Rare Event Searches with CUORE and DM-Ice Experiments

Kyungeun E. Lim (for the CUORE and DM-Ice collaborations)

Dec. 1, 2015, High Energy Seminar, UC Davis
Rare Event Searches:
Finding a signal (Wally) among huge backgrounds (Crowd)
Rare Event Searches:
Need a low background environment (Less crowd)
Rare Event Searches for **Nuclear-Particle-Astrophysics:**
Need a low background environment (Underground)
A World of Underground Laboratories
Experiments at the Gran Sasso National Laboratory are housed in and around three huge halls carved deep inside the mountain, where they are shielded from cosmic rays by 1,400 metres of rock.
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For an interactive version of this graphic go to: http://www.nature.com/news/gran-sasso-chamber-of-physics-1.10696
Why do we care about Neutrino and Dark Matter?

Neutrino and Dark Matter are the main drivers ask for the New Physics beyond the Standard Model of Particle Physics.
Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE: An array of TeO$_2$ bolometers to search for $0\nu\beta\beta$ and other rare events
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
- WIMP Dark Matter Search with CUORE
- DM-Ice: NaI(Tl) detectors to test WIMP discovery claim
- Summary
What we know about Neutrinos

Neutrino Mass Splitting

- **Normal Hierarchy**
  - $m_1^2$
  - $m_2^2$
  - $m_3^2$

- **Inverted Hierarchy**
  - $m_1^2$
  - $m_2^2$
  - $m_3^2$

- **Degenerate**
  - $m_1^2$
  - $m_2^2$
  - $m_3^2$

**Mass Splittings**
- Atmospheric: $~2 \times 10^{-3} \text{eV}^2$
- Solar: $~7 \times 10^{-5} \text{eV}^2$

**Energy Scales**
- Solar: $7 \times 10^{-5} \text{eV}^2$
- Atmospheric: $2 \times 10^{-3} \text{eV}^2$
- 100 - 500 meV


Kyungeun E. Lim (Yale University)
2015 NOBEL PRIZE IN PHYSICS

Takaaki Kajita
Arthur B. McDonald

“For the greatest benefit to mankind”
Alfred Nobel
What we don’t know about Neutrinos

Neutrino Mass Splitting

$m^2$

$m_3^2$

$m_2^2$

$m_1^2$

$m^2$

$m_1^2$

$m_2^2$

$m_3^2$

Normal Hierarchy

Inverted Hierarchy

atmospheric

$\sim 2\times 10^{-3}\text{eV}^2$

solar

$\sim 7\times 10^{-5}\text{eV}^2$

$100 - 500\text{meV}$

Degenerate

Is the neutrino its own antiparticle?

$\nu_e$

$\nu_\mu$

$\nu_\tau$

solar

$\sim 7\times 10^{-5}\text{eV}^2$

atmospheric

$\sim 2\times 10^{-3}\text{eV}^2$

$\nu_e$

$\nu_\mu$

$\nu_\tau$

Neutrino(less) double-beta decay

\[ 2\nu\beta\beta \]
- Allowed in SM
- Observed in several nuclei
  \( T_{1/2}^{2\nu} \sim 10^{18}-10^{21} \text{ yr} \)

\[ 0\nu\beta\beta \]
- Beyond SM
- Hypothetical process only if \( \nu = \bar{\nu} \) and \( m_\nu > 0 \)

**Observation of 0\nu\beta\beta**
1. will establish that neutrinos are Majorana Particles (\( \nu = \bar{\nu} \))
2. will demonstrate lepton number is not a symmetry of nature
3. will provide indirect info about the \( \nu \) mass
4. may provide info about the mass hierarchy in combination with direct neutrino mass measurement
Look for peak in the detector at the Q-value of decay.

Good energy resolution of a detector suppresses intrinsic background from $2\nu\beta\beta$. 

Signature of $0\nu\beta\beta$
Signature of $0\nu\beta\beta$

- Look for peak in the detector at the $Q$-value of decay.
- Good energy resolution of a detector suppresses intrinsic background from $2\nu\beta\beta$. 

( Assumes BR $0\nu/2\nu = 1\%$ and detector energy resolution is $2\%$)
Search for $0\nu\beta\beta$

Decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

Well defined

Difficult to calculate

- Probes absolute mass scale
- Sensitive to hierarchy

<table>
<thead>
<tr>
<th>$T_{1/2}^{0\nu}$</th>
<th>$0\nu\beta\beta$ half-life</th>
</tr>
</thead>
<tbody>
<tr>
<td>$G^{0\nu}(Q,Z)$</td>
<td>phase space factor ($\propto Q^5$)</td>
</tr>
<tr>
<td>$M^{0\nu}$</td>
<td>Nuclear Matrix Element (NME)</td>
</tr>
<tr>
<td>$m_{\beta\beta}$</td>
<td>effective Majorana mass of $\nu_e$</td>
</tr>
<tr>
<td>$m_e$</td>
<td>electron mass</td>
</tr>
</tbody>
</table>

$$\langle m_{\beta\beta} \rangle \equiv \sum_{i=1}^{3} U_{ei}^2 m_i$$
Search for $0\nu\beta\beta$

Decay rate:

$$\frac{T_{1/2}^{0\nu}}{1} = G^{0\nu}(Q, Z) \left| M^{0\nu} \right|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

$T_{1/2}^{0\nu}$ sensitivity

$$\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

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<td>electron mass</td>
</tr>
<tr>
<td>$a$</td>
<td>isotopic abundance of source</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>detection efficiency</td>
</tr>
<tr>
<td>$M$</td>
<td>total detector mass</td>
</tr>
<tr>
<td>$b$</td>
<td>background rate /mass/energy</td>
</tr>
<tr>
<td>$t$</td>
<td>exposure time</td>
</tr>
<tr>
<td>$\delta E$</td>
<td>energy resolution (spectral width)</td>
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</tbody>
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Search for $0\nu\beta\beta$

