td>
<td>2.8 ( \mu )s</td>
</tr>
</tbody>
</table>

Predicting an appropriate rate of interactions using this method requires an examination of cross-section calculations for neutrino-gallium interactions, which are generally well understood for \( {^{71}_{31}}Ga \) in light of its previous use in solar neutrino experiments [15]. As for the \( {^{69}_{31}}Ga \) interactions, there is much less information to be found; however, the inclusion of \( {^{69}_{31}}Ga \) as a possible interaction nucleus is partially because of its notable natural abundance [30]. Since this is a very small detector, the amount of gallium necessary will in turn be very small, and it is not out of the question to use isotopically pure gallium compounds in this assembly. Table 4 shows the average cross sections for interactions between neutrinos from the various proton-proton chain steps and \( {^{71}_{31}}Ga \). All of these cross-sections are on the order of \( 10^{-46} \) cm\(^2\), leading to a necessity of the most
gallium dopant reasonably achievable in the liquid scintillator. Such a required parameter is not to be taken lightly; the amount of dopant is limited by the decreasing light attenuation abilities of the scintillator as more dopant is added to the mixture. A complete understanding of the doping limits will be relegated to later laboratory studies; thus, an upper limit of 10% dopant content will be assumed for this study.

Table 4: Interaction cross-sections for neutrino interactions with $^{71}_{31}$Ga as calculated in J.N. Bahcall’s 1997 study of gallium experiments. Note the increase in cross-section with neutrino energy and the overall low magnitude of the cross-sections [15].

<table>
<thead>
<tr>
<th>$\nu$ Source</th>
<th>Average $\nu$ Energy</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp</td>
<td>0.2668 MeV</td>
<td>11.72[1.0±0.023]×10$^{-46}$ cm$^2$</td>
</tr>
<tr>
<td>$^7$Be @ 862 keV</td>
<td>0.8618 MeV</td>
<td>71.7[1.0$^{+0.07}_{-0.03}$]×10$^{-46}$ cm$^2$</td>
</tr>
<tr>
<td>pep</td>
<td>1.445 MeV</td>
<td>204[1.0$^{+0.17}_{-0.07}$]×10$^{-46}$ cm$^2$</td>
</tr>
<tr>
<td>hep</td>
<td>9.628 MeV</td>
<td>7.14[1.0$^{+0.32}_{-0.16}$]×10$^{-42}$ cm$^2$</td>
</tr>
<tr>
<td>$^8$B</td>
<td>6.735 MeV</td>
<td>2.40[1.0$^{+0.32}_{-0.15}$]×10$^{-42}$ cm$^2$</td>
</tr>
</tbody>
</table>

2.4 Background Rates and the Application of Veto Array Methods

Of immediate importance to this study is the contribution of galactic gamma-rays and galactic cosmic-rays to the observed particle signals, especially since the detector will be outside of the protection of Earth’s magnetic field and unable to carry the amount of shielding available to Earth-based detectors. A most recent study of this background has been performed by the Fermi Gamma-Ray Space Telescope and its Large Area Telescope (LAT) instrument, quantifying the gamma-ray background reliably from 100 MeV to approximately 300 GeV [31]. Some data has been given for the range between 20 MeV and 100 MeV; however, the efficiency of Fermi-LAT drops considerably for these energies as a result of the steel shell which surrounds the instrument and effectively stops radiation below 20 MeV [32]. Details of the tungsten shielding characteristics for the hypothetical NuSol concept will be discussed in the next section, although the performance of the tungsten shield will likely be very similar to that of the thin steel used in Fermi-LAT. With the limitations of Fermi-LAT in the low-energy regime in mind, much of the veto-array
development efforts outlined here will focus on particle energies above 100 MeV. The galactic cosmic-ray background is taken to be 3 to 5 orders of magnitude greater in flux than the gamma-ray background [32].

