Discovering the Secrets of the Elusive Neutrino and Going Beyond

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ABSTRACT: The early history of the Elusive Neutrino and the discovery of neutrino oscillation implying neutrino mass will be presented. Current ongoing experiments like NOvA and the future Dune experiment at the Fermilab accelerator complex aim to understand the mass hierarchy of the neutrino flavors and are related to the important search for CP (charge parity) violation in the neutrino sector that could explain the matter anti-matter asymmetry of the Universe. Today we know that much of the Universe is composed of Dark Matter; why it is important, but how we are soon reaching the limit of discovery because the solar neutrino flux on Earth are a background to searching for direct Dark Matter observation. Futuristic ideas about how a neutrino space probe detector can be used to study the solar interior, solar nuclear fusion and dark matter trap in the Sun's core will be explained. It would also greatly enhance the study of neutrinos for particle and nuclear physics and by going away from the Sun overcome the neutrino backgrounds in direct searches for dark mater.
Outline:

- History of the Neutrino: proposal and discovery
- Missing Solar Neutrino Mystery and the discovery of Neutrino oscillations
- Elusive Secrets of the Neutrino: CP-violation, mass, its own anti-particle and sterile neutrino
- Using the Neutrino to understand our Sun
- Dark Matter discovery and neutrino background from the Earth and Sun
- Futuristic Ideas for space-craft based Neutrino and Dark Matter Studies
History of the Neutrino: proposal and discovery

In the early days after the discovery of radioactive decays, alpha and gamma decays conserved energy, but beta decays (the emission of an electron) violated energy conservation.
History: W. Pauli proposes Neutrino

Expected most of the energy $E_{\text{max}}$ of decay to be observed when detecting the Beta-particle, but it was not!
W. Pauli proposed another invisible particle, eventually named neutrino, that carries away some of the missing unobserved energy.
Directly observing the Neutrino

Using inverse beta decay:

\[
\overline{\nu}_e + p^+ \rightarrow n^0 + e^+ 
\]

The liquid scintillator is doped with Gd which has a high neutron cross-section.

So this produces a double signal, prompt $e^+$ annihilation, and delayed neutron capture. X-ray background eliminated.
Positron and Neutron timing

Two signals eliminates the X-ray and gamma-ray backgrounds. Charged particles are vetoed by an active shield.
The zoo of particles

In the 1950s and 60s particle physics was a collection of newly discovered particles:

- Heavier versions of protons and neutrons
- Strange particles that decayed with beta decays into these heavy protons, or regular protons
- Mesons that decayed into only leptons or photons
- Strange mesons.

Many of these came from cosmic rays or were made in new high energy accelerators.
The zoo of particles

It was soon learned that these particles could be organized into tables:

The idea of quarks were created, where:

- Baryons are made of three quarks
- Mesons are made of a quark and anti-quark
There are different types of Neutrinos

Decays of pi-mesons produced neutrinos, and a spark chamber both shielded and having an active veto for charged particles from these mesons saw neutrinos that when interacting produced charged leptons of both muon and electron type, showing two different species of neutrino flavors were present in the pi-meson decays.
Summary of Particle Physics:

Today in particle physics we know:

- all observed hadronic particles (baryons and mesons) can be built out of the 3 flavors of quarks,
- we know there are three flavors of leptons,
- all quantum forces interact through the exchange of forces carriers, and
- all these particles have their anti-particle.
Missing Solar Neutrino Mystery and the discovery of Neutrino oscillations

It has long been known that the core of the Sun runs off of Nuclear Fusion. These reactions release heat that eventually makes the light we see, but should also make lots of neutrinos. Ray Davis experiment first searched for these neutrinos on Earth.
Missing Solar Neutrino Mystery and the discovery of Neutrino oscillations

This experiment of Ray Davis observed solar neutrinos four times less than expected. This created the “Case of the Missing Solar Neutrinos” Why?:

- Our Sun inside is different than expected
- Particle Physics is different than expected

\[ \nu_e + ^{37}\text{Cl} \leftrightarrow ^{37}\text{Ar} + e^- \]
Missing Solar Neutrino Mystery and the discovery of Neutrino oscillations

The answer came from another experiment, Super-K in Japan, studying Atmospheric neutrinos created by Cosmic Ray air showers. Using a large 22 kTon water Cherenkov detector underground.
Using the Neutrino to understand our Sun
The Kamland experiment has been studying solar neutrinos. It is 1 kTon of Liquid Scintillator.

