Physics at DUSEL

Steve Elliott
Outline

• Double beta decay
• Solar neutrinos
• If Time
  – Gravity waves
  – Underground accelerators
In many even-even nuclei, β decay is energetically forbidden. This leaves ββ as the allowed decay mode.

Example ββ Decay Scheme

ββ(2ν): Allowed weak decay

\[ 2n \rightarrow 2p + 2e^- + 2\bar{\nu}_e \]
\(\beta\beta(0\nu)\): requires massive Majorana \(\nu\)

Decay rate is proportional to square of mass

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

\[
(RH \bar{\nu}_e) \quad (LH \nu_e)
\]

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

**\(\beta\beta\) History**

- \(\beta\beta(2\nu)\) rate first calculated by Maria Goeppert-Mayer in 1935.
- First observed directly in 1987.
- Why so long? **Background**
  - \(\tau_{1/2}(U, \text{Th}) \sim T_{\text{universe}}\)
  - \(\tau_{1/2}(\beta\beta(2\nu)) \sim 10^{10} T_{\text{universe}}\)
- But next we want to look for a process with:
  - \(\tau_{1/2}(\beta\beta(0\nu)) \sim 10^{17} T_{\text{universe}}\)
There are a lot of them!

- Detector technology exists
- High isotopic abundance or an enriched source exists.
- High energy = fast rate
- High energy = above background
**Homestake DUSEL Initial Suite of Experiments**

**DUSEL Experiment Development and Coordination**

**Frequently studied isotope.**

**Previous Results**

<table>
<thead>
<tr>
<th>Element</th>
<th>Mass Limit (meV)</th>
<th>Decay Time (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{48}$Ca</td>
<td>$&lt;$(7.2-44.7) eV</td>
<td>$&gt;1.4x10^{22}$ y</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$&lt;0.35$ eV</td>
<td>$&gt;1.9x10^{25}$ y</td>
</tr>
<tr>
<td>$^{76}$Ge</td>
<td>$&lt;$(0.33-1.35) eV</td>
<td>$&gt;1.6x10^{25}$ y</td>
</tr>
<tr>
<td>$^{78}$Ge</td>
<td>$=0.44$ eV</td>
<td>$=1.2x10^{25}$ y</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$&lt;$(1.2-3.2) eV</td>
<td>$&gt;2.1x10^{23}$ y</td>
</tr>
<tr>
<td>$^{100}$Mo</td>
<td>$&lt;$(0.6-2.7) eV</td>
<td>$&gt;5.8x10^{23}$ y</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$&lt;1.7$ eV</td>
<td>$&gt;1.7x10^{23}$ y</td>
</tr>
<tr>
<td>$^{128}$Te</td>
<td>$&lt;$(1.1-1.5) eV</td>
<td>$&gt;7.7x10^{24}$ y</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$&lt;$(0.41-0.98) eV</td>
<td>$&gt;3.0x10^{24}$ y</td>
</tr>
<tr>
<td>$^{136}$Xe</td>
<td>$&lt;$(1.8-5.2) eV</td>
<td>$&gt;4.5x10^{23}$ y</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$&lt;3.0$ eV</td>
<td>$&gt;1.2x10^{21}$ y</td>
</tr>
</tbody>
</table>
An exciting time for $\beta\beta$!

For at least one neutrino:

$$m_i > \sqrt{\delta m_{\text{atmos}}^2} \approx 50\text{meV}$$

Capability of the technologies:

$$\langle m_{\beta\beta} \rangle \leq 50\text{meV}$$

$< m_{\beta\beta} >$ in the range near 50 meV is very interesting.

Solar Neutrinos

Thanks to Bruce Vogelaar for assistance with content
**Solar Neutrino Production**

- **CNO chain:**
  - $^{13}\text{N}$, $^{15}\text{O}$, and $^{17}\text{F}$ neutrinos

- **pp chain:**
  - $\text{pp}$, $\text{p} + \text{e}^-$ (pep), $^7\text{Be}$, and $^8\text{B}$ neutrinos

**Extraordinary Neutrino Beam Free of Charge**

- **WELL DEFINED HIGHEST FLUX** (~$10^{11}\text{cm}^{-2}\text{s}^{-1}$)
  - **PURE FLAVOR SOURCE** - $\nu_e$ only
  - **LONGEST BASELINE** (10$^8$ km)
  - **HIGH DENSITY UP TO 160 g/cm$^3$; ~ 10$^{11}$ g/cm$^2$ path**
  - **LOWEST ENERGIES** (keV to MeV)
  - **PRESENCE OF HIGH MAGNETIC FIELDS**
  - **FULL SPECTRUM:** ENERGY DEPENDENT EFFECTS