Solar particle expectations are based off of data from the Helios space probes which measured solar wind properties near the Sun between 1974 and 1985 [26]. Early in this design study, a key unanswered question was the extent of variability of the solar particle flux in relation to distance from the Sun’s surface. No measurements of this particle flux have been made at the distance which the detector is expected to operate, so an attempt was made to find a trend in the Helios data between the probes’ aphelion and perihelion. These examinations of the Helios data found no significant correlation between the particle counts and the distance of the probes from the Sun; rather, the particle counts were punctuated by a small number of dramatic increases in count which showed no discernible correlation with any physical variable. This indicates that the solar particle flux is dependent upon completely random variations in solar activity and will require more advanced studies to adequately simulate its effects on the particle events visible to the detector. Based off the observed count rates for particles above 20 MeV (where the instrument’s passive shielding can be expected to be less effective), the rates of solar-origin charged particles can only be expected to be approximately 1 per second with 10 per second as a worst case scenario [26]. Most of the efforts of this design study have focused on the galactic background as opposed to the solar background, so further study of the solar particle background is strongly encouraged.

2.5 A Note on Tungsten Shielding

For much of this design study, tungsten has been viewed as the baseline configuration material for shielding [1, 27]. An examination of the attenuation data for gamma-rays in tungsten from the National Institute of Standards XCOM database reveals a generally favorable shielding of gamma-rays below 1 MeV; however, the effects of pair production become significant above 1 MeV, making the material much less effective at
shielding gamma rays. Some interest has been expressed in using steel and the more recent Geant4 simulations have reflected this interest.

2.6 Summary of the Detection Method

Altogether, these fundamental considerations form the basis of a novel space-based detection method for solar neutrinos. Its detection method, shown visually in the conceptual illustration of Figure 8, relies upon:

- Shielding of the detector with sufficiently thick (0.5 cm in the current configuration) tungsten or steel, which reduces the flux of sub-MeV scale background radiation significantly.

- A plastic-scintillator based veto array for the active filtering of highly energetic background radiation, where any signal from the veto that is effectively simultaneous with a signal in the main detector volume is rejected from the final corrected readout.

- Double signals from a gallium-doped liquid scintillator, where the gallium used is included at enough concentration to ensure a large number of interactions but not so much as to reduce the optical transparency of the scintillator significantly. The double-signal interaction is possible because of the germanium excited state decays likely to happen after a neutrino-gallium interaction of the appropriate energy. Since the majority of solar neutrinos detectable with gallium interactions are across a defined energy distribution, the conversion electron from the neutrino-gallium interactions should also be in a similarly defined range. The decay of the germanium excited state emits a gamma-ray or X-ray of a singular energy value, and within a time span defined by the half-life of the decay. A combination of two signals with these energy and timing characteristics in the correct sequence is very likely to be from this neutrino interaction.
- Placement of the spacecraft in an orbit with perihelion close enough (7 solar radii at maximum and possibly closer) for necessarily enhanced neutrino flux.

If this kind of a neutrino detection experiment is to be realized, its detection method must guarantee an ability to find neutrino events with an efficiency of 80% or better and in a way which allows for simple reconstruction of the neutrino energy spectrum observed. For this design study, finding if and how these specifications can be met is a primary goal.

Figure 8: Conceptual illustration of detection methods and signal processing. The veto array signal (in red) is subtracted from the main detection volume signal (in blue), which is represented here by the “no” symbols overlaid on the duplicate signals in both. The corrected signal is examined for double-signals (the green spikes) which fall into the right energy magnitude and the right timing separation (the yellow dashes) to be possible neutrino interaction events.
CHAPTER 3
SIMULATION METHODS

The problem presented for this study is essentially one of optimization, and is best approached through the use of Monte Carlo methods. It has been attacked from two angles: an event-by-event analysis of the detector’s response characteristics through the use of a specialized simulation software—Geant4—and from another direction, a crude Monte Carlo simulation of the detector’s overall event readout. Both of these efforts have benefitted from the other; however, the latter of the two approaches is the focus of this thesis. In this chapter, the Monte Carlo simulation utilized is described in detail, with a brief overview of the Geant4-derived information applied to the Monte Carlo.

3.1 Application of the MIXMAX Random Number Generator Family

The heart of Monte Carlo simulations is the ability to produce random numbers that are at least in some minimal sense “random.” Since any means of producing numbers via computational methods will suffer from some kind of cyclic tendency and/or numerical instability, random number generator programs are more often considered “pseudorandom” in their abilities. For this project, accurately simulating naturally random occurrences of particle detections requires a pseudorandom number generator that is as least “pseudo” as possible. Early in this project, the random number generation functions available in standard C++ packages proved unsuitable for use; they produce values which fall into a regular pattern of magnitude and will generally avoid generating numbers very near zero or one.

