Probing New Physics in Neutrino Experiments
Discoveries and Opportunities in Neutrino Astroparticle Physics

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University of Wisconsin
Why neutrinos?
330 neutrinos per cm$^3$.

0.5 proton and one billion photons per cm$^3$

One billion more neutrinos than protons.

Big-Bang neutrinos are approximately as numerous as the Big-Bang photons.

“neutrinos are the most abundant particles in the Universe besides photons”
“neutrinos are the most abundant particles in the Universe besides photons”
Why is the neutrino mass so small?

PDG 2000 + SNO + SK

$\nu_3 < \nu_1 < \nu_2 < (\nu_3)$

mass ranges of the matter particles

neutrinos

quarks

charged leptons

increasing mass:

$\times 1/100,000$ mass of electron

mass of electron

$\times 100,000$ mass of electron
Matter in the Universe

- Heavy Elements: 0.03%
- Ghostly Neutrinos: ~0.3%
- Dark Energy: 70%
- Dark Matter: 25%
- Stars: 0.5%
- Free Hydrogen and Helium: 4%


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<table>
<thead>
<tr>
<th>species</th>
<th>$n_i$ (m$^{-3}$)</th>
<th>$\Omega_i = \rho_i/\rho_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$ (CBR)</td>
<td>$n_\gamma = (4.104 \pm 0.009) \times 10^8$</td>
<td>$\Omega_\gamma = (5.06 \pm 0.4) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\nu_e, \nu_\mu, \nu_\tau$</td>
<td>$n_\nu = (3/11)n_\gamma$ (per species)</td>
<td>$0.0006 &lt; \Omega_\nu &lt; 0.015$</td>
</tr>
<tr>
<td>baryons</td>
<td>$n_b \sim 0.25 \pm 0.01$</td>
<td>$\Omega_b = (0.044 \pm 0.004)$</td>
</tr>
<tr>
<td>cold dark matter</td>
<td>$n_X = \rho_{CDM}/m_X$ (m$_X$ unknown)</td>
<td>$\Omega_{CDM} = 0.226 \pm 0.04$</td>
</tr>
<tr>
<td>&quot;vacuum&quot;</td>
<td>0</td>
<td>$\Omega_A \sim 0.73 \pm 0.04$</td>
</tr>
<tr>
<td>total</td>
<td></td>
<td>$\Omega_T \sim 1.02 \pm 0.02$</td>
</tr>
</tbody>
</table>
```

“neutrinos are highly abundant but with little mass”
Neutrinos and the Early Universe

at $T \sim 1 \text{ MeV} \ (\sim 1 \text{ sec})$
neutrinos decouple
relic neutrino spectrum
left over

at $T < 100 \text{ keV}$
deuterium formation,
followed by BBN

$\text{n+p} \leftrightarrow \text{d+γ}$

at $T < 1 \text{ eV} \ (380,000 \text{ yrs})$
photons decouple, cannot break up atoms
no more free charges to scatter photons
Universe becomes transparent

$p+e^- \leftrightarrow \text{H+γ}$
Even small $m_{\nu}$ influences structure of Universe

"neutrinos have influenced the large and small-scale structure of the Universe"
Neutrinos and Supernovae

“without neutrinos dying stars would not explode”

no oscillations
oscillations in SN envelope
Earth effects included

Ref: G. Raffelt

Accretion Phase
Kelvin-Helmholtz Cooling Phase
Neutrinos and Supernovae

neutrino oscillation effects on supernova light-element synthesis

“neutrinos helped cook the light elements in the Universe”
Baryon Asymmetry & Sakharov Conditions

Sakharov, 1967

1. baryon number violation
2. violation of C and CP
3. departure from thermal equilibrium

Fukugita, Yanagida, 1986

Leptogenesis

“neutrinos might have been essential for the disappearance of antimatter”
Neutrinos and the Universe

very early universe | big bang nucleosynthesis | CMB | late time structure formation

large-scale structure
Neutrinos and the Universe

very early universe | big bang nucleosynthesis | CMB | late time structure formation

