Introduction to Neutrino Physics

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Cosmic Ray Vision from the Southern Sky

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Discovery of the Neutrino

Prediction of its existence (1930)
(Wolfgang Pauli)

Neutrino Theory (1933)
(Enrico Fermi)

First Detection (1953)
(F. Reines, C. Cowan)
1930: PREDICTION of the EXISTENCE of the NEUTRINO.

Wolfgang PAULI

Study of Nuclear Beta Decay
Nuclear BETA Decay

Carbon-14
6 protons,
8 neutrons

Nitrogen-14
7 protons,
7 neutrons

+ electron

Missing Energy
Momentum
Angular momentum
Nuclear BETA Decay

Carbon-14
6 protons,
8 neutrons

→

Nitrogen-14
7 protons,
7 neutrons

+ electron

neutrino
1933
Enrico Fermi
[Nobel Prize in 1938]

develops the theory of Beta Decay

Current-Current Interaction
Fermi: Current-Current Interaction

\[ n \rightarrow p + \nu + e^- \]
Fermi: Current-Current Interaction

Neutrino Cross section

\[ \sigma \approx 10^{-44} \text{ cm}^2 \]
Fermi: Current-Current Interaction

Neutrino Cross section

$$\sigma \approx 10^{-44} \text{ cm}^2$$
Neutrino Energy
few MeV

\[ \sigma \approx 10^{-44} \text{ cm}^2 \]

Interaction Probability

\[ = 10^{-11} \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ \nu_e + n \rightarrow p + e^- \]
\[ n \to p + e^- + \bar{\nu}_e \]

Quark description

\[ \nu_e + n \to p + e^- \]
\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ \nu_e + n \rightarrow p + e^- \]

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

Detection Method
Neutrino Discovery (antineutrinos from Nuclear Reactors)

Reines e Cowan
1953-1956
$\bar{\nu}_e + p \rightarrow n + e^+$

\[
E_{\text{visible}}^{\text{prompt}} = (E_{e^+} - m_e) + 2m_e
\]
\[
= E_{\bar{\nu}_e} - (m_e + m_n - m_p)
\]
\[
\simeq E_{\bar{\nu}_e} - 1.8 \text{ MeV}
\]

\[
m_p + E_{\bar{\nu}_e} \simeq m_n + E_{e^+}
\]
\[
E_{e^+} \simeq E_{\bar{\nu}_e} - (m_n - m_p)
\]

Delayed coincidence
$e^+ \quad n$
Delayed neutron capture 
(after thermalization of the neutron)

\[ n + p \rightarrow d + \gamma (2.2 \text{ MeV}) \]

**Neutrino Detection:**

Delayed Coincidence 
of prompt energy release (the positron) 
and delayed neutron capture photon
Standard Model

\[ SU(3) \otimes SU(2) \otimes U(1) \]

8 Gluons

\[ W^+ \quad W^- \quad Z^0 \quad B \]

Interactions are due to the EXCHANGE of SPIN 1 Particles
Neutral Currents

$e^- \rightarrow e^-$

$e^- \rightarrow e^- \rightarrow \gamma$

$e^- \rightarrow e^- \rightarrow Z^0$

$\nu_e \rightarrow \nu_e \rightarrow Z^0 (M = 91 \text{ GeV})$
Interactions are due to the EXCHANGE of SPIN 1 Particles

ELECTROMAGNETISM
Exchange of Photons

\[ M(\gamma) = 0 \]

STRONG Interaction
Exchange of Gluons

\[ M(\text{gluon}) = 0 \]

WEAK Interaction
Exchange of 3 Massive Particles

\[ M(W^\pm) \approx 85 \, M_{\text{proton}} \]
\[ M(Z^0) \approx 97 \, M_{\text{proton}} \]
Potential of a point electric charge

\[ V_{\text{elettrico}} = \frac{e}{r} \]

Potential Weak Force

\[ V_{\text{debole}} = \frac{g}{r} e^{-\frac{c}{\hbar} M r} \]

Short Range

\[ V_{\text{debole}} = \frac{g}{r} e^{-r/R_0} \]

\[ R_0 = \frac{\hbar}{c M} \]

\[ R_0 \approx 2 \times 10^{-16} \text{ cm} \]
Comparing the Cross section of two Processes:

\[ e^- + p \rightarrow e^- + p \]

\[ \nu_e + n \rightarrow e^- + p \]
Rutherford Formula:

\[ e^- + p \rightarrow e^- + p \]

\[ Q^2 = (p_e - p'_e)^2 \]

\[ \frac{d\sigma_{ep}}{dQ^2} \sim \frac{\alpha^2}{Q^4} (\hbar c)^2 \]
\[ \nu_e + n \rightarrow e^- + p \]

\[ e \rightarrow g = \frac{e}{\sin \theta_{\text{Weinberg}}} \]

\[ Q^2 \rightarrow (Q^2 + M_W^2) \]

\[ M_W = 80 \text{ GeV} \]

\[ \frac{d\sigma_{\nu n}}{dQ^2} \sim \frac{(4\pi g^2)^2}{(M_W^2 + Q^2)^2} \]

\[ \sim \frac{(4\pi g^2)^2}{M_W^4} \frac{1}{(1 + Q^2/M_W^2)^2} \]
\[ \sigma_{\nu n} = \int dQ^2 \frac{d\sigma_{\nu n}}{dQ^2} \]

\[ \approx \left( \frac{4\pi g^2}{M_W^4} \right)^2 \left( Q_{\text{max}}^2 - Q_{\text{min}}^2 \right) \]

\[ Q_{\text{max}}^2 = (p_\nu + p_n)^2 = M^2 + 2M E_\nu \]

\[ \sigma_{\nu}(E_\nu) \sim \frac{\alpha^2}{M_W^4} M_p E_\nu (\hbar c)^2 \sim 10^{-38} E(\text{GeV}) \text{ cm}^2 \]
PARITY SYMMETRY

Can we understand if we see the real world or a “Mirror Image” of the world?
Spin $\frac{1}{2}$ Particles are described by 4 components “Dirac Spinors”

Left and Right Chirality Projectors

$$\psi_L = \left( \frac{1 - \gamma_5}{2} \right) \psi$$

$$\psi_R = \left( \frac{1 + \gamma_5}{2} \right) \psi$$

Only the Left-Chirality component of a fermion interacts with the W bosons.