For aforementioned reasons, the MIXMAX family of pseudorandom number generators have been utilized here. The basis of this pseudorandom number generator type are mathematical operation sets known as Ansov C-systems, which when defined on a torus have strong instabilities in their trajectories [33]. These instabilities guarantee a high
entropy in their numerical output, making them ideal for random number generation: the period of the MIXMAX generator is $10^{4.389}$ for a defined operator dimension of 240 [33]. Not only does this family of generators allow for the most random numerical output, they are also extremely efficient computationally, requiring less than 10 nanoseconds per invocation [33]. Since this Monte Carlo will be simulating many billions of events of at least four different varieties (neutrino interaction, germanium decay, gamma-ray, and cosmic-ray), the shortest computational time possible is absolutely necessary. Even with the use of the MIXMAX generator, the computational time required for these simulations is lengthly: a 10-day simulation using 30, 2.3 GHz cores on a 34-core total machine takes approximately 7 days to complete.

### 3.2 Program Structure and Output

A basic consideration of this detector design is the rate at which the phototube electronics read the events in the scintillator volume. In other terms, what is the time window for a particle event to be read in the detector? An early, highly conservative approach was to use readout bins with a span of 100 nanoseconds; however, this was more for ease of development during initial coding. Considering the current state of particle detection technology, a much shorter time window can easily be accomplished. Thus, a more appropriate bin size is 10 nanoseconds and has been used since the procurement of a research-grade, 34-core computer for this study.

It is now possible to give an overview of the working process of the Monte Carlo code constructed. First and foremost, the code “makes” event windows: a certain length of simulation time is specified and a loop is initiated for which each cycle of the loop corresponds to a sequential 10-nanosecond bin, continuing until the total time represented by all completed loop cycles equals the input time. In each cycle and for each possible particle outcome therein, a random number is generated and compared to a selected range of numbers within the probability associated with the particle outcome in question. If the
random number is in the range, an appropriate particle event is registered as taking place in the time window. Since the number of windows in a single day of data collection exceed 8 trillion, the probability of a neutrino being detected in any single time bin is exceptionally low, hence the need for a very capable pseudo-random number generation method. Other particle events, though more probable, are still relatively infrequent in comparison. When a particle event happens, a similar number comparison process is used to assign an energy value to the particle detected. For neutrino events, the initial energy value is actually that of the conversion electron emitted when a neutrino interacts with a gallium nucleus, and this energy assignment is in turn followed by additional steps to determine if and when the resultant germanium nucleus decays. When such a decay takes place, an X-ray or gamma-ray is generated in accordance with the initial state of the germanium nucleus. Each time bin containing an event is recorded in a text file (see Figure 9) which contains three columns: the bin number, a four-digit binary identifier of the particle event(s), and the energy value of the event(s).

Figure 9: Output samples. The first column contains the sequential number of the time bin. In the second bin, the four-digit binary identifier takes the scheme as follows: ***1 is a neutrino conversion electron, **1* is a background gamma-ray, *1** is a background cosmic-ray, and 1*** is a secondary decay event. The third column gives the total energy of the event in MeV. Since these examples are selections from 10-nanosecond bin runs, just multiply the number in the first column by 10 to get the time elapsed in nanoseconds.
The frequency of background events for these simulations are all post-veto, meaning that the Monte Carlo does not directly simulate the effect of the veto array on background signal. Later developments of these simulations could allow this to be directly simulated in the event sequence; however, such developments were too involved for the length of time leading up to this thesis. No matter the case, other more sophisticated simulation packages must be used in some way to accurately characterize the effectiveness of the veto array.