Understanding neutrino mass and neutrino properties is needed for:

• Cosmology
• Nuclear astrophysics
• Interpretation of supernova signals
• Particle physics beyond the Standard Model
Neutrinos from the Big Bang

~330 neutrinos per cm$^3$
0.5 proton per cm$^3$

Supernova Neutrinos

Atmospheric Neutrinos

Geo Neutrinos

High Energy Cosmic Cosmic Neutrinos

Accelerator&Reactor Neutrinos

Solar Neutrinos
Neutrino Energies

Big-Bang neutrinos $\sim 0.0004$ eV

Neutrinos from the Sun $< 20$ MeV depending of their origin.

Atmospheric neutrinos $\sim$ GeV

Antineutrinos from nuclear reactors $< 10.0$ MeV

Neutrinos from accelerators up to GeV ($10^9$ eV)
The Experimental Quest
Postulate of the Neutrino

Chadwick, 1914

\[ N \rightarrow N' + e^- \text{ some nuclei emit electrons!} \]

Fermi, 1934

Pauli, 1930

Fig. 5. Energy distribution curve of the beta-rays.
Early Experimental History of the Neutrino

1956 - “Observation of the Free Antineutrino” by Reines and Cowan

inverse beta decay

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
Neutrinos in the Standard Model

Discovery of $\nu_\mu$ and $\nu_\tau$

Accelerator studies of $\nu$

The Standard Model

- 3$\nu$ flavors
- upper limits on $m_\nu$ from kinematic studies.
- massless $\nu$ (ad hoc assumption in Standard Model)
Birth of Neutrino Astrophysics

1938  Bethe & Critchfield
\[ p + p \rightarrow ^2H + e^+ + \nu_e \]

1947  Pontecorvo, 1949 Alvarez
propose neutrino detection through
\[ ^{37}\text{Cl} + \nu_e \rightarrow ^{37}\text{Ar} + e^- \]

1960's  Ray Davis builds chlorine detector.
John Bahcall, generates first solar model calculations and \( \nu \) flux predictions.

“...to see into the interior of a star and thus verify directly the hypothesis of nuclear energy generation in stars...” (Bahcall, 1964)
Neutrinos interact only weakly with matter…

A neutrino passing through the Earth would have a $10^{-8}$ chance of interaction.

Natural backgrounds make experiments challenging.

Cosmic rays and natural radioactivity can easily overwhelm the meager signal from the most intense neutrino source that exists

.... this is why we go underground
Cl-Ar Solar Neutrino Experiment at Homestake

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

The Nobel Prize in Physics 2002
What is the Solution?

Experimental Errors?
But all experiments show similar effect.

Astrophysics wrong?
Perhaps, but even with all fluxes as free parameters, cannot reproduce the data. \( P_{\text{MSM}} < 1.7\% \) at 95\% CL

New neutrino physics such as oscillations?
In 1968 Pontecorvo suggests that if lepton number is not conserved, \( \nu_e \) could change into \( \nu_\mu \). Since the Cl-Ar detector was sensitive only to \( \nu_e \), it would appear that the flux was low.

KMH, Robertson PRL 77:3270 (1996)
The Sudbury Neutrino Observatory
The Solar Neutrino Problem and Its Resolution

Too few $\nu_e$ observed from the Sun.

Even with all solar neutrino fluxes as free parameters, cannot reproduce the data. $P_{\text{MSM}} < 1.7\%$ at 95% CL

KMH, Robertson PRL 77:3270 (1996)

Model-independent evidence for solar neutrino flavor change in 2002
Neutrino Oscillation

**Neutrino States**

<table>
<thead>
<tr>
<th>Mass States</th>
<th>Weak States</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>First</td>
</tr>
<tr>
<td>$\nu_1$</td>
<td>$\nu_e$</td>
</tr>
<tr>
<td>Second</td>
<td>Second</td>
</tr>
<tr>
<td>$\nu_2$</td>
<td>$\nu_\mu$</td>