For a massless particle CHIRALITY = HELICITY
Particles: Left-chirality

\[ e^-, \; \mu^-, \; \tau^- \]
\[ \nu_e, \; \nu_\mu, \; \nu_\tau \]
\[ u, \; d, \; s, \; c, \; b, \; t \]

\[ P_{\text{Left}} \approx 1 - \frac{m^2}{E^2} \]

\[ P_{\text{Right}} \approx \frac{m^2}{E^2} \]

Anti-Particles: Right-chirality

\[ e^+, \; \mu^+, \; \tau^+ \]
\[ \bar{\nu}_e, \; \bar{\nu}_\mu, \; \bar{\nu}_\tau \]
\[ \bar{u}, \; \bar{d}, \; \bar{s}, \; \bar{c}, \; \bar{b}, \; \bar{t} \]

\[ P_{\text{Left}} \approx \frac{m^2}{E^2} \]

\[ P_{\text{Right}} \approx 1 - \frac{m^2}{E^2} \]
### Fermion Particles in the Standard Model

**Left Panel**

\[
\begin{pmatrix}
  u \\
  d'
\end{pmatrix}_L \quad
\begin{pmatrix}
  c \\
  s'
\end{pmatrix}_L \quad
\begin{pmatrix}
  t \\
  b'
\end{pmatrix}_L \\

\begin{array}{l}
  d_R \\
  s_R \\
  b_R \\
  u_R \\
  c_R \\
  t_R
\end{array}
\]

\[Y = -\frac{1}{2}\]

**Right Panel**

\[
\begin{pmatrix}
  H^+ \\
  H^0
\end{pmatrix}
\]

\[Y = +\frac{1}{2}\]

\[
\begin{pmatrix}
  \nu_e \\
  e
\end{pmatrix}_L \quad
\begin{pmatrix}
  \nu_\mu \\
  \mu
\end{pmatrix}_L \quad
\begin{pmatrix}
  \nu_\tau \\
  \tau
\end{pmatrix}_L \\

\begin{array}{l}
  e_R \\
  \mu_R \\
  \tau_R \\
  (\nu_e)_R \\
  (\nu_\mu)_R \\
  (\nu_\tau)_R
\end{array}
\]

\[Y = -\frac{1}{2}\]

\[Y = -1\]

\[Y = 0\]
Neutrino Neutrino
Neutrino

Possible Picture

MIRROR

Impossible Picture

Neutrino
Neutrino

Possible Picture

Impossible Picture

PARITY VIOLATION
$^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e$

Conservation of angular momentum
DISCOVERY of PARITY VIOLATION

Lee and Yang

“Madame” Wu
Cobalt-60 in a Cryostat
The Experiment (Dec. 1956) lead by: “Madame” Chien-Shiung Wu that determined that “PARITY” is VIOLATED

\[ ^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \bar{\nu}_e \]
Neutrino Possible Picture

Anti-Neutrino Possible Picture

Charge Conjugation Operation
APPROXIMATE SYMMETRY of NATURE

**CP Transformation**

\[ C = \text{Charge Conjugation} \]
\[ \text{[Particle} \quad \leftrightarrow \quad \text{Anti-Particle} \text{]} \]

\[ P = \text{Parity} \]
\[ \text{[Reflection in a Mirror]} \]
Paul M. Dirac
The NEUTRINO FLAVOR
3 type (FLAVORs) of Neutrinos

\[ \nu_e \quad \nu_\mu \quad \nu_\tau \]

\[ \overline{\nu}_e \quad \overline{\nu}_\mu \quad \overline{\nu}_\tau \]
In 1947 Powell, Occhialini and Lattes discover the existence of the pion thanks to observation of Cosmic Rays with Emulsions in the Chacaltaya Laboratory.

\[ \pi^\pm, \mu^\pm, e^\pm \]
The accelerator, the neutrino beam and the detector

Part of the circular accelerator in Brookhaven, in which the protons were accelerated. The pi-mesons ($\pi$), which were produced in the proton collisions with the target, decay into muons ($\mu$) and neutrinos ($\nu_\mu$). The 13 m thick steel shield stops all the particles except the very penetrating neutrinos. A very small fraction of the neutrinos react in the detector and give rise to muons, which are then observed in the spark chamber.

Based on a drawing in Scientific American, March 1963.
**FLAVOR**

\[ \nu_e \ (\overline{\nu}_e) \to e^- \ (e^+) \]

\[ \nu_\mu \ (\overline{\nu}_\mu) \to \mu^- \ (\mu^+) \]

\[ \nu_\tau \ (\overline{\nu}_\tau) \to \tau^- \ (\tau^+) \]

\[ W^\pm \]
First Generation:
Ordinary Matter

3 GENERATIONS
of elementary fermions

First Generation:
Ordinary Matter
PION DECAY

\[ \pi^+ = [\bar{u}d] \]
\[ \pi^- = [\bar{d}u] \]
\[ \pi^0 = \frac{1}{\sqrt{2}}[\bar{u}u + [\bar{d}d]] \]

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \downarrow \]
\[ e^+ + \nu_e + \bar{\nu}_\mu \]
\[ \pi^+ \rightarrow e^+ \nu_e \] Dynamically suppressed

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \] Kinematically Forbidden

\[ \pi^+ \rightarrow \tau^+ \nu_\tau \]
Decay is nearly forbidden by Angular Momentum Conservation

CHIRALITY versus HELICITY

\( \mathcal{V}_e \)

Pion (spin 0)

\( e^- \)
Particles: Left-chirality

\[ e^-, \mu^-, \tau^- \]
\[ \nu_e, \nu_\mu, \nu_\tau \]
\[ u, \ d, \ s, \ c, \ b, \ t \]

Anti-Particles: Right-chirality

\[ e^+, \mu^+, \tau^+ \]
\[ \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau \]
\[ \bar{u}, \ \bar{d}, \ \bar{s}, \ \bar{c}, \ \bar{b}, \ \bar{t} \]

\[ P_{\text{Left}} = 1 - \frac{m^2}{E^2} \]

\[ P_{\text{Right}} = \frac{m^2}{E^2} \]
MUON DECAY: \[ \mu^- \rightarrow \nu_\mu + e^- \bar{\nu}_e \]
How Many Light Neutrinos Exist?

Answer: 3

\[ Z^0 \rightarrow \nu_\alpha + \bar{\nu}_\alpha \]

\[ \Gamma_{\nu\bar{\nu}} = 166.9 \text{ MeV} \]

\[ \Gamma_{\text{invisible}} = N_\nu \Gamma_{\nu\bar{\nu}} \]

\[ \Gamma_{\text{invisible}} = \Gamma_{\text{tot}} - \Gamma_{\text{vis}} = 498 \pm 4.2 \text{ MeV} \]

\[ N_\nu = \frac{\Gamma_{\text{inv}}}{\Gamma_{\nu\bar{\nu}}} = 2.994 \pm 0.012 \]
NEUTRINO FLAVOR OSCILLATIONS
3 Neutrinos states: 3 masses $m_1, m_2, m_3$

States with definite masses in general do **not** coincide with the "flavor" states.

Flavor basis: $$\{ |\nu_e\rangle, \ |\nu_\mu\rangle, \ |\nu_\tau\rangle \}$$

Mass basis: $$\{ |\nu_1\rangle, \ |\nu_2\rangle, \ |\nu_3\rangle \}$$
\[ W^- \rightarrow \bar{u} + d' \]
\[ \rightarrow \bar{c} + s' \]
\[ \rightarrow \bar{t} + b' \]
\[-(+2/3) + (-1/3) = -1\]

\[ W^+ \rightarrow e^+ \nu_e \]
\[ \rightarrow \mu^+ \nu_\mu \]
\[ \rightarrow \tau^+ \nu_\tau \]
Cabibbo, Kobayashi, Maskawa matrix

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} = V^{\text{CKM}} \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