In Solar Astrophysics it has improved our knowledge of the nuclear fusion core:
Using Solar Neutrino to understand particle physics

The Kamland experiment has constrained the mass limits of the electron type neutrinos. Its improvement to the energy dependence of survival probability adds a better understanding to SM.
Elusive Secrets of the Neutrino:

• Neutrino Oscillation means that some of the neutrinos have a non-zero mass, what is the neutrino masses and their hierarchy?
• The early Universe forms equally with matter and anti-matter, why is only matter left? This could be due to CP-violation in the neutrino sector.
• The neutrino may be its own anti-particle, if so then double beta decay should exist.
• Is there another sterile type of neutrino other than the 3 flavors of neutrinos currently know?
Beta Decay and the Neutrino

Beta decay of the Weak Nuclear Force is actually a process at the quark level and the transition is that of quarks changing.
Quark and Neutrino Coupling

The transition of the quarks can be described by the CKM matrix which gives the coupling strength of the different species of quarks.

Likewise, the neutrino oscillation transition can be described by a similar matrix for the different flavor of neutrinos called the PMNS matrix.

\[ V_{\text{CKM}} = \begin{pmatrix}
V_{ud} = 0.975 & V_{us} = 0.211 & V_{ub} = 0.005 \\
V_{cd} = 0.211 & V_{cs} = 0.974 & V_{cb} = 0.04 \\
V_{td} = 0.005 & V_{ts} = 0.041 & V_{tb} = 0.999
\end{pmatrix} \]

\[
|V| = \begin{pmatrix}
\nu_e & 0.84 \pm 0.01 & 0.54 \pm 0.02 & 0.05 \pm 0.05 \\
\nu_\mu & 0.38 \pm 0.06 & 0.60 \pm 0.06 & 0.70 \pm 0.06 \\
\nu_\tau & 0.38 \pm 0.06 & 0.60 \pm 0.06 & 0.70 \pm 0.06
\end{pmatrix}
\]
Neutrino Oscillation experiments

To fully understand the neutrino oscillation PMNS matrix we need to study many different types of neutrinos and their transitions.

- Solar or Reactors produce electron type neutrinos
- Decays of Pi-mesons produce muon type neutrinos
- To understand the Tau type neutrino we need to look for transitions of muon or electron type into tau neutrinos.
Fermilab long-baseline muon-type neutrino experiments: Minos, NOvA and Dune

Intense high-energy neutrinos need large detectors.

A long base-line to give the space for neutrinos to oscillate.
NOvA oscillation

Real oscillation events in the Far Detector are being seen.

They are created as muon-type neutrinos and are showing up as electron-type neutrinos.
Solar and Reactor Neutrinos

- Solar and Reactor Neutrinos are produced as electron-type and can be studied by the disappearance of flux of electron-type neutrinos.

- These require smaller path length detectors, but still need a lot of mass to get enough neutrino interaction events.

All of these many experiments have given us the PMNS neutrino oscillation matrix, but also they tell us other things:
ν versus ν̅ detection in Oil

Anti-neutrino detection from Reactors

ν̅ → e^+

p^+ → n^0

protons from Hydrogen

capture neutron on Gd with 0.1 ms window

3%

n^0 in 12C

neutrino detection from Sun

ν → e^−

p^+ → n^0

12N decay to e^+ 12C

10 ms half-life

96.5%

e^+ annihilates on atomic shell electrons, clean peak signal

only source of neutrons from Carbon

e^+ annihilates on atomic shell electrons, clean peak signal

neutrons from Carbon

protons from Hydrogen

only source of neutrons from Carbon

protons from Hydrogen

only source of neutrons from Carbon

neutrons from Carbon
Neutrino Mass hierarchy

We can use these oscillation parameters to determine the mass difference squared.

Because like with the quadratic equation has two solutions, this often gives us two possible outcomes, so two neutrino mass structures are possible.
CP-violation with Neutrinos, parameters both Dirac or Majorana (anti-neutrino to neutrino oscillation) are possible.
Future DUNE experiment and Neutrino CP-violation
Sterile Neutrino

There have been hints of a sterile 4$^\text{th}$ type of neutrino. Many searches, but still very un-confirmed. They could be very massive, non interacting (maybe right-handed) and could even be a possible dark matter candidate.
Dark Matter discovery and neutrino background from the Earth and Sun

- How do we know dark matter exists
- How to search for dark matter
- Backgrounds to direct dark matter searches
- Effects of dark matter in our Sun's core
Evidence for Dark Matter

First evidence for dark matter was the mystery of galaxy rotation curves, the measured visible matter present did not match the expected rotation rate.
Evidence for Dark Matter

More evidence for dark matter comes from Einstein Lensing of invisible matter bending the path of light around an object.
Evidence for Dark Matter

Using these techniques then the location of dark matter can be mapped out.

