Fundamental Symmetry and Neutrino Physics

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Physics 403

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Do we understand the Universe we live in?

Standard Cosmological Model

Standard Model of Particle Physic
Standard Models are incomplete...

• What’s the origin of matter – antimatter asymmetry in today’s Universe?

• What is dark matter or dark energy?

• What is the nature of gravity?

• Can all forces in nature be unified?
In Search of “New” Standard Model

- LHC: direct search for new particles
  - Discovery of Higgs!
  - Hints of New Physics?

- Precision measurements:
  - EDMs of $e$, $n$, atoms, etc.
  - Weak mixing angle
  - $0
\nu\beta\beta$
  - Muon $g-2$
  - Lepton flavor violation
  - $\pi$, $K$ and $B$ decays
  - Unitarity tests
Fermilab Muon g-2 result – new physics?

Theory: $g$-fac.: $2.00233183620(86)$ anomalous mag. moment: $0.00116591810(43)$

Experiment: $g$-fac.: $2.00233184122(82)$, anomalous mag. moment: $0.00116592061(41)$
Neutrino Oscillation and Neutrino Mass

Super-K: atmospheric $\nu_\mu$ neutrino oscillation
SNO: solar $\nu_e$ flavor transformation
K2K: accelerator $\nu_\mu$ oscillation
Kamland: reactor $\overline{\nu}_e$ disappearance and oscillation

Neutrinos have Mass

The first evidence of physics beyond the Standard Model!
Our Sun is a copious source of electron type neutrinos …

In a famous experiment 1968 (Nobel prize (2002), Ray Davis)
Observe solar electron-type neutrinos $\nu_e$

Detection in a huge underground vat of cleaning fluid (615 tons) via the reaction

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

radioactive argon atoms collected periodically and counted:

Produced at only 15 atoms per month!

Experiment located 1500m underground Homestake Gold Mine in SD
3 million times less cosmic ray interactions (bkgrds) due to muons (which are very penetrating particles), compared to the surface.

Far too few (~1/3) solar neutrinos were seen compared to predicted solar production!
The plot thickens – some good fortune …

1983 experiments (for protons decay) also good neutrino detectors … cross check Homestake.

In the Kamioka Mine in Japan

- Depth of 1000m
- Water tank (3000 tons for the first one)
- Instrumented to observe light flashes from produced from μ’s or e’s.

(led by M. Koshiba, also a 2002 Nobelist)

Particles are produced along the ν direction:
For the first time directional information.

A massive detector, known as “SuperK”, clearly observed ν’s from the Sun, and confirmed the signal of missing solar ν’s.

In addition, SuperK was able to observe ν’s produced in the upper atmosphere by cosmic rays – “atmospheric ν’s”, and to tell where they were coming from, leading to a: Breakthrough Observation in 1998

(An aside: An unexpected dividend at Kamioka

The luckiest break since 1604! : Super Nova SN1987A
10^{58} neutrinos produced from 168,000 light years away. 11 observed in 13 second interval by KamiokaNDE II)

Physicist watersports: afloat in a raft inspecting PMTs
Atmospheric neutrinos originate in cosmic ray “showers”

The showers produce electron, muon (and tau) type neutrinos, in a mix that can be predicted.

Neutrinos can reach SuperK from above or from below (the Earth is hardly a barrier at all to a neutrino, after all.)

Stunning Result
Oberved neutrino rates & mixture differed for the two directions!

Were flavors changing in transit?
2002 Sudbury Neutrino Observatory

SNO

Electron Scattering

Charge Current

Neutral Current
Unknown Properties of Neutrinos

Major Questions in Neutrino Physics

- Majorana particle, (i.e. its own antiparticle)
- Absolute mass scale of neutrinos.
- Mass hierarchy
- CP violation phase
- Anomalies (Sterile neutrinos?)