3.3 Geant4 Simulations of Veto Array Performance

Geant4 is, in brief, a package of software tools which allows for the simulation of particle interactions in user-defined detector designs (see Figure 10). For this design study, it has been used to simulate the rejection efficiency of the veto array for galactic gamma-rays and galactic cosmic-rays [27]. As stated in the previous chapter, the raw gamma-ray and cosmic-ray rates are based upon data returned from the Fermi-LAT space telescope instrument. The overall results of these simulations are given in Figure 11, where the veto array is shown to operate exceptionally, performing with over 90% efficiency for the rejection of gamma-rays and cosmic-rays over 100 MeV [27]. Also reflected in these Geant4 results are the effects of the shielding material on the particle rates.
Figure 10: Examples of the visualization available in the Geant4 graphical user interface feature as applied to this detector concept. The various particle interaction products and their paths are shown as the linear features throughout the images. The detector and its forward heat shield is shown clearly in these simulations of (a) a 10 GeV gamma-ray entering the detector through the side, (b) a 10 GeV cosmic-ray proton entering the detector through the side, and (c) a 10 GeV cosmic-ray proton entering head-on.
Figure 11: Performance of the veto array as simulated in Geant4 for galactic gamma rays (a) and galactic cosmic rays (b). Here the blue diamonds give the post-veto rates of particles in the select energy bin and the red squares give the rejection success percentage in each energy bin.

As Figure 11 shows, the count rate expressed in these plots is over a series of wide energy bins. Adapting this data to the precision required for the Monte Carlo simulation required much trial-and-error to extract a usable energy spectrum from the Geant4 simulation results.
3.4 Methods of Analysis and Interpretation

To simulate the process of finding neutrino events, a “toy” detector code is applied to the data file from the Monte Carlo. The use of “toy” here is meant to emphasize that it is merely a way of testing the ability to isolate possible neutrino-related signals and not a final—or even recommended—algorithm for this purpose. It simply looks for events in close succession that fall in the right time range and energy values to possibly be the neutrino-related double-pulse signals, then examines the events’ binary codes to determine which are true detections or not. Other codes are often applied which collect basic statistics, e.g. number of overall events, number of each kind of event, etc. Most often, a basic statistics code is applied which finds the number of overall events and the number of each type.
4.1 Decay Profile Reproduction Capability

Any valid Monte Carlo simulation of the detection methods proposed here must be able to accurately reproduce the decay profiles of the germanium excited states. Examining the decay characteristics as produced for the $^{69}\text{Ge}$ excited states has shown that the code possesses an appropriate ability to simulate the decay of these states; however, the simulated decay characteristics of the $^{71}\text{Ge}$ m1 excited state are more difficult to confirm as a result of its long half-life. The included plots (Figure 12 and Figure 13) were constructed by filtering the neutrino interaction events from a week-long simulation using an earlier version of the code which incorporated many more background gamma-ray events; thus, finding the sequential primary and secondary events from the $^{71}\text{Ga}$ interactions was problematic. Later iterations of the code used much reduced low-energy gamma-ray rates, resulting in an improved ability for the toy algorithms to find the interactions. At the same time, the overall probability of neutrino interactions was significantly reduced in later code iterations when correct cross-sections were incorporated, so the earlier data runs still provide the largest number of decay events to examine. For this reason, the decay timing plots based off of the earlier simulations are given here.
Figure 12: Plots showing the number of decayed nuclei versus time surpassed for an observed number of excited germanium nuclei in simulation. An expected number is included which is calculated from the appropriate decay function applied to an identical number of nuclei.
4.2 Performance Optimization through Closer Orbital Perihelion

Although the minimal configuration required for the spacecraft was taken to be 7 solar radii perihelion at first, this distance was based off of very optimistic expectations for gallium-neutrino interaction cross-sections. Even with the artificially amplified rate of neutrino interactions used in the early stages of development, the limitations of the 7 solar radii perihelion became evident from these very rudimentary tests (see Figure 14). Upon application of the prototype algorithm, the best performance consistently possible was a 50% true detection rate. This would go up to over 80% if the perihelion were placed at 3 solar radii, giving a rough indication that the closer distance would be necessary. In the final update to the Monte Carlo code before this writing, true interaction cross-sections were utilized, making the rate of neutrino interactions plausible under any mission parameter much lower than before. To accomplish a neutrino interaction rate over 1 per day, the detector must reach a 3 solar radii perihelion. It must be stressed that the orbital parameters ultimately
selected for such a mission can only guarantee this proximity to the Sun for a short period of time, especially if the orbit is highly elliptical as used historically for the Helios missions and the Parker Solar Probe. If the orbit can allow a significantly close altitude for only a few hours, then detection over a longer timespan must be a cumulative data collection over many orbits rather than a sequentially consecutive measurement in time.

| The total number of events is 18463333 |
| The number of neutrino events is 926 |
| The number of secondary decay events is 534 |
| The number of true detections is 246 |
| The number of false detections is 275 |

(a)

| The total number of events is 1845623 |
| The number of neutrino events is 942 |
| The number of secondary decay events is 553 |
| The number of true detections is 258 |
| The number of false detections is 10 |

(b)

Figure 14: Comparison of double-signal identification algorithm performance for simulations at 7 solar radii perihelion (a) and 3 solar radii perihelion (b). Note that the overall number of events and the number of neutrino events detected here are based off of early design stage rates.