Pontecorvo, Maki, Nakagawa, Sakata Matrix

\[
\begin{pmatrix}
    \nu_e \\
    \nu_\mu \\
    \nu_\tau
\end{pmatrix} = U^{\text{PMNS}} \begin{pmatrix}
    \nu_1 \\
    \nu_2 \\
    \nu_3
\end{pmatrix}
\]
2 Flavor case

\[ |\nu_\mu\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]

\[ |\nu_\tau\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \]

\[ \Delta m^2 = m_2^2 - m_1^2 \]
Neutrino Propagation

\[ |\nu(0)\rangle = |\nu_\mu\rangle = \cos \theta |\nu_1\rangle + \sin \theta |\nu_2\rangle \]

\[ E_i = \sqrt{p^2 + m_i^2} \simeq p + \frac{m_i^2}{2p} \simeq E + \frac{m_i^2}{2E} \]

Different mass components have different energy

\[ |\nu(t)\rangle = \cos \theta e^{-iE_1 t} |\nu_1\rangle + \sin \theta e^{-iE_2 t} |\nu_2\rangle \]

\[ \nu \text{ state at time } t \]

\[ \nu_\mu \text{ created at } t = 0 \text{ with momentum } p \]
Oscillation Probability

\[ P(\nu_\mu \rightarrow \nu_\tau; t) = \]

\[ = \left| \langle \nu_\tau | \nu(t) \rangle \right|^2 \]

\[ = \left| \{- \sin \theta \langle \nu_1 \rangle + \cos \theta \langle \nu_2 \rangle \} \{ \cos \theta e^{-iE_1 t} | \nu_1 \rangle + \sin \theta e^{-iE_2 t} | \nu_2 \rangle \} \right|^2 \]

\[ = \cos^2 \theta \sin^2 \theta \left| e^{-iE_2 t} - e^{-iE_1 t} \right|^2 \]

\[ = 2 \cos^2 \theta \sin^2 \theta \{ 1 - \cos[(E_2 - E_1)t] \} \]

\[ = \sin^2 2\theta \sin^2 \left[ \frac{\Delta m^2}{4E} t \right] \]
\[ P(\nu_\mu \rightarrow \nu_\tau; L) = \sin^2 2\theta \sin^2 \left[ 1.27 \Delta m^2 (\text{eV}^2) \frac{L(\text{Km})}{E(\text{GeV})} \right] \]
3 Flavor Oscillations

\[ m_3 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \]

\[ m_2 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \]

\[ m_1 \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \quad \]

\[ |\nu_e\rangle = U^*_{e1} |\nu_1\rangle + U^*_{e2} |\nu_2\rangle + U^*_{e3} |\nu_3\rangle \]

\[ |\nu_\mu\rangle = U^*_{\mu1} |\nu_1\rangle + U^*_{\mu2} |\nu_2\rangle + U^*_{\mu3} |\nu_3\rangle \]

\[ |\nu_\tau\rangle = U^*_{\tau1} |\nu_1\rangle + U^*_{\tau2} |\nu_2\rangle + U^*_{\tau3} |\nu_3\rangle \]

\[ N_{\text{Dirac}}^{\text{(physical phases)}} = \frac{n(n + 1)}{2} - (2n - 1) \]

3 X 3

Unitary Matrix

3 angles

6 phases
Mixing Matrix: 3 angles, 1 phase

(relevant for neutrino oscillations)

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

\[ U^* : \text{Mixing Matrix for Antineutrinos} \]

More complex expressions for the Oscillation Probabilities
3 - Flavor Transitions

\[ |\nu(0)\rangle = |\nu_\alpha\rangle = \sum_j U_{\alpha j}^* |\nu_j\rangle \]

\[ |\nu(t)\rangle = \sum_j U_{\alpha j}^* e^{-iE_j t} |\nu_j\rangle \]

\[ A(\nu_\alpha \rightarrow \nu_\beta; t) = \langle \nu_\beta | \nu(t) \rangle \]

\[ = \{ U_{\beta k} \langle \nu_k | \} \{ e^{-iE_j t} U_{\alpha j}^* |\nu_j\rangle \} \]

\[ = U_{\beta k} U_{\alpha j}^* e^{-iE_j t} \langle \nu_k | \nu_j \rangle \]

\[ = U_{\beta j} U_{\alpha j}^* e^{-iE_j t} \]
Oscillation Probability

\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j} U_{\alpha j}^* e^{-i m_j^2 \frac{L}{2E}} \right|^2 \]

\[ = \sum_{j=1,3} |U_{\beta j}|^4 |U_{\alpha j}|^4 \]

\[ + \sum_{j<k} 2 \text{Re}[U_{\beta j} U_{\beta k}^* U_{\alpha j}^* U_{\alpha k}] \cos \left( \frac{\Delta m_{jk}^2 L}{2E} \right) \]

\[ + \sum_{j<k} 2 \text{Im}[U_{\beta j} U_{\beta k}^* U_{\alpha j}^* U_{\alpha k}] \sin \left( \frac{\Delta m_{jk}^2 L}{2E} \right) \]

\[ L, E \]
\[ P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_j U_{\beta j} U_{\alpha j}^* e^{-i m_j^2 \frac{L}{2E_\nu}} \right|^2 \]

\[ P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \quad \text{CP violated} \]

\[ P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\nu_\beta \rightarrow \nu_\alpha) \quad \text{T violated} \]

\[ P(\nu_\alpha \rightarrow \nu_\beta) = P(\bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha) \quad \text{CPT conserved} \]
The "BOX description" of the Neutrinos

\[ P_{\alpha j} = \left| \langle \nu_\alpha | \nu_j \rangle \right|^2 = \left| U_{\alpha j} \right|^2 \]
Neutrino Description

Normal Hierarchy

\[ \nu_e \nu_\mu \nu_\tau \]

Inverted Hierarchy

\[ \nu_e \nu_\mu \nu_\tau \]

Mass of the lightest Neutrino \( m_0 \)

\( \nu_1 \quad \nu_2 \quad \nu_3 \)
DIRAC or MAJORANA?
Dirac Particle

\[ e^e_L \quad e^e_R \]
\[ e^+_L \quad e^+_R \]

Majorana Particle

\[ \nu_L \quad \nu_R \]
\[ \nu_L \quad \nu_R \]
\[ \bar{\nu}_L \quad \bar{\nu}_R \]
\[ \nu_L \quad \bar{\nu}_R \]
Gedanken Experiment

Massive Neutrino at rest in the center of this room.

Spin pointing Down
Accelerate the neutrino to relativistic energy in the direction opposite to the spin.

A few of the Left-Handed particles interact and generate Negative Muons.
Crucial Gedanken Experiment

Accelerate the neutrino to relativistic energy In the direction parallel to the spin

Right-Handed particles Never Interact

The Neutrino is a DIRAC $\nu_\mu$ Particle

Layer of Matter
Accelerate the neutrino to relativistic energy in the direction parallel to the spin.

Right-Handed particles interacting generate positive muons.

The neutrino is a Majorana $\nu_\mu$ particle.
Neutrino at Rest with spin pointing downward.
Double beta decay

![Diagram showing even mass number and nuclear mass with beta decay paths for N,Z odd and N,Z even cases]
Double Beta Decay

\[ \frac{76}{32}\text{Ge} \rightarrow \frac{76}{34}\text{Se} + e^- e^- \bar{\nu}_e \bar{\nu}_e \]
Double Beta Decay

\[ \nu_e = \bar{\nu}_e \]

Neutrino-less Double beta decay
Resolution
TABLE V. Isotopic abundance and $Q$-value for the known $2\nu\beta\beta$ emitters [175].