Best tools for investigating neutrino flavor phenomena in Vacuum and in Matter

**For ASTROPHYSICS**

Best tool for unprecedented look at how a real Star works - in the past, present and future
Neutrino Oscillation Explanation

MSW explanation: resonant conversion at \(^{8}\text{B}\) energies

Solar data: \(\Delta m_{12}^2, \theta\) add anti-neutrinos (KamLAND and CPT)

MSW-LMA is based on the combined results from many complementary experiments

DUSEL Experiment Development and Coordination
Homestake DUSEL Initial Suite of Experiments

Neutrino Mixing Studies

Is \(\theta_{13}\) different from zero?
normalization at low energies \(\propto \cos^4(\theta_{13})\)

Time dependencies in the Sun’s opacity or energy production?
\(\nu_e\)’s take \(\sim 8\) min to reach Earth
\(\nu_x\)’s reflect energy produced \(\sim 40,000\) yrs ago

Is there a subdominant energy source in the sun?
if \(\theta_{13}\) measured with reactors, a low pp neutrino flux may indicate other energy sources

Is the MSW mechanism correct?
- is it really vacuum oscillation at low energies?
- slight discrepancy with Cl data and \(^{8}\text{B}\) spectral upturn & diurnal effect

Do nuclear reactions fully account for the Sun’s energy output today?

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Are there non-standard $\nu$ interactions?

still need $pp$ flux to confirm, since luminosity constraint is built into these predictions

Are there sterile neutrinos?
Is CPT violated in the neutrino sector?
do $\nu_e$ and anti-$\nu_e$ (from KamLAND) observations agree?
How much CNO? important for opacity

To answer these questions with confidence we need both charged current and electron scattering measurements of solar neutrinos at both $pp$ and $^7Be/pep$ energies!

- any forced re-interpretation of solar result would have a major impact on all neutrino programs

- experiments already underway and some in advanced R&D can accomplish these goals
Some of the Experiments Proposed for DUSEL

- Double Beta Decay: Both sensitive to key 50-meV range
  - EXO
    - 1-10 tonnes of liquid Xe
  - MAJORANA-GERDA joint proposal for 1-tonne of Ge detectors
- Solar Neutrinos
  - LENS
    - In based metal-loaded liquid scintillator
  - CLEAN
    - Liquid Ne: 50-100 tonnes

These Experiments Need Depth

![Graph showing the rate per nucleus per year for cosmic-ray neutrons, dark matter, neutrino mass, and solar neutrinos as a function of depth, measured in meters of water equivalent.](chart.png)
Nuclear Astrophysics

Thanks to Michael Wiescher for assistance with content

The Human Factor

Each heavy atom in our body was built and processed through \( \sim 100-1000 \) star generations since the beginning of time!

We are made of star stuff

Carl Sagan
An Important Example

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$ determines the amount of Carbon which we are made of and Oxygen which we breathe.

Handicaps: low cross section, high background solution underground!

$10^{-6}$ reduction of Cosmic Rays by moving underground.
Low energy cross section extrapolations still carry substantial uncertainties; besides improved experimental techniques (background reduction, detection efficiency) better theoretical tools (R-matrix theory) are required.

Uncertainties still exist for most of the reactions in stellar H, He, C, ... burning. New modeling results, open new questions about reaction flow pattern.

Underground accelerator approach is promising, but needs to be coupled with event identification techniques (difficult for low energy reactions)

Superior energy stability and resolution are required for an underground accelerator.

Thanks to Vuk Mandic for assistance with content
**Gravitational Waves**

- Newtonian gravity: instantaneous action at a distance.
- General Relativity: the “signal” travels at the speed of light.
- Einstein’s field equations reduce to the wave equation.

- **Two polarizations:**

**Why Do GW R&D Underground?**

- The scientific motivation for exploring 1-Hz region of gravitational waves is very strong.
  - Many sources: inspiral, periodic, stochastic.
- Seismic noise and gravity gradient noise are among the major obstacles for reaching 1-Hz scale.
  - Both of these should be significantly suppressed underground.
Final Thoughts

The Physics program is very rich and requires a deep underground laboratory.