4.3 Effects of Dopant Concentration

Similar to the situation of perihelion position, the earlier phase of simulations indicated an important improvement in performance if the dopant was set to 10% of the scintillator mass as opposed to the very conservative 1% concentration. These early tests even indicated that when applied in combination with the 3 solar-radii perihelion, the true detection rate would be over 90%. With the more realistic interaction numbers applied, a more reasonable expectation is 80%. Most importantly, the rate of neutrino interactions can only be expected to meet or exceed three neutrinos per day if the amount of gallium used in the scintillator volume is 10 kg or greater. If the percentage of dopant is by mass,
there is still an additional 15 kg available which could push the number of neutrinos per
day to seven; however, further testing will be required to confirm this notion.

4.4 Conversion-Electron Energy Spectrum and Isotopic Optimization

For simplicity, the baseline configuration used the natural isotopic abundance of
gallium in the dopant; however, as the given output examples in Figure 15 and Figure 16
show, this introduces some complexities. Because the natural abundance allows for three
different threshold energies, the spectrum of conversion electrons is more spread out across
the energy ranges observable. Beyond specific examinations of the secondary gamma/X-ray
energies and the timing of the events observed, there are no immediately apparent ways the
detector can discriminate between the three possible neutrino-gallium interaction schemes.
The mixed isotope also allows for more opportunities with no interaction at all.
Conducting these simulations with only $^{71}_{31}$Ga shows how the reconstruction of the neutrino
spectrum detected is much easier, since there is only an addition of 0.4 MeV to the
observed conversion electron spectrum energies for a corresponding neutrino energy
spectrum. Also, the 0.4 MeV threshold makes this the lowest energy detection option of the
gallium double-signal interactions, in addition to the lower probability of no detection.
Figure 15: Energy spectrum of conversion electrons from the simulation outputs referenced in Figure 16. The red-circle data is for the pure $^{71}$Ga simulation while the blue-diamond data is for the mixed $^{69}$Ga/$^{71}$Ga simulation. Notice the amplified features of the pure isotope simulation.
Figure 16: Comparison of double-signal identification algorithm performance for simulations at 7 solar radii perihelion (a) and 3 solar radii perihelion (b). Note that the overall number of events and the number of neutrino events detected here are based off of early design stage rates. A plot of these counts is given in Figure 15.

4.5 Expectation of Neutrino Counts and Resolution of Neutrino Spectrum Features

Based off of the roughly 3 to 4 events per day rate that are proven plausible here and the existing orbital parameters of the Parker Solar Probe, an orbit in which the spacecraft is near the perihelion distance for 30 cumulative days will allow for interactions of over 90 solar neutrinos in a short period of time. The number of these events which are followed by a secondary decay event is roughly 43%, which in combination with the best ability of the
prototype selection algorithm allows for a little over 30 detections per month. Additional dopant, provided that laboratory testing shows concentrations above 10% are achievable, can multiply this number of detections significantly; hence, if the given monthly number can be met or improved, certain features of the neutrino energy spectrum can be observed individually.
CHAPTER 5

CONCLUSION

This study has shown via the use of Monte Carlo simulations that a near-solar orbit neutrino detection spacecraft is theoretically possible for specific mission parameters. A detection rate of 3 to 4 neutrinos per day can be achieved if the spacecraft is placed in an orbit of 3 solar radii perihelion and contains at least 10 kg of gallium dopant. These simulations, in combination with Geant4 simulations of the detector assembly, have confirmed the veto array concept’s viability for reducing background signals above 100 MeV. For the low-energy backgrounds, all information available concerning the Fermi-LAT measurements in combination with studies of tungsten shielding has shown that backgrounds below 20 MeV are reduced effectively by such shielding. Further studies should focus on more detailed examinations of solar particle contributions, the effect of background particle interaction showers on detections, and further improvement of galactic background simulations.
REFERENCES
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41