</tr>
</tbody>
</table>

$$
|\nu_a\rangle = \cos \theta |\nu_1\rangle - \sin \theta |\nu_2\rangle \\
|\nu_b\rangle = \sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle \\
$$

<table>
<thead>
<tr>
<th>$\nu_1$</th>
<th>$\nu_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$</td>
<td>$E_1$</td>
</tr>
<tr>
<td>$= \sqrt{p^2 + m^2_1} / 2$</td>
<td>$= \sqrt{p^2 + m^2_2} / 2$</td>
</tr>
</tbody>
</table>

**Time Evolution**

$$
P_{i\rightarrow i} = \sin^2 2\theta \sin^2 \left(1.27 \Delta m^2 L / E \right)
$$

 Pontecorvo, 1968

oscillation $\rightarrow$ energy and baseline-dependent effect
Reactor Antineutrinos in Japan

Japanese Reactors

Kashiwazaki
Takahama
Ohi

55 reactors

Reactor Isotopes

$^{235}\text{U} : ^{238}\text{U} : ^{239}\text{Pu} : ^{241}\text{Pu} = 0.570 : 0.078 : 0.0295 : 0.057$

~ 200 MeV per fission
~ 6 $\bar{\nu}_e$ per fission
~ $2 \times 10^{20} \bar{\nu}_e$/GW$_{th}$-sec

reactor $\nu$ flux ~ $6 \times 10^6$/cm$^2$/sec

<table>
<thead>
<tr>
<th>Decay Products</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinetic energy of fragments</td>
<td>165 ± 5</td>
</tr>
<tr>
<td>Energy of prompt photons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Kinetic energy of neutrons</td>
<td>5 ± 0.5</td>
</tr>
<tr>
<td>Energy of $\beta$ decay electrons</td>
<td>7 ± 1</td>
</tr>
<tr>
<td>Energy of $\beta$ decay antineutrinos</td>
<td>10</td>
</tr>
<tr>
<td>Energy of $\gamma$ decay photons</td>
<td>6 ± 1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>200 ± 6</strong></td>
</tr>
</tbody>
</table>
KamLAND Antineutrino Detector

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

$$E_{\bar{\nu}_e} \approx E_p + E_n + 0.8 \text{ MeV},$$

through inverse $\beta$-decay

liquid scintillator target:
- proton rich $> 10^{31}$ protons
- good light yield
KamLAND (Anti-)Neutrino Program

**Reactor Antineutrinos**


**Terrestrial (Geo-)Antineutrinos**


**Nucleon decay studies**


\[ \tau(n \rightarrow inv) > 5.8 \times 10^{29} \text{ years} \]

\[ \tau(nn \rightarrow inv) > 1.4 \times 10^{30} \text{ years} \]

**Muon spallation studies**

*in preparation*

**Supernova watch**

*in progress*

**Limit on Anti-Neutrinos from the Sun**


**Solar \(^8\)B Neutrinos**

*in preparation*
KamLAND 2003: First Direct Evidence for Reactor $\bar{\nu}_e$ Disappearance


Observed $\bar{\nu}_e$: 54 events

No-Oscillation: $86.8 \pm 5.6$ events

Background: $1 \pm 1$ events

Livetime: 162.1 ton-yr
KamLAND 2005: Evidence of Spectral Distortion in Energy Spectrum

Phys. Rev. Lett. 94:081801, 2005

- Observed $\bar{\nu}_e$: 258 events
- No-Oscillation: $365.2 \pm 23.7$ (syst.)
- Background: $17.8 \pm 7.3$ events
- Livetime: 766.3 ton-yr

best fit $\chi^2 = 24/17$

- Fiducial volume syst.: 4.7%
- Total systematics = 6.5%

Spectral Distortions: A unique signature of neutrino oscillation!

Simple, rescaled reactor spectrum is excluded at 99.6% CL ($\chi^2 = 37.3/18$)

Next Step: Reduce systematic error with improved calibrations.
Measuring Neutrino Oscillation Parameters

Solar Neutrinos + KamLAND 2003 ($\bar{\nu}_e$ rate)

Beginning of precision neutrino physics

Agreement between oscillation parameters for $\bar{\nu}$ and $\nu$
KamLAND 2008: Precision Measurement of Neutrino Oscillation Parameters


- increased livetime: 1491 days
- lowered analysis threshold
- modified analysis to enlargen the fiducial volume $R_p, R_d < 6.0m$