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    yticklabels={atmospheric $\sim 3 \times 10^{-3} \text{eV}^2$},
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\addplot [green] coordinates {(-1,0) (1,0)};
\addplot [blue] coordinates {(-1,0) (1,0)};
\end{axis}
\end{tikzpicture}
```
Double Beta Decay

Observation of $0\nu\beta\beta$:
- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Two neutrino double beta decay

Neutrinoless double beta decay
The EXO-200 Detector

- High purity heat transfer fluid HFE7000
- > 50 cm
- 25 mm ea
- Double-walled cryostat
- LXe vessel 1.37 mm
- Lead shielding > 25 cm
- Veto panels

Diagram showing the internal components of the EXO-200 Detector, including high purity and heat transfer fluid, double-walled cryostat, LXe vessel, lead shielding, and veto panels.
The EXO-200 time projection chamber uses both scintillation and ionization signals to fully reconstruct energy depositions inside liquid xenon.

Event topology is a powerful tool not only for gamma background rejection, but also for signal discovery.
EXO-200 installation site: WIPP

- EXO-200 installed at WIPP (Waste Isolation Pilot Plant), in Carlsbad, NM
- 1600 mwe flat overburden (2150 feet, 650 m)
- U.S. DOE salt mine for low-level radioactive waste storage
- Cleanroom installed on adjustable stands to compensate salt movements.
- Salt “rock” low activity relative to hard-rock mine

\[ \Phi_\mu \sim 1.5 \times 10^5 \text{ yr}^{-1} \text{ m}^{-2} \text{ sr}^{-1} \]

\[ U \sim 0.048 \text{ ppm} \]

\[ Th \sim 0.25 \text{ ppm} \]

\[ K \sim 480 \text{ ppm} \]

EXO-200 0νββ Results

• EXO-200 uses liquid xenon time projection chamber (TPC) to search for 0νββ of 136Xe
• Successful operation from 2011 – 2018 with total 136Xe isotope exposure of 234.1 kg·yr.
• Experimental sensitivities continue to exceed statistics due to improvements in hardware and analysis.
• Setting one of the strongest limits on this rare decay.

Combined Phase I + II:
Limit $T_{1/2}^{0\nu\beta\beta} > 3.5 \times 10^{25}$ yr (90% C.L.)
$\langle m_{\beta\beta} \rangle < (93 - 286)$ meV
Sensitivity $5.0 \times 10^{25}$ yr

2012: Phys. Rev. Lett. 109, 032505
2014: Nature 510, 229-234
2018: Phys. Rev. Lett. 120, 072701
From EXO-200 to nEXO

EXO-200 as a technology demonstrator

nEXO: a 5000 kg enriched LXe TPC

2.5MeV $\gamma$ attenuation length
8.5 cm = 

150 kg

5000 kg
Pre-Conceptual Design of nEXO

- 5 tones of single phase LXe TPC.
- Ionization charge collected by anode.
- 178nm lights detected by \( \sim 4 \text{ m}^2 \) SiPM array behind field shaping rings.
- Combining light and charge to enhance the energy resolution.

*nEXO pre-CDR, arXiv:1805.11142*
Tagging $\beta\beta$ decay daughter Ba

$^{136}_{54}Xe \rightarrow ^{136}_{56}Ba^{++} + 2e^- + 2\bar{\nu}_e$

$\leq 58$-atom

$\leq 15$-atom

$\leq 4$-atom

$0$-atom

nEXO Sensitivity (with Ba tagging)

What can Neutrino tell us about the Universe?

• What role did neutrino play in the evolution of the universe? (~ 4% mass of the universe, absolute mass scale? Number of species? … double beta decay experiment, tritium decay experiment, sterile neutrino search…)

• Can neutrino be responsible for the matter and anti-matter asymmetry? (CP violation phase? … long baseline neutrino experiment)

• Neutrino might be the best probe deep into the universe (IceCube…)

• Supernovae neutrinos, relic neutrinos…