<table>
<thead>
<tr>
<th>Isotope</th>
<th>isotopic abundance (%)</th>
<th>$Q_{\beta\beta}$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>0.187</td>
<td>4.263</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>7.8</td>
<td>2.039</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>9.2</td>
<td>2.998</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>2.8</td>
<td>3.348</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>9.6</td>
<td>3.035</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>7.6</td>
<td>2.813</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>34.08</td>
<td>2.527</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>8.9</td>
<td>2.459</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>5.6</td>
<td>3.371</td>
</tr>
</tbody>
</table>
$T_{1/2}^{2\nu}[^{76}\text{Ge}] \approx 1.78 \times 10^{21} \text{ yr}$

$T_{1/2}^{0\nu}[^{76}\text{Ge}] \geq 2 \times 10^{25} \text{ yr}$
TABLE VII. In this table, the main features and performances of some past, present and future $0\nu\beta\beta$ experiments are listed.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotope</th>
<th>Technique</th>
<th>Total mass [kg]</th>
<th>Exposure [kg yr]</th>
<th>FWHM @ $Q_{\beta\beta}$ [keV]</th>
<th>Background [counts/keV/kg/yr]</th>
<th>$S^{0\nu (90% \text{ c. l.)}} [10^{25} \text{ yr}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Past</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cuoricino, [179]</td>
<td>$^{130}\text{Te}$</td>
<td>bolometers</td>
<td>40.7 ($\text{TeO}_2$)</td>
<td>19.75</td>
<td>5.8 ± 2.1</td>
<td>0.153 ± 0.006</td>
<td>0.24</td>
</tr>
<tr>
<td>CUORE-0, [180]</td>
<td>$^{130}\text{Te}$</td>
<td>bolometers</td>
<td>39 ($\text{TeO}_2$)</td>
<td>9.8</td>
<td>5.1 ± 0.3</td>
<td>0.058 ± 0.006</td>
<td>0.29</td>
</tr>
<tr>
<td>Heidelberg-Moscow, [181]</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>11 ($\text{enrGe}$)</td>
<td>35.5</td>
<td>4.23 ± 0.14</td>
<td>0.06 ± 0.01</td>
<td>1.9</td>
</tr>
<tr>
<td>IGEX, [182, 183]</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>8.1 ($\text{enrGe}$)</td>
<td>8.9</td>
<td>$\sim$ 4</td>
<td>$\lesssim$ 0.06</td>
<td>1.57</td>
</tr>
<tr>
<td>GERDA-I, [167, 184]</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>17.7 ($\text{enrGe}$)</td>
<td>21.64</td>
<td>3.2 ± 0.2</td>
<td>$\sim$ 0.01</td>
<td>2.1</td>
</tr>
<tr>
<td>NEMO-3, [185]</td>
<td>$^{100}\text{Mo}$</td>
<td>tracker + calorimeter</td>
<td>6.9 ($^{100}\text{Mo}$)</td>
<td>34.7</td>
<td>350</td>
<td>0.013</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Present</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EXO-200, [186]</td>
<td>$^{136}\text{Xe}$</td>
<td>LXe TPC</td>
<td>175 ($\text{enrXe}$)</td>
<td>100</td>
<td>89 ± 3</td>
<td>$(1.7 ± 0.2) \cdot 10^{-3}$</td>
<td>1.1</td>
</tr>
<tr>
<td>KamLAND-Zen, [187, 188]</td>
<td>$^{136}\text{Xe}$</td>
<td>loaded liquid scintillator</td>
<td>348 ($\text{enrXe}$)</td>
<td>89.5</td>
<td>244 ± 11</td>
<td>$\sim$ 0.01</td>
<td>1.9</td>
</tr>
<tr>
<td><strong>Future</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CUORE, [189]</td>
<td>$^{130}\text{Te}$</td>
<td>bolometers</td>
<td>741 ($\text{TeO}_2$)</td>
<td>1030</td>
<td>5</td>
<td>0.01</td>
<td>9.5</td>
</tr>
<tr>
<td>GERDA-II, [174]</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>37.8 ($\text{enrGe}$)</td>
<td>100</td>
<td>3</td>
<td>0.001</td>
<td>15</td>
</tr>
<tr>
<td>LUCIFER, [190]</td>
<td>$^{82}\text{Se}$</td>
<td>bolometers</td>
<td>17 ($\text{Zn}^{82}\text{Se}$)</td>
<td>18</td>
<td>10</td>
<td>0.001</td>
<td>1.8</td>
</tr>
<tr>
<td>MAJORANA D., [191]</td>
<td>$^{76}\text{Ge}$</td>
<td>Ge diodes</td>
<td>44.8 ($\text{enr/natGe}$)</td>
<td>100$^a$</td>
<td>4</td>
<td>0.003</td>
<td>12</td>
</tr>
<tr>
<td>NEXT, [192, 193]</td>
<td>$^{136}\text{Xe}$</td>
<td>Xe TPC</td>
<td>100 ($\text{enrXe}$)</td>
<td>300</td>
<td>12.3 − 17.2</td>
<td>$5 \cdot 10^{-4}$</td>
<td>5</td>
</tr>
<tr>
<td>AMoRE, [194]</td>
<td>$^{100}\text{Mo}$</td>
<td>bolometers</td>
<td>200 ($\text{Ca}^{\text{enrMoO}_4}$)</td>
<td>295</td>
<td>9</td>
<td>$1 \cdot 10^{-4}$</td>
<td>5</td>
</tr>
<tr>
<td>nEXO, [195]</td>
<td>$^{136}\text{Xe}$</td>
<td>LXe TPC</td>
<td>4780 ($\text{enrXe}$)</td>
<td>12150$^b$</td>
<td>58</td>
<td>$1.7 \cdot 10^{-5}$</td>
<td>66</td>
</tr>
<tr>
<td>PandaX-III, [196]</td>
<td>$^{136}\text{Xe}$</td>
<td>Xe TPC</td>
<td>1000 ($\text{enrXe}$)</td>
<td>3000$^c$</td>
<td>12 − 76</td>
<td>0.001</td>
<td>11$^c$</td>
</tr>
<tr>
<td>SNO+, [197]</td>
<td>$^{130}\text{Te}$</td>
<td>loaded liquid scintillator</td>
<td>2340 ($\text{natTe}$)</td>
<td>3980</td>
<td>270</td>
<td>$2 \cdot 10^{-4}$</td>
<td>9</td>
</tr>
<tr>
<td>SuperNEMO, [198, 199]</td>
<td>$^{82}\text{Se}$</td>
<td>tracker + calorimeter</td>
<td>100 ($^{82}\text{Se}$)</td>
<td>500</td>
<td>120</td>
<td>0.01</td>
<td>10</td>
</tr>
</tbody>
</table>

$^a$ our assumption (corresponding sensitivity from Fig. 14 of Ref. [191]).
$^b$ we assume 3 tons fiducial volume.
$^c$ our assumption by rescaling NEXT.
\[ \left[ t^{1/2} \right]^{-1} = G_{0\nu} \left| M \right|^2 \left| f(m_i, U_{ei}) \right|^2 \]

\[ f(m_i, U_{ei}) \equiv \frac{m_{\beta\beta}}{m_e} = \frac{1}{m_e} \left| \sum_{k=1,2,3} U_{ek}^2 m_k \right| \]

\[ m_{\beta\beta} = \left| \sum_{i=1,2,3} e^{i\xi_i} \left| U_{ei}^2 \right| m_i \right| \]
WHY is the NEUTRINO MASS so much smaller than the other Fermion Masses?