Dark matter can be shown to be grouping in different locations than visible baryonic matter, but that dark matter is also present near visible baryonic matter.
Dark Matter

- In the early Universe Dark Matter dominated and as time passed a Dark-Energy accumulated.
- Today Visible baryonic matter is ~5%, Dark Matter ~25% and the rest Dark Energy.
- Science would like to directly detect and study Dark Matter, what is it?
How can we detect Dark Matter

<table>
<thead>
<tr>
<th>Force</th>
<th>Dark Matter Observed</th>
<th>Dark Matter Searches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Strong Nuclear Force</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Weak Nuclear Force</td>
<td>No</td>
<td>Yes (but none seen)</td>
</tr>
</tbody>
</table>

- So far Dark Matter only seen by its Gravitational influence.
- Most direct dark matter searches hope it interacts through the Weak Nuclear Force but this is not certain.
Direct detection Dark Matter Searches

WIMP–nucleon cross section [cm²] vs. WIMP Mass [GeV/c²]

- 100 eV rms ionization
- 50 eV rms phonons
- ⁸B solar neutrinos
- COHERENT NEUTRINO SCATTERING
- Atmospheric and DSNB Neutrinos
- Surface rejection demonstrated < 0.6 evt/0.3 ton yr

Cylindrical Surface rejection still needs to be satisfactorily demonstrated
Dark Matter Backgrounds

• On Earth Background to direct Dark Matter search are from:
  - Atmospheric Cosmic Ray air showers have neutrinos
  - Geo-neutrinos from the Earth, crust and core
  - Nuclear Reactor neutrinos

• Solar Neutrinos dominate the low mass search regions for Dark Matter.
Neutrinos Produced in our Sun

- Right: Neutrino flux from various solar nuclear fusion processes.
- Left: Is predicted location of solar fusion processes.
Neutrinos Produced in our Sun

Dark matter in the core of the Sun can change both the location of rate for nuclear fusions and the rate of burning of various processes. Where the location would be the most sensitive measurement.

[Diagram showing neutrino flux from various solar nuclear fusion processes and predicted location of solar fusion processes.]
Futuristic Ideas for space-craft based Neutrino and Dark Matter Studies

By leaving the Earth we can change the solar neutrino flux, and eliminate the Terrestrial backgrounds from neutrino sources.

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

<table>
<thead>
<tr>
<th>Distance from Sun</th>
<th>Solar Neutrino intensity relative to Earth</th>
</tr>
</thead>
<tbody>
<tr>
<td>696342 km</td>
<td>46400</td>
</tr>
<tr>
<td>1500000 km (~3 Sun R)</td>
<td>10000</td>
</tr>
<tr>
<td>4700000 km (~7 Sun R)</td>
<td>1000</td>
</tr>
<tr>
<td>15000000 km</td>
<td>100</td>
</tr>
<tr>
<td>474340000 km</td>
<td>10</td>
</tr>
<tr>
<td>Mercury</td>
<td>6.7</td>
</tr>
<tr>
<td>Venus</td>
<td>1.9</td>
</tr>
<tr>
<td>Earth</td>
<td>1</td>
</tr>
<tr>
<td>Mars</td>
<td>0.4</td>
</tr>
<tr>
<td>Asteroid belt</td>
<td>0.1</td>
</tr>
<tr>
<td>Jupiter</td>
<td>0.037</td>
</tr>
<tr>
<td>Saturn</td>
<td>0.011</td>
</tr>
<tr>
<td>Uranus</td>
<td>0.0027</td>
</tr>
<tr>
<td>Neptune</td>
<td>0.00111</td>
</tr>
<tr>
<td>Pluto</td>
<td>0.00064</td>
</tr>
<tr>
<td>KBP</td>
<td>0.0002</td>
</tr>
<tr>
<td>Voyager 1 probe 2015</td>
<td>0.00006</td>
</tr>
</tbody>
</table>
Futuristic Ideas for space-craft based Neutrino and Dark Matter Studies

Leaving the plane of the solar system would bring new science, allowing study of the nuclear core in 3D and solar mass that the neutrino must go through.
In a close solar orbit, the neutrino would be de-coherent, allowing unique studies of Physics.

<table>
<thead>
<tr>
<th>Neutrino Energy (MeV)</th>
<th>Oscillation length (km)</th>
<th>Coherence Length (km)</th>
<th>$\sigma_\nu$ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>34</td>
<td>$2.44 \times 10^5$</td>
<td>$3.15 \times 10^{-9}$</td>
</tr>
<tr>
<td>5</td>
<td>170</td>
<td>$6.10 \times 10^5$</td>
<td>$3.15 \times 10^{-9}$</td>
</tr>
<tr>
<td>10</td>
<td>340</td>
<td>$2.44 \times 10^7$</td>
<td>$3.15 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

Table 2: Shown in this table are numerical values of the oscillation and coherence lengths for three different neutrino energies. See Ref. [4].

This would allow for measuring neutrino oscillation peaks over changing distance from the Sun. It would give us details about:

- the oscillation model
- Study disappearance changes for sterile neutrinos
- Vacuum propagation oscillation effects without matter
In a close solar orbit, the neutrino would be de-coherent, allowing unique studies of Physics.