- reduced uncertainty in $^{13}\text{C}(\alpha,n)^{16}\text{O}$ backgrounds
- reduced systematics in target protons by calibrating fiducial volume
KamLAND Full-Volume Calibration

inside view of KamLAND detector

4π calibration system
Full-Volume Calibration

Design Concept

Calibration Data

$^{60}\text{Co}$ sources along pole

$^{60}\text{Co}/^{68}\text{Ge}$ source at end
Full-Volume Calibration

Design Concept

Calibration Data

Vertex distribution of $^{60}$Co/$^{68}$Ge composite source in $4\pi$ calibration runs.
KamLAND 2008: Precision Measurement of Oscillation

Prompt event energy spectrum for $\bar{\nu}_e$

- number of events expected (no-oscillation): $2179 \pm 89$ (syst)
- observed: $1609$
- bkgd: $276 \pm 23.5$

- significance of disappearance (with 2.6 MeV threshold): $8.5\sigma$
- no-osc $\chi^2/\text{ndf}=63.9/17$
- significance of distortion: $>5\sigma$
- best-fit $\chi^2/\text{ndf}=21/16$ (18% C.L.)

- systematic uncertainties:
  - fiducial volume reduced from 4.7% → 1.8%

- total systematics: 4.1%

<table>
<thead>
<tr>
<th>$\Delta m^2_{21}$</th>
<th>Detector-related (%)</th>
<th>Reactor-related (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy scale</td>
<td>1.9</td>
<td>$\nu_e$-spectra [7]</td>
</tr>
<tr>
<td>Fiducial volume</td>
<td>1.8</td>
<td>$\bar{\nu}_e$-spectra</td>
</tr>
<tr>
<td>Energy threshold</td>
<td>1.5</td>
<td>Reactor power</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.6</td>
<td>Fuel composition</td>
</tr>
<tr>
<td>Cross section</td>
<td>0.2</td>
<td>Long-lived nuclei</td>
</tr>
</tbody>
</table>
KamLAND 2008: Precision Measurement of Oscillation

L/E Dependence

\[ P_{ee} = 1 - \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2 \frac{L}{E}}{4} \right) \]

\[ P_{ee} = (\cos^2 \theta + \sin^2 \theta \exp \left( -\frac{m_e L}{2\tau \frac{E}{L}} \right))^2 \]

\[ P_{ee} = 1 - \frac{1}{2} \sin^2 2\theta \left( 1 - \exp \left(-\gamma \frac{L}{E} \right) \right) \]

L\_0=180km

Solar neutrino problem solved! L/E figure demonstrates \( \bar{\nu} \) oscillation.

1970-1995 first identified by Ray Davis (missing solar \( v_e \))
2002-2008 SNO observes neutrino flavor change, finds evidence for neutrino mass
2003-2008 KamLAND demonstrates \( \bar{\nu} \) oscillation, precision measurement of \( \Delta m^2 \)
KamLAND 2008: Oscillation Parameters

Rate-Shape-Time Analysis

KamLAND only
\[ \tan^2 \Theta = 0.56 \pm 0.14 \]
\[ \Delta m^2 = 7.58 \pm 0.21 \times 10^{-5} \text{ eV}^2 \]

KamLAND+solar
(combined under assumption of CPT invariance)
\[ \tan^2 \Theta = 0.47 \pm 0.06 \]
\[ \Delta m^2 = 7.59 \pm 0.21 \times 10^{-5} \text{ eV}^2 \]
A Decade of Discovery: 1998 - 2008

**SNO:** solar $\nu_e$ flavor transformation

**KamLAND:** reactor $\bar{\nu}_e$ disappearance and oscillation
Things we know ...
Precision Measurement of Oscillation Parameters

Neutrino Mass Splitting

- KamLAND provides most precise value of $\Delta m_{12}^2$ ($\sim 2.8\%$)
- KamLAND improves the definition of $\tan^2 \theta_{12}$ when combined with solar data (assumption of CPT invariance)
Precision Measurement of Oscillation Parameters

**Neutrino Mixing Angles**

\[ U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} = \begin{pmatrix} 0.8 & 0.5 & U_{e3} \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix} \]

**U_MNSP Matrix**

Maki, Nakagawa, Sakata, Pontecorvo

\[