Possible Answer:

Because the Neutrino is a Majorana Fermion.
Neutrino as Astrophysical Messenger
Essentially *all our knowledge* about the Universe outside the solar system, Stars, Galaxies, ..... is because we have "seen" it

[that is we have observed *photons* emitted from this far regions of space.]
Light (Photons)

“Nuncius Sidereus”

Messenger from the stars
History of Astronomy:

Improvement of the “telescope”. Expansion of the range of wavelengths available for observations.

New telescopes “new eyes”

New astrophysical objects.
Deeper understanding of known astrophysical objects.
New, more dramatic expansion of our method to "SEE" the Universe

Use of NEW PARTICLES as "MESSENGERS of the STARS"

- Photons
- Neutrinos
- Cosmic Rays
- Gravitational Waves
New, more dramatic expansion of our method to “SEE” the Universe

Use of NEW PARTICLES as “MESSENGERS of the STARS”

Photons

Neutrinos

Cosmic Rays

Gravitational Waves

A “Messenger” with very different properties that will allow us to “SEE” the universe in a profoundly different way.

Very small cross section. Neutrinos arrive from the “deep interior” of astrophysical sources.
Neutrino Astronomy has just been born at the end of the last Century.

Two (+1) astrophysical objects have been “seen” in neutrinos:

The SUN

SuperNova SN1987A

The Earth: (Geophysical Neutrinos detection)
Natural Neutrino Fluxes
SOLAR NEUTRINOS

Source of Energy of the SUN: Nuclear Fusion

\[ 4p + 2e^- \to ^4\text{He} + 2\nu_e \]

Energy Released per each Cycle

\[ Q = 4m_p + 2m_e - m_{^4\text{He}} = 26.73 \text{ MeV} \]

\[
\Phi_{\nu_e} \approx \frac{1}{4\pi d^2} \frac{2 L_{\odot}}{(Q - \langle E_\nu \rangle)}
\]

\[
\phi_{\nu_\odot} \sim 6 \times 10^{10} \text{ (cm}^2 \text{ s)}^{-1}
\]
SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)

\[ \nu_e + ^{37}\text{Cl} \rightarrow ^{37}\text{Ar} + e^- \]

On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of \( \text{C}_2\text{Cl}_4 \), so that the expected \( ^{37}\text{Ar} \) production rate is well above the background of the counter, 0.2 count per day. Using Bahcall’s expression,

\[ \sum_{\nu} \phi_{\nu} (\text{solar}) \sigma_{\text{abs}} \]

\[ = (4 \pm 2) \times 10^{-35} \text{ sec}^{-1} (^{37}\text{Cl} \text{ atom})^{-1}, \]

then the expected solar neutrino captures in 100 000 gallons of \( \text{C}_2\text{Cl}_4 \) will be 4 to 11 per day, which is an order of magnitude larger than the counter background.
Super Kamiokande

DATA/SM = 0.465 ± 0.015

SK-I: $^8$B Solar Neutrino Flux
(1496 days) hep-ex/0508053
Electron total energy: 5.0-20MeV

22400 ± 230 solar $\nu$ events
NEUTRINOS from SUPERNOVAE EXPLOSIONS (Gravitational Collapse)

Energy $\sim 30$ MeV
Neutrinos from Supernovae

Sanduleak -69 202

Supernova 1987A
23 February 1987
From Georg Raffelt

**Onion Structure**

- H
- He
- O-Si

**Collapse (Implosion)**

- Degenerate iron core:
  - $\rho \approx 10^9$ g cm$^{-3}$
  - $T \approx 10^{10}$ K
  - $M_{Fe} \approx 1.5 M_{\text{sun}}$
  - $R_{Fe} \approx 8000$ km
Newborn Neutron Star

~ 50 km

Neutrino Cooling

Proto-Neutron Star
\[ \rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \, \text{g cm}^{-3} \]
\[ T \approx 30 \, \text{MeV} \]

From Georg Raffelt
Newborn Neutron Star

~ 50 km

Gravitational binding energy
$E_b \approx 3 \times 10^{53} \text{ erg} \approx 17\% M_{\odot} c^2$

This shows up as
99\% Neutrinos
1\% Kinetic energy of explosion
(1\% of this into cosmic rays)
0.01\% Photons, outshine host galaxy

Neutrino luminosity
$L_\nu \approx 3 \times 10^{53} \text{ erg / 3 sec}$
$\approx 3 \times 10^{19} L_{\odot}$

While it lasts, outshines the entire visible universe

Proto-Neutron Star
$\rho \approx \rho_{\text{nuc}} = 3 \times 10^{14} \text{ g cm}^{-3}$
$T \approx 30 \text{ MeV}$
The neutrinos from SN1987A still the subject of many works every year!
### Detector Data

<table>
<thead>
<tr>
<th>Detector</th>
<th>$N_{\text{events}}$</th>
<th>$\langle E_{e^+} \rangle$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>KII</td>
<td>11</td>
<td>15.4 ± 1.1</td>
</tr>
<tr>
<td>IMB</td>
<td>8</td>
<td>31.9 ± 2.3</td>
</tr>
</tbody>
</table>
Kamiokande + IMB detection of SN1987A

Controversial Results from other detectors [LSD – Mont Blanc]
A. Mirizzi and G. G. Raffelt,
"New analysis of the SN 1987A neutrinos with a flexible spectral shape,"

Maxwell-Boltzmann Energy Distribution

\begin{align*}
N_{\mu/\nu}/10\text{ MeV} &
\begin{cases}
7 & 0 < E < 10 \\
6 & 10 \leq E < 20 \\
5 & 20 \leq E < 30 \\
4 & 30 \leq E < 40 \\
3 & 40 \leq E < 50 \\
2 & 50 \leq E < 60 \\
1 & 60 \leq E < 70 \\
0 & E \geq 70
\end{cases} \\
N_{\mu/\nu}/10\text{ MeV} &
\begin{cases}
7 & 0 < E < 10 \\
6 & 10 \leq E < 20 \\
5 & 20 \leq E < 30 \\
4 & 30 \leq E < 40 \\
3 & 40 \leq E < 50 \\
2 & 50 \leq E < 60 \\
1 & 60 \leq E < 70 \\
0 & E \geq 70
\end{cases}
\end{align*}

\begin{align*}
E_{\text{tot}} \times 10^{33} \text{ erg} &
\begin{cases}
30 & 0 < E < 5 \\
20 & 5 \leq E < 10 \\
10 & 10 \leq E < 15 \\
0 & E \geq 15
\end{cases} \\
E_{\text{tot}} \times 10^{33} \text{ erg} &
\begin{cases}
30 & 0 < E < 5 \\
20 & 5 \leq E < 10 \\
10 & 10 \leq E < 15 \\
0 & E \geq 15
\end{cases}
\end{align*}
\[ \varphi(E) = \frac{1}{E_0} \frac{(\alpha + 1)^{(\alpha+1)}}{\Gamma(\alpha + 1)} \left( \frac{E}{E_0} \right)^\alpha \exp \left[ - (\alpha + 1) \frac{E}{E_0} \right] \]

A. Mirizzi and G. G. Raffelt,
"New analysis of the SN 1987A neutrinos with a flexible spectral shape,"
23 February 1987

.... 32 years ago ......

