Direct Neutrino Mass Measurements

Coherent Neutrino Scattering

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A bit of context behind the two topics...

We would like to invite you to give one of these Challenge talks. The argument(s) would be "New technologies for measuring neutrino masses" together with "Neutrino coherent scattering".

-- Mauro Mezzetto

Yes, I am happy to partake in the Challenge talks! One question of clarification: are you asking me to give a talk on both of these topics [...]?

-- Me

Yes — Mauro

Ok <gulp>

— Me
Luckily, there are some similarities...
... for one, these challenges are long standing
Both measurements access key neutrino properties...

**ν Mass Scale**

\[ m_\beta^2 \equiv \sum_{i=1}^{3} |U_{ei}|^2 m_i^2 \]

Incoherent sum of neutrino mass eigenstates.

Relates directly to the energy-momentum dispersion of neutrinos.

**ν Weak Probe**

Probes the weak coupling of neutrinos to nuclei.

Coherent interaction with entire nucleus.
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and in principle, the measurements are simple.

Measure the kinetic energy spectrum of the decay electron (for beta decay), or de-excitation energy (for electron capture).

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e \]
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Coherent Elastic Neutrino Nucleus Scattering

Measure the kinetic energy of the outgoing recoil.

Cross-section proportional to (roughly) the square of the number of neutrons.

Large cross-section increase.
and also connect to other branches of physics.

Neutrino mass connects back to cosmological observations.

\[ \sum m_i \equiv \sum_{i=1}^{3} m_i \]

Limits on the neutrino mass scale from cosmology are affected by model extensions (such as additional parameters) or new physics (neutrino self-interaction or dark matter interactions).
and also connect to other branches of physics.

The coherent process likewise provides allows insight into new physics at small momentum exchange.

Also gives insight into supernova physics, nuclear structure, solar physics and much more.
A World-wide effort is already underway for direct measurements.
Electron transfers all of its energy to the absorbing medium.

Calorimetric
(Cryogenic Bolometers)

Electromagnetic filtering of electrons of selected energy.

Electromagnetic Collimation
(MAC-E Filter)

Use photon spontaneous emission from electron in magnetic field.

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(Cyclotron Radiation Emission Spectroscopy)
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ECHo & HOLMES

KATRIN
A World-wide effort is also underway for coherent neutrino scattering, too.
Ionization Detectors
(Germanium & Si-CCD)
Large mass, keV scale

CONUS, CONNIE, TEXONO

MINER, Ricochet, NuCLEUS

Cryogenic Bolometers
Smaller detectors, sub-keV scale
particle discrimination via ionization, photon tagging
We have made great strides in last few years...

2 million events, 780 hours of data.

Excellent goodness-of-fit: p-value=0.56.

\[ m^2(\nu_e) = (-1.0^{+0.9}_{-1.1}) \text{ eV}^2 \ (90\% \text{ C.L.}) \]

\[ m_\beta \leq 1.1 \text{ eV} \ (90\% \text{ C.L.}) \]
We have made great strides in last few years...

Process finally measured at the spallation neutron source by the COHERENT collaboration. Now measured for Cs and Ar targets.
but both programs have ambitious goals.

**ν Mass**

Resolve whether the neutrino mass scale is quasi-degenerate in the next few years.

And eventually push down to the inverted ordering scale.

**ν Coherent Scattering**

A first detection from reactor neutrinos in the next few years.

Build $O(10 \text{ kg})$ detectors over the next decade.

Does the technology being pursued get us there?
So, both these measurements have a common wish list...

Sufficient statistics

Background Reduction

Superior Energy Resolution
Common challenges:

Sufficient Statistics

Electron Energy

Endpoint of the Tritium $\beta$-decay Spectrum

Only a tiny fraction of the spectrum yields information about the neutrino mass.

Large activities are required in order to probe the spectrum at the few eV level.

Insufficient Phase Space
Common challenges:

In the case of coherent scattering, coherence helps a lot.

That said, the cross-sections are still small.

Two work-arounds: operate at higher energies (COHERENT), or with large fluxes (nuclear reactors).
Common challenges:

**Direct Measurements**

- KATRIN data with 1 $\sigma$ error bars $\times$ 50
- Fit result

**CENNS Detectors**

- Background "wall"
- Rydberg atoms
- Radon decays

Reduction of backgrounds is crucial for experiments of both sorts, though the causes for these backgrounds depends on the specific technology deployed.
Common challenges:

**Direct Measurements**
- Magnetic field optimization
- Radon removal

**CENNS Detectors**
- Magnetic shielding from surfaces
- Active Veto Passive shielding
- Electron/recoil event discrimination

Different mitigation strategies are used which also depend on the technology that is deployed.
For direct measurements, energy resolution is needed to extract the spectral shape near the endpoint.