\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{23} & \sin \theta_{23} \\ 0 & -\sin \theta_{23} & \cos \theta_{23} \end{pmatrix} \begin{pmatrix} \cos \theta_{13} & 0 & e^{-i\Delta m_{21}} \sin \theta_{13} \\ 0 & 1 & 0 \\ -e^{i\Delta m_{21}} \sin \theta_{13} & 0 & \cos \theta_{13} \end{pmatrix} \begin{pmatrix} \cos \theta_{12} & \sin \theta_{12} & 0 \\ -\sin \theta_{12} & \cos \theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2 + i\beta} \end{pmatrix}
\]

- atmospheric, K2K
- reactor and accelerator
- SNO, solar SK, KamLAND
- $0\nu\beta\beta$

\[ \theta_{23} = \sim 45^\circ \quad \theta_{13} = ? \quad \theta_{12} = \sim 32^\circ \]
KamLAND and solar best fit values are not the same!

CPT-violation?

Other new physics?

\[ \sin^2 2\theta_{13} \neq 0? \]
What we don’t know ...
Neutrino Particle Properties

Is there $\mu - \tau$ symmetry in neutrino mixing?

What is the absolute mass scale?

Do $\nu$ and $\bar{\nu}$ behave the same?

Can we search for leptonic $CP$?
Current Knowledge of $\theta_{13}$

Direct search at Chooz and Palo Verde

At $\Delta m_{31}^2 = 2.5 \times 10^{-3}$ eV$^2$,

$\sin^2 2\theta_{13} < 0.15$

allowed region

Global Fit

$\sin^2 2\theta_{13} < 0.11$ (90% CL)

$\sin^2 \theta_{13} = 0.9^{+2.3}_{-0.9} \times 10^{-2}$

$\sin^2 2\theta_{13} = 0.04$

Fogli et al., hep-ph/0506083
Precision Measurement of $\theta_{13}$ with Reactor Antineutrinos

Search for $\theta_{13}$ in new oscillation experiment with multiple detectors

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$

Small-amplitude oscillation due to $\theta_{13}$ integrated over $E$

Large-amplitude oscillation due to $\theta_{12}$

$\sim 1-1.8 \text{ km}$

$> 0.4 \text{ km}$

Karsten Heeger, Univ. of Wisconsin

Columbia University, February 16, 2009
Concept of Reactor $\theta_{13}$ Experiments

Measure ratio of interaction rates in **multiple** detectors

$$\frac{N_f}{N_n} = \left( \frac{N_{p,f}}{N_{p,n}} \right) \left( \frac{L_n}{L_f} \right)^2 \left( \frac{\epsilon_f}{\epsilon_n} \right) \left[ \frac{P_{\text{sur}}(E, L_f)}{P_{\text{sur}}(E, L_n)} \right]$$

- Measured Ratio of Rates
- Detector Mass Ratio, H/C
- Detector Efficiency Ratio
- $\sin^2 2\theta_{13}$

Distance $L \sim 1.5 \text{ km}$
Angra
- R&D
- nuclear proliferation studies

Daya Bay
- international collaborations
- started construction

Daya Bay will reach $\sin^2 2\theta_{13} < 0.01$
Daya Bay, China
http://dayawane.ihep.ac.cn/

Karsten Heeger, Univ. of Wisconsin
Columbia University, February 16, 2009

Daya Bay

near detector

far detector

entrance

570 m

290 m

720 m

~ 1000 $\bar{\nu}$ events/detector/day

RPCs
water pool

antineutrino detectors
Construction of the Daya Bay Antineutrino Detectors

detector tank
photomultipliers
calibration system
acrylic target vessels

Karsten Heeger, Univ. of Wisconsin
Columbia University, February 16, 2009

2008 Outstanding Junior Investigator Award, DOE HEP
Ratio of Measured to Expected $\bar{\nu}_e$ Flux

Expected precision in Daya Bay to reach $\sin^2 2\theta_{13} < 0.01$

past experiments
- ILL
- Savannah River
- Bugey
- Rovno
- Goesgen
- Krasnoyarsk
- Palo Verde
- Chooz
- KamLAND

past reactor experiments = 1 detector

next generation of experiments > 2 detectors
Future of Neutrino Oscillation Experiments

- early measurement of $\theta_{13}$ will help make decision on future long-baseline experiments

- precision measurement of $\theta_{13}$ useful for combined analysis with T2K and NoVA, 2σ hint for CP possible?