We want a new close-by (... but not too much..... )
Gravitational Collapse
Supernova

Scientific Potential
(with the new detectors) is very important
$^{238}\text{U} \xrightarrow{100\%} ^{206}\text{Pb} + 8^4\text{He} + 6e^- + 6\bar{\nu}_e + 51.7 \text{ [MeV]}$

$^{232}\text{Th} \xrightarrow{100\%} ^{208}\text{Pb} + 6^4\text{He} + 4e^- + 4\bar{\nu}_e + 42.7 \text{ [MeV]}$

$^{40}\text{K} \xrightarrow{89.28\%} ^{40}\text{Ca} + e^- + \bar{\nu}_e + 1.311 \text{ [MeV]}$
Geoneutrino results

Data-set:
749.1 days
Fiducial:
5 m radius

152 events observed
"signal" $25^{+19}_{-18}$

Nature 436, 28 July 2005
BOREXINO (March 2010)

9.9 \text{ events (1 sigma)}

3.9_{-1.3}^{+5.8} \text{ events/}(100 \text{ ton \cdot yr})
Cosmic Ray

Air nucleus

2 muon neutrinos

1 electron neutrino

Super-K Detector

ATMOSPHERIC NEUTRINOS

Isotropic flux of cosmic rays

atmosphere

Zenith

θ

super-K

25 km

10000 km

neutrino direction

Up-Down Symmetric Flux
(for $E_\nu >$ few GeV)
Atmospheric $\nu$ energy spectrum

\[ \phi_{\nu} \times E_{\nu}^2 \text{ (m}^2 \text{sec}^{-1} \text{sr}^{-1} \text{GeV)} \]

- $\nu_e$
- $1.5 \times \nu_\mu$
- $0.75 \times \nu_e$
- $\nu_\mu$

- This Work
- HKKMS06
- Bartol
- Fluka

\[ E_{\nu} \text{ (GeV)} \]
\[ \phi_{\nu_{\alpha}}(E, \theta) = \phi_{\nu_{\alpha}}(E, \pi - \theta) \]
Atmospheric Neutrino events

Soudan-2 detector

\[ \nu_\mu + n \rightarrow \mu^- + p \]
\[ \nu_e + N \rightarrow e^{\pm} + N' \]
\[ \nu_\mu + N \rightarrow \mu^{\pm} + X \]
Cherenkov Radiation

\[ \beta = \frac{v}{c} > \frac{1}{n} \]

\[ \cos \theta_{Ch} = \frac{1}{\beta n} \]

- in water, \( n = 1.33 \)
  as \( \beta \rightarrow 1, \theta_{Ch} \rightarrow 41 \text{ degrees} \)

\(~340 \text{ photons/cm pathlength} \)
\( 300 \text{ nm} < \lambda < 600 \text{ nm} \)
IMB detector
SuperKamiokande detector

- 50,000 tons of ultrapure water
- 2 m of water = veto counter
- Fiducial volume = 22,500 tons
- 11,146 (20 inch) PMT's
- 1,885 veto PMT's

42 m

39 m

1 Km underground
11,146 20 inch Photomultipliers (PMT's) (40% of surface is sensitive)
Neutrino Event Classes

- \( e \) (or \( \mu \))
- \( \nu_e \) (or \( \nu_\mu \))
- \( \nu_\mu \)
- \( \nu \)-induced \( \mu \) (from below)
- Contained (any direction)
- sub GeV
- multi GeV
- through-going muons
- stopping muons
Super-Kamiokande data

1489 day FC+PC data + 1678 day upward going muon data

1-ring e-like
Sub-GeV e-like

1-ring μ-like
Sub-GeV μ-like

multi-ring μ-like
Sub-GeV Multi-ring μ-like

up-going μ
Upward Stopping μ
stopping

Multi-GeV e-like

Multi-GeV μ-like + PC

No osc.

Osc.

Multi-GeV Multi-ring μ-like

Upward Through Going μ

Through going

Up-going
Down-going

< 1.3GeV

> 1.3GeV
\[ P_{\nu_\mu \to \nu_\mu} (L, E_\nu) = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 L}{4E_\nu} \right) \]

\[ P_{\nu_\mu \to \nu_\mu} = \begin{cases} 
1 & \text{for } L \text{ small,} \\
1 - \frac{\sin^2 2\theta}{2} & \text{for } L \text{ large.} 
\end{cases} \]

\[ \approx \frac{\lambda^*_\text{osc}}{2} \approx \frac{2\pi \langle E_\nu \rangle}{|\Delta m^2|} \]
HIGH ENERGY NEUTRINO DETECTION

The Km3 concept
"Beaded string"
- 4 cables x 4km to shore.
- 1070m depth
IceCube Lab

IceTop
- 81 Stations, each with
- 2 IceTop Cherenkov detector tanks
- 2 optical sensors per tank
- 324 optical sensors

IceCube Array
- 86 strings including 8 DeepCore strings
- 60 optical sensors on each string
- 5160 optical sensors

December, 2010: Project completed, 86 strings

DeepCore
- 8 strings-spacing optimized for lower energies
- 480 optical sensors

Eiffel Tower
- 324 m

125 m string separation
17 m between PMT's

IceCube total strings 59

Deployment of the strings
ANTARES
Running since 2007
885 10” PMTs
12 lines
25 storeys/line
3 PMTs / storey
2500 m deep
~0.01 km³
450 m

40 km to shore

Junction Box

Interlink cables

© François Montanet
High-energy events in IceCube-40

~ EeV air shower

~100 TeV nm induced muon
A cascade event, candidate for a high energy $\sim 50$ TeV
Observation of neutrino-induced muons
(see ½ of the sky)
IceCube - Point Sources – 7 years

No significant PS reported

No correlation with list of 74 sources in both hemispheres. Galactic & Extragalactic

Most recent data periods:
~80k northern hemisphere evt/yr (atm ν)
~35k southern hemisphere evt/yr (atm μ)
~200 starting tracks. Southern sky

ANTARES – Point Sources

Most significant cluster in the full-sky search (1.9σ post-trial significance) \( \alpha = 343.8^\circ, \delta = 23.5^\circ \)

Sensitivities and upper limits at a 90% C.L. on the signal flux from the Full-sky and the Candidate list searches (Neyman method)

Phys. Rev. D96 (2017), 082001

ANTARES is the most sensitive instrument for a large fraction of the southern sky below 100 TeV

IceCube is the most sensitive instrument in the northern sky and a fraction of the southern sky.
New class of events where the Neutrino interacts inside the detector Fiducial Volume

“High Energy Starting Events"

**HESE**

Outer Layer of the detector is used as a veto

No PMT us have a hit in the veto
With an “early time”

[charged particles can exit the detector, but not enter]
Starting events

- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

loss in statistics is compensated by event definition
“TRACK”

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>71.4 ± 0.1</td>
<td>55542.5516214</td>
<td>-0.4</td>
<td>110.6</td>
<td>≤ 1.2</td>
<td>Track</td>
<td></td>
</tr>
</tbody>
</table>
"Shower"
Two Classes of events