Order few eV resolution now achieved by major efforts.

Common challenges:

Direct Measurements

- KATRIN
- ECHo
- Project 8

Superior energy resolution

- 32-keV γ energy: (32153.6 ± 2.4) eV
- Vénos, et al: (32151.7 ± 0.5) eV

For CENNS measurements, energy resolution is needed to move the energy threshold for recoils as low as possible.
Sufficient statistics

Background Reduction

Superior Energy Resolution

In certain cases, experiments in both categories implement very similar technology to achieve their goals.

e.g.: Magnetic $\mu$-calorimeters, Transition Edge Sensors, and NTDs
Sufficient statistics

Background Reduction

Superior Energy Resolution

In certain cases, experiments in both categories implement very similar technology to achieve their goals.

e.g. Multiplexing of signals to increase target mass
Sufficient statistics

Background Reduction

Superior Energy Resolution

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Traveling Wave Parametric Amplifier
(over 2000 Josephson junctions)

Detecting microwave signals at femtowatt scale

e.g. Operating at the quantum noise limit for microwave detection
Much of these advances are due to great advances in superconducting technology.

High quality production of JJ junctions, superconducting leads.

Driven by strong recent development for superconducting circuits for quantum computing.

However, unique challenges still remain for using these new technologies for neutrino physics:
Do these technology scale?

Can they operate in harsh environments?

What backgrounds lurk in this new space?
“We choose to go to the Moon. We choose to go to the Moon in this decade and do the other things, not because they are easy, but because they are hard.”
Thank you for your attention.
Bibliography


Backup Slides
(In case people ask questions)
Micro calorimeters which are sensitive to changes in temperature (energy deposition).
Contain the full decay energy.
Magnetic Adiabatic Collimation with Electrostatic Filtering

(only electrons with enough energy can overcome potential barrier)
High Magnetic Field (Bs)

- $10^{11} \text{ e}^\text{-} / \text{second}$

Low Field

- $B_A$

High Magnetic Field (Bs)

- $1 \text{ e}^\text{-} / \text{second}$

The following diagram illustrates the electron trajectories under different magnetic field conditions. The magnetic field lines are shown entering and exiting the analysis plane, with the electrode system and detector positioned accordingly.
Cyclotron Radiation Emission Spectroscopy (CRES)

Frequency Approach

\[ ^3\text{H} \rightarrow ^3\text{He}^+ + e^- + \bar{\nu}_e \]

- Source transparent to microwave radiation
- No e- transport from source to detector
- Leverages precision inherent in frequency techniques

B. Monreal and JAF, Phys. Rev D80:051301
KATRIN Outlook

KATRIN continues to collect data (Runs 2 & 3 already obtained). A 1000 day data set is expected to reach design goal.

Comprehensive campaign to reduce and mitigate backgrounds, including radon and Rydberg events.

Better measurement/control of plasma instabilities in source.

Target Sensitivity:
200 meV (90% C.L.)

Increased statistics
Background mitigation
Assessment of plasma effects
Beyond the Degeneracy Scale

Any experiment with a molecular tritium ($T_2$) source will have a systematic penalty associated with uncertainty in the width of rotational and vibrational states of the daughter $^3$He$^+$ populated in the decay.

In order to push to the next target mass scale (10), one will need to switch to an atomic tritium source.

Comparison of $T_2$ and $T$ ground states

Comparison of $T_2$ and $T$ decay schemes


The endpoint for T$_2$ is higher than for atomic tritium. Thus, any atomic tritium experiment must be extremely pure (T$_2$ / T < 10^{-5}).

At low densities, recombination occurs mainly on surfaces. Thus a magnetic trap is necessary to prevent recombination. Can utilize magnetic moment of atomic tritium.

$$\Delta E = -\mu \cdot \vec{B}$$

Ioffe traps and Halbach arrays can have large fields near surfaces, with a large uniform region in the center suitable for CRES.

**Solution:** A large volume magnetic trap for T atoms.
Ultimate atomic tritium experiment combines R&D from Phase III into large RF array tritium trap.

- Conversion from molecular to atomic.
- Demonstrate transport, cooling and trapping of tritium.
- Detection via CRES antenna array

Current Project 8 R&D effort (Phase III) focused on developing these technologies.

Target Mass Sensitivity

\[ m_\beta < 40 \text{ meV} \]