Future of Neutrino Oscillation Experiments

Large Detectors and Long Baselines
- search for CP violation with neutrino beam
- $v$ mass hierarchy
- proton decay ($10^{34}$ yrs $\rightarrow 10^{35}$ yrs)
- astrophysics
- atm. $v$, geo $v$

requires international collaborations, R&D in US, Europe, and Japan
decision in ~ 2012-2015?
Neutrino Mass and Particle Nature

\[ \Delta m_{\text{atm}}^2 \quad m_\nu > 0.04 \text{ eV} \]

**What is the absolute mass scale?**

**What is the mass hierarchy?**

**Are neutrinos their own antiparticles?**
Neutrinoless Double Beta Decay: $0\nu\beta\beta$

**2\nu mode:** conventional 2\textsuperscript{nd} order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} \left| M_{2\nu} \right|^2$$

G are phase space factors

**0\nu mode:** hypothetical process only if $M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{0\nu} = G_{0\nu} \left| M_{0\nu} \right|^2 \left( \langle m_{\beta\beta} \rangle \right)^2$$

$G_{0\nu} \sim Q^5$

$0\nu\beta\beta$ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

$0\nu\beta\beta$ may allow us to determine
- absolute neutrino mass scale
- neutrino mass hierarchy
CUORE Double Beta Decay Experiment

CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers with mass of ~ 200 kg of $^{130}\text{Te}$.

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

19 Cuoricino-like towers with 13 planes of 4 crystals each
TeO$_2$ Bolometers

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

Signal size: 1 mV

Voltage signal $\propto$ energy deposited

Time constant: $\tau = C/G = 0.5$ s

Energy resolution: $\sim 5$-10 keV at 2.5 MeV

Heat sink: Cu structure (8-10 mK)

Thermal coupling: Teflon ($G = 4$ pW/mK)

Thermometer: NTD Ge-thermistor ($dR/dT \approx 100$ k$\Omega$/µK)

Absorber: TeO$_2$ crystal
Search for 0νββ in $^{130}$Te

**Experimental Signature of 0νββ**
- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable background due to 2νββ

$Q(^{130}\text{Te}) = 2530.3 \pm 2$ keV

Cuoricino summed spectrum
- energy = key event signature
CUORE Detector Calibration System

need to place sources next to crystals to allow calibration of all bolometers

motion system:
insertion and extraction of sources in and out of cryostat

guide tubes:
no straight vertical access

source strings:
move under own weight in guide tubes

→ individual energy calibration of all 988 bolometers
    critical for summing energy spectra

2008 Outstanding Junior Investigator Award, DOE NP
CUORE Sensitivity

If Klapdor is right...

\[ m \nu \sim 0.45 \text{ eV} \]

Assumption

- Klapdor \( \langle m \rangle \) & matrix element for Te-130
- \( T^{1/2} = 2.5 \times 10^{24} \text{ y} \) (this is the current Cuoricino limit)
- Background: 0.01 c/keV/kg/year, resolution: 5 keV FWHM, 5 years of running
- Conservative scaling of \(^{60}\text{Co}\) and \(^{208}\text{Tl}\) peaks

If no signal,

\[ 1\sigma \text{ limit: } T^{1/2} = 2 \times 10^{26} \text{ y} \]
Probing the Neutrino Mass Scale

\[ \Gamma_{0\nu} = G_{0\nu} |M_{0\nu}|^2 \left< m_{\beta\beta} \right>^2 \]

Double Beta Decay experiments measure the effective neutrino mass scale

“one or two 0νββ experiments on ton-scale” (e.g. Majorana and CUORE), decision in ~2013
CUORE-II?
Future Opportunities with Bolometric Neutrino Mass Studies

advanced bolometers

other isotopes

Already tested bolometrically, as good as TeO$_2$