"Tracks"
\[ \nu_\mu (\bar{\nu}_\mu) + N \rightarrow \mu^{\mp} + \text{hadrons} \]

"Showers"
\[ \nu_e (\bar{\nu}_e) + N \rightarrow e^{\mp} + \text{hadrons} \]
\[ \nu_\tau (\bar{\nu}_\tau) + N \rightarrow \tau^{\mp} + \text{hadrons} \]
\[ \nu_\alpha (\bar{\nu}_\alpha) + N \rightarrow \nu_\alpha (\bar{\nu}_\alpha) + \text{hadrons} \]
Tau Neutrinos

\[ \tau^- \rightarrow \nu_\tau + (\mu^- + \bar{\nu}_\mu) \]
\[ \tau^- \rightarrow \nu_\tau + (e^- + \bar{\nu}_\mu) \]
\[ \tau^- \rightarrow \nu_\tau + (q_d + \bar{q}_u) \]

Path-length of tau's before decay

\[ \tau_\tau = 2.9 \times 10^{-13} \]

\[ \ell_\tau = c \tau \frac{E}{m} \simeq 49 \text{ m} \quad E_{\text{PeV}} \]
Atmospheric neutrino self veto

Two cases

1. Stefan Schöbert et al.  
   Can be evaluated analytically

2. Veto by an unrelated $\mu$  
   --also applies to $\nu_e$  
   Requires Monte Carlo or numerical integration
Some neutrinos are absorbed in the Earth.

\[ \sin(\delta) = -\cos(\theta) \] at the South Pole.
Effect of VETO: rejection of atmospheric neutrinos

\[ \sin(\delta) = -\cos(\theta) \] at the South Pole
Effect allows to separate atmospheric charm from isotropic astrophysical.
Absorption of neutrinos in the Earth

\[
P_{\text{surv}} \quad = \quad 1.0
\]
\[
\cos \theta_{\text{zenith}}
\]

\[E_\nu = 10^4, 10^5, 10^6, 10^7 \text{ GeV}\]
Fraction of up-going neutrinos (isotropic flux) that survives crossing the Earth.
$E = \frac{M_{W}^{2}}{2m_{e}} = 6.3 \text{ PeV}$
"Glashow Resonance"

\[
E^* = \frac{M_W^2 - m_e^2}{2m_e} \approx 6.4 \text{ PeV}
\]

\[
\bar{\nu}_e + e^- \rightarrow W^- \rightarrow \ldots
\]

\[
(p_{\bar{\nu}_e} + p_e)^2 = M_W^2
\]

\[
m_e^2 + 2m_e E_{\bar{\nu}} = M_W^2
\]
High-Energy Starting Events (HESE) – 7.5 yr

No evidence for point sources, nor a correlation with the galactic plane
High-Energy Starting Events (HESE) – 7.5 yr

Prior result 6 years ICRC 2017 arXiv:1710.01191
Updates to calibration and ice optical properties
103 events, with 60 events >60 TeV
→ Changes to RA, Dec, energy

Poster #175. Wandkowsky et al. (IceCube)
High Energy Starting Events

4 years data

Track [(small) black circles]
Showers [(large) blue circles]

Galactic equator

$E_{\text{vis}} \gtrsim 30$ TeV
IceCube 4-years HESE events

Celestial coordinates

Galactic plane

Galactic coordinates

horizon
First evidence for an extra-terrestrial h.e. neutrino flux
High Energy Starting Events [HESE]

First evidence for an extra-terrestrial h.e. neutrino flux

3 “PeV events” carry most of the statistical significance for an excess
Upgoing (neutrino induced) Muons

IC2012-2014

Rate per Bin / Hz vs Muon Energy Proxy / GeV

Upgoing muon events

$E_\mu \gtrsim 200 \text{ TeV}$

Muon Energy Proxy / PeV

Equatorial

EXTRA-GALACTIC NEUTRINOS

Main candidate sources

Intimate relation with UHECR [extragalactic cosmic rays]
The 3-dimensional lampposts ensemble “paradox” [Kepler – Olbers paradox].

Linear sequence of lampposts:
Most of the light you receive from the nearest lamppost

3D ensemble of lampposts: [Euclidean static space]
Light diverges!
Homogeneous (in average) density of sources: spherical shells between radii: 1, 2, 3, 4, ....

All spherical shells contribute equally.: DIVERGENCE!

\[
\left( \frac{1}{4\pi R^2} \right) \left( 4\pi R^2 \Delta R \right)
\]
Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ....

All spherical shells contribute equally.: DIVERGENCE!

\[
\left( \frac{1}{4\pi R^2} \right) (4\pi R^2 \Delta R)
\]

Divergence cured
By cosmological effects

\[ R_{	ext{Hubble}} = \frac{c}{H_0} \approx 3 \text{ Gpc} \]
Expected flavor composition
of High energy astrophysical neutrinos

[Standard mechanism of production]

\[ \nu_e \sim \nu_\mu \sim \nu_\tau \]
Space averaged flavor transition probability

Neutrinos created in volume of sufficiently large linear size

\[ X_{\text{source}} \gg \frac{E}{|\Delta m_{jk}^2|} \]

Oscillating terms average to zero
\[ \langle P(\nu_\alpha \rightarrow \nu_\beta) \rangle = \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2 \]

\[
\begin{pmatrix}
1 - 2v & v & v \\
v & (1 - v)/2 & (1 - v)/2 \\
v & (1 - v)/2 & (1 - v)/2
\end{pmatrix}
\approx
\begin{pmatrix}
0.6 & 0.2 & 0.2 \\
0.2 & 0.4 & 0.4 \\
0.2 & 0.4 & 0.4
\end{pmatrix}
\]

\[ \theta_{13} \approx 0 \]

\[ \theta_{23} \approx 45^\circ \]

\[ v = \cos^2 \theta_{12} \sin^2 \theta_{12} \approx 0.2 \]

\[
\begin{pmatrix}
0.6 & 0.2 & 0.2 \\
0.2 & 0.4 & 0.4 \\
0.2 & 0.4 & 0.4
\end{pmatrix}
\begin{pmatrix}
1 \\
2 \\
0
\end{pmatrix}
= \begin{pmatrix}
1 \\
1
\end{pmatrix}
\]

\[ \pi^+ \rightarrow \mu^+ \nu_{\mu} \]

\[ \downarrow \]

\[ e^+ \nu_e \bar{\nu}_{\mu} \]
"Standard mechanism"

\[
\begin{pmatrix}
1 \\
2 \\
0
\end{pmatrix} \Rightarrow \begin{pmatrix}
1 \\
1 \\
1
\end{pmatrix}
\]

much more "astrophysically plausible"

"Muon absorption"

\[
\begin{pmatrix}
0 \\
1 \\
0
\end{pmatrix} \Rightarrow \begin{pmatrix}
v \\
(1 - v)/2 \\
(1 - v)/2
\end{pmatrix} \approx \begin{pmatrix}
0.2 \\
0.4 \\
0.4
\end{pmatrix}
\]

Very high magnetic field

"Neutron decay"

\[
\begin{pmatrix}
1 \\
0 \\
0
\end{pmatrix} \Rightarrow \begin{pmatrix}
1 - 2v \\
v \\
v
\end{pmatrix} \approx \begin{pmatrix}
0.6 \\
0.2 \\
0.2
\end{pmatrix}
\]

Nuclear fragmentation
Include best fit of oscillation parameters (delta dependence)

Significant presence of tau-neutrinos
A 5.9 PeV event in IceCube

Resonance: $E_\nu = 6.3$ PeV
Typical visible energy is 93%

Event identified in a partially-contained PeV search (PEPE)
 Deposited energy: $5.9 \pm 0.18$ PeV (stat only)
ICRC 2017 arXiv:1710.01191

Potential hadronic nature of this event under study
Resolved sources

Contribution of all unresolved sources
Claudio Kopper (University of Alberta) and Erik Blaufuss (University of Maryland) report on behalf of the IceCube Collaboration (http://iccube.wisc.edu/).