Detailed studies of electron-type neutrino oscillation survival probability gives information about the parameters in the oscillation model unassailable any other way.
Detector and Space-craft parameters

- Smallest and lightest detector possible
- Closest orbit to the Sun possible, with changes in distance and latitude
- Solar shade that stops most of the Electromagnetic radiation from the Sun
- Fast detector to allow for higher rates
- Active veto array to ensure neutrino event contained
- Long mission life to get the most data
Simulation studies of simple detector

Funded by a small KS-NASA EPSCoR Partnership Development grant.

Neutrino detector for close sun orbit

- phototube
- Liq. Scint, Volume
- fast plastic scintillator with wavelength shifting Fibers read out by phototube.
- HV generation and counting logic
- Tungsten shielding with active cooling

Accepted % of Events per MeV for Radii of Maximum Acceptance for Various Volume

<table>
<thead>
<tr>
<th>Volume Details</th>
<th>Accepted % (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7cm radius, 2.5kg detector</td>
<td></td>
</tr>
<tr>
<td>15cm radius, 25kg detector</td>
<td></td>
</tr>
<tr>
<td>31cm radius, 250kg detector</td>
<td></td>
</tr>
<tr>
<td>25cm radius, 100kg detector</td>
<td></td>
</tr>
</tbody>
</table>

Energy in MeV

Percent of Recoverable Events
A solar neutrino detector close to the Sun could do a large amount of unique science:

- Detector needed is small, so can be launched into space.
- Image Nuclear furnace in 3D by changing solar latitude
- Study neutrino matter effects off the solar plane, Sun bulge is less
- Neutrino oscillation where it is de-coherent would allow us to:
  - Study details of oscillation and neutrino models
  - Clearly determine if there are sterile neutrinos
- Indirect gravity search for dark matter trapped in Sun's core
- Closer to the Sun with higher signal to noise allows for a very small nuclear fusion rates study of our Sun

A small dark matter detector for the region where solar neutrino backgrounds are high could be just 12 kg.
NASA pioneering spacecrafts: small devices put into remarkable places

Using a small spark-chamber detector NASA opened our eyes to the Gamma-ray Universe.

The Hubble Space Observatory is a small unremarkable telescope, but where it sits it becomes the greatest observatory.

Can we expect a similar advancement of science using a small neutrino or dark matter detector in space?
Conclusion

• After the Neutrino was confirmed to exist the Physics study continues to struggle to understand its secrets.

• Solar Neutrinos have played a new recent rule in understanding the neutrino and studying the nuclear furnace of our Sun.

• Terrestrial Neutrinos made it possible to discovery neutrino oscillations but provide a background to solar and super-nova neutrinos.

• There is the potential to learn a lot by studying neutrinos with a spacecraft close to the Sun, and Dark Matter by going away from the Sun.
Backup Slides
Electron and Proton Spectrum from the Helios Solar space-probe.

Figure 3: left: prompt spectra; right: shock spectra – Open circles (triangles): protons (electrons) HELIOS 1; full circles (triangles): protons (electrons) HELIOS 2
Dama/Libra Dark Matter Experiment

Un-known correlation with Earth's orbit, a space craft would be able to go out of the Ecliptic plane and have a different period than Earth.
Mission design considerations

- Desired perihelion (closest approach) around 7-10 solar radii

- A small inclination (15-20 deg) of the final orbit with respect to the ecliptic plane is desired; this can be achieved by suitable gravity assist maneuver
**Objectives**

Develop a miniaturized neutrino detector suitable for a 3U-6U CubeSat (1U refers to 10 cm x 10 cm x 10 cm)

Operate the detector in a relevant geocentric orbit and compare its performance to that measured on the ground

**Research Team**

WSU Physics (POC: Dr. Nick Solomey)

WSU College of Engineering (POC: Dr. Atri Dutta)

NASA Marshall Spaceflight Center (POC: Dr. Les Johnson, Dr. Nasser Barghouty)

National Institute of Aviation Research – NIAR (POC: Dr. Tom Aldag)

**Approach**

Analyze comprehensive mission scenarios to determine suitable orbits for operation of the miniaturized detector operation, and to determine the optimal design of the CubeSat subsystems

Environmental testing of the CubeSat to make it launch ready

Launch opportunity through NASA’s CubeSat Launch Initiative

Measure neutron signals by the CubeSat in orbit and comparison with in-laboratory tests

**Potential Impact**

Advance the Technology Readiness Level (TRL) of the liquid-scintillator based detector

Provide greater operating confidence for a mission in which a detector is placed in a heliocentric orbit

Advance Kansas CubeSat research infrastructure (Kansas is an EPSCOR state)