CaF$_2$, Ge, PbMoO$_4$, CdWO$_4$

isotope enrichment
(up to 3x more sensitive)

experimental infrastructure does not need to change for this

in case of discovery, cross-checks are mandatory:
- check background lines
- test nuclear models and matrix elements
- reduce systematic uncertainty on $\langle m_{\beta\beta} \rangle$
MARE - Calorimetric Search for Neutrino Mass

Beta Decay Studies of $m_\nu$

Absorber = Re single crystal (99.99% purity) typical dim. 300x300x300 μm surfaces cleaned to optical level 63% of 187- Re

$E_0 = (2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{syst}})$ eV

Prospects of MARE-II

$\sim 5 \times 10^4$ elements (5 arrays)
$\Delta E \sim 5$ eV
$\Delta t \sim 1$ μs
$10^{14}$ decays in 3 years
$m_\nu < 0.2$ eV 90% CL

"alternative approach to KATRIN, different systematics"

m($\nu$) < 15 eV
10 crystals:
8751 hours $\times$ mg (AgReO$_4$)
## Ways to Determine the Neutrino Mass Scale

<table>
<thead>
<tr>
<th>Methods</th>
<th>Present Sensitivity</th>
<th>Future Sensitivity (5-15 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology (CMB+LSS)</td>
<td>0.5-1 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>(model-dependent)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0\nu\beta\beta) (nuclear matrix element)</td>
<td>0.5 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>Weak Decay Kinematics</td>
<td>2.2 eV</td>
<td>0.2 eV</td>
</tr>
<tr>
<td>(direct)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Ways to Determine the Neutrino Mass Scale

<table>
<thead>
<tr>
<th>Methods</th>
<th>Present Sensitivity</th>
<th>Future Sensitivity (5-15 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmology (CMB+LSS) (model-dependent)</td>
<td>0.5-1 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>0νββ (nuclear matrix element)</td>
<td>0.5 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>Weak Decay Kinematics (direct)</td>
<td>2.2 eV</td>
<td>0.2 eV</td>
</tr>
</tbody>
</table>
The Open Questions
• Are $\nu$'s Dirac or Majorana particles?
• What are the absolute $\nu$ masses?
• What is the ordering of $\nu$ mass states?
• Is there CP violation for neutrinos?

Non-accelerator experiments were key in discovering neutrino mass and oscillations in the past decade (1998-2008)

A Strategy for the Next Decade
• $\nu$ mass, scale, hierarchy: towards a ton-scale detector for the determination of the fundamental nature and mass of neutrinos (> CUORE, Majorana)
• direct $\nu$ mass: R&D on bolometer, tritium trapping,... (> MARE)
• CP, $\nu$ mass hierarchy: CPa megaton-scale detector for the search for proton decay, for neutrino astrophysics, and for the investigation of neutrino properties (> DUSEL LBL)

stay tuned ....
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technical staff
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total: ~ 20 people
Cryogenic Detectors for Dark Matter Searches

- cryogenic detector array with a target mass of several hundred kg to be built in European laboratory

cryogenic detectors have low energy threshold, excellent energy resolution

~3-4 eV for small cryodetectors
~100 eV for large absorbers with thresholds at ~1 keV
~115 eV for Ge detectors
~2350 eV for NaI-Tl scintillators

multi-material target

current sensitivity $4 \times 10^{-8}$ pb at 30 Gev/c^2

“EURECA aims to explore $10^{-9}$- $10^{-10}$ pb region”....demonstrator in 2009/2010?