On 22 Sep, 2017 IceCube detected a track-like, very-high-energy event with a high probability of being of astrophysical origin. The event was identified by the Extremely High Energy (EHE) track event selection. The IceCube detector was in a normal operating state. EHE events typically have a neutrino interaction vertex that is outside the detector, produce a muon that traverses the detector volume, and have a high light level (a proxy for energy).

After the initial automated alert (https://gcn.gsfc.nasa.gov/notices_amon/50579430_130033.amon), more sophisticated reconstruction algorithms have been applied offline, with the direction refined to:

Date: 22 Sep, 2017
Time: 20:54:30.43 UTC
RA: 77.43 deg (-0.80 deg/+1.30 deg 90% PSF containment) J2000
Dec: 5.72 deg (-0.40 deg/+0.70 deg 90% PSF containment) J2000

We encourage follow-up by ground and space-based instruments to help identify a possible astrophysical source for the candidate neutrino.

The IceCube Neutrino Observatory is a cubic-kilometer neutrino detector operating at the geographic South Pole, Antarctica. The IceCube realtime alert point of contact can be reached at roc@icecube.wisc.edu
Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Tompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430

.... Great source of excitement ......

Texas Survey of Radio Sources [365 Mhz, (1974-1983)]
66841 sources [TXS .....]
Very Long Baseline Array (VLBA)  
[ensemble of 10 radio telescopes]

8000 km baseline
\[ z = 0.3365 \pm 0.0010 \]
\[ \dot{\Omega} = 332 \pm 82 \ \mu\text{as/year} \]
\[ d = 706 \ \text{Mpc} \]
\[ \beta_{\text{app}} = \frac{\dot{\Omega} d}{c} = 3.7 \pm 0.9 \]
<table>
<thead>
<tr>
<th></th>
<th>Source</th>
<th>Flux [10^{-9} \text{ cm}^{-2} \text{ s}^{-1}]</th>
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<tr>
<td>1</td>
<td>3C 454.3</td>
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<td>2</td>
<td>PKS 1510-08</td>
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<tr>
<td>3</td>
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<td>4C 21.35</td>
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<td>PKS 0426-380</td>
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<td>8</td>
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</table>

Flux [10^{-9} \text{ cm}^{-2} \text{ s}^{-1}]
\[ \alpha = 2.059 \pm 0.042 \]

\[ \Phi_\gamma[1 \div 100 \text{ GeV}] = 4.94 \times 10^{-9} \text{ cm}^{-2} \text{ s}^{-1} \]

\[ L(E) = \phi_\gamma(E) \times E^2 \approx 4.5 \times 10^{45} \frac{\text{erg}}{\text{s}} \]
Three More Topics:

[1.] “Cosmogenic Neutrinos”

[2.] Neutrinos from Dark Matter Self-annihilation

[3.] New Concepts for Neutrino detection
Neutrino Astronomies
Energy Loss Mechanisms for Protons:

Greisen-Zatsepin-Kuzmin (GZK) suppression

NEUTRINO PRODUCTION
Proton Energy Evolution with Redshift

![Proton Energy Evolution with Redshift](image-url)
DG $\nu_T$ interacting in the mountains

Regular proton shower

Deep DG $\nu$ shower

Auger SD

Upgoing ES $\nu_T$ shower

Muonic component of the shower

E-M component of the shower
High Energy Proton Horizon

Invisible in High energy Photons
Invisible in Cosmic Rays

“VISIBLE” with NEUTRINOS
Dark Matter detection with neutrino telescopes.

Accretion of DM Particles in the Sun (and Earth)
Number of neutrinos in the sun

\[ \frac{dN}{dt} = C_c - C_a N^2 - C_e N \]

<table>
<thead>
<tr>
<th>Capture Rate</th>
<th>Annihilation Rate</th>
<th>Evaporation Rate</th>
</tr>
</thead>
</table>

\[ \Gamma_a(t) = \eta \int_{\text{Sun}} d^3x \langle \sigma_{\text{ann}} v \rangle n^2(t, x) = \frac{C_a}{2} N^2 \]
\[
\frac{dN}{dt} = C_c - C_a N^2
\]

\[
N(t) = \sqrt{\frac{C_c}{C_a}} \tanh \left\{ \frac{t}{\tau_c} \right\}
\]

\[
\tau_c \equiv (C_c C_a)^{-1/2}
\]

\[
t \gg \tau_c \quad \Rightarrow \quad \sqrt{\frac{C_c}{C_a}}
\]

\[
t = t_\odot = 4.6 \text{ Gyr}
\]

\[
\tau_{c, \odot} \approx 10^8 \text{ yr}
\]

\[
\Gamma_a(t) = \frac{C_c}{2} \tanh^2 \left\{ \frac{t}{\tau_c} \right\} \quad t \gg \tau_c \quad \frac{C_c}{2}
\]

**Annihilation Rate**
SuperKamiokande detector

- 50,000 tons of ultrapure water
- 2 m of water = veto counter
- Fiducial volume = 22,500 tons
- 11,146 (20 inch) PMT's
- 1,885 veto PMT's

42 m

39 m

1 Km underground
Muon (up-going) from the direction of the SUN.
No excess from the sun direction (cos theta = 1)
Red line = estimated Background from atmospheric neutrinos
Neutrino Astronomy: beyond the “Km3 concept”

Radio, Acoustic,.....
Radio Detection of neutrinos

ANITA-II over Antarctica

http://arxiv.org/abs/1003.2961
RICAP 25-05-2011
Tom Gaisser

FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

Vpol: 1 neutrino candidate; HPol: 25 1019 eV
RICE experiment architecture

- Antarctic ice is neutrino target
- In-ice array of radio antennas
- 20 channels, 200-500 MHz
- Depths 100-300 meters
- Signal digitized at the surface
- Deployed near South Pole Station
10^7 to 10^{11} \text{ GeV}: \text{Radio ice Cherenkov detection}

\textbf{Askaryan Radio Array (ARA)}
- a very large radio neutrino detector at the South Pole


Scientific Goal:
• Discover and determine the flux of highest energy cosmic neutrinos.
• Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:
Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole

Areal coverage: \(~150\text{km}^2\)
10^7 to 10^{11} \text{ GeV}: \text{Radio ice Cherenkov detection}

ARIANNA

- Poster 18-3: J. Tatar. S. Barwick

31 x 31 array
[30 km x 30 km]

ARIANNA

US, S. Korea, England, New Zealand
Barwick, astro-ph/0610631