Decay rate:

$$(T_{1/2}^{0\nu})^{-1} = G^{0\nu}(Q, Z) |M^{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

where $T_{1/2}^{0\nu}$ sensitivity $\propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

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Detector Building/Source Selection Strategies:
- Large total mass
- Ultra-low background
- Good energy resolution
- High $Q$-value
- High isotopic abundance
- NME

Keywords:
- isotopic abundance of source
- detection efficiency
- total detector mass
- background rate /mass/energy
- exposure time
- energy resolution (spectral width)
Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
- CUORE: An array of TeO$_2$ bolometers to search for $0\nu\beta\beta$ and other rare events
- CUORE-0: $0\nu\beta\beta$ search w/ a single CUORE tower
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- Summary
The CUORE 0νββ Search

CUORE: Cryogenic Underground Observatory for Rare Events

Cuoricino (2003-2008)

Achieved (2008)

\[ T_{1/2}^{0\nu} > 2.8 \times 10^{24} \text{ yr (90\% C.L.)} \]

CUORE-0 (2013-2015)

Achieved (2015)

CUORE (2016-2020)

Projected (2020)

\[ T_{1/2}^{0\nu} > 9.5 \times 10^{25} \text{ yr (90\% C.L.)} \]
High isotopic abundance, low background at the Q-value makes $^{130}\text{Te}$ appealing for $0\nu\beta\beta$ search.
TeO₂ Bolometers

- Measure energy deposition through temperature rise.
- Provides excellent energy resolution.

- Crystal absorber: $E \rightarrow \Delta T$
- Biased $T$ sensor: $\Delta T \rightarrow \Delta V$
- Thermal coupling: $T_0 \sim 13$ mK
The CUORE Detector

- **Pulse Tube Refrigerator (5)**
- **Dilution Refrigerator**
- **Top Lead Shield (6 tons)**
- **Outer Lead Shield**
- **Inner Roman Lead Shield**
- **988 TeO$_2$ bolometers (19 towers)**
- **PE + H$_3$BO$_3$ Shield**
The CUORE Detector

doi:10.1038/news.2010.186 (nature)
The Coldest $\sim m^3$ in the Known Universe

CUORE: The Coldest Heart in the Known Universe

The CUORE collaboration at the INFN Gran Sasso National Laboratory has set a world record by cooling a copper vessel with the volume of a cubic meter to a temperature of 6 milliKelvins: it is the first experiment ever to cool a mass and a volume of this size to a temperature this close to absolute zero (0 Kelvin). The cooled copper mass, weighing approx. 400 kg, was the coldest cubic meter in the universe for over 15 days.

CUORE is an international collaboration involving some 130 scientists mainly from Italy, USA, China, Spain, and France. CUORE is supported by the Istituto Nazionale di Fisica Nucleare (INFN) in Italy; the Department of Energy Office of Science (Office of Nuclear Physics), the National Science Foundation, and Alfred P. Sloan Foundation in the United States.
**Outline**

- Neutrinoless double-beta decay (0νββ) search
- CUORE: An array of TeO$_2$ bolometers to search for 0νββ and other rare events
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- Summary
The CUORE-0 Experiment

- 52 (13 x 4) crystals, 39 kg of $\text{TeO}_2$ ($11$ kg of $^{130}\text{Te}$), 4 kg of copper structure.
- Validated new cleaning and assembly procedures for CUORE.
- Verified understanding on the background sources.
- Tested DAQ & Analysis framework for CUORE.
- Reported the limit on the half-life of $0\nu\beta\beta$ with 9.8 kg-yr of $^{130}\text{Te}$ exposure.


Data Acquisition
continuously sample and record the bolometer signal @ 125 S/s

Bolometer Pulse

Raw Data Processing
- software trigger thresholds (30-120 keV)
- signal, noise, pulser events
- filter pulse to optimize energy resolution
- signal (thermal) gain correction
- energy calibration (V → keV)

Blinding

ROOT
Data Trees

Event Selection
- remove low quality events
- single pulse in 7.1s window
- require pulse shape to be expected signal
- no other pulse in coincidence in other bolometers

Analysis efficiency!
Analysis Procedure: Results & Interpretation

Data Acquisition

Raw Data Processing

Experimental Input

Event Selection

Unbinned likelihood (UEML) fit Bayesian approach

Statistical Treatment

CUORE-0 Preliminary Exposure: 18.1 kg \cdot yr

60 Co

Salted Peak

NOT 0vDBD

Event Rate [counts/keV/kg/y]

Energy [keV]

Isotope Exposure [kg y]

\( T^{0}_{\text{ee}} \) [y] 90% C.L. Sensitivity

\( m_{\text{lightest}} \) [eV]

\( m_{\text{lightest}} \) [eV]

CUORE-0 Projected

Cuoricino limit

CUORE-0 Preliminary

Event Rate [counts/keV/kg/y]

Event Selection

Nuclear Physics
Energy resolution is evaluated for each bolometer and dataset by fitting the 2615 keV peak from $^{208}$Tl in the calibration data.

The obtained resolution is < 5 keV, which is the CUORE goal.
Background Comparison with Cuoricino

- γ background (from $^{232}$Th) was not reduced since the cryostat remained the same.
- γ background (from $^{238}$U chain) was reduced by a factor of 2.5 due to better radon control.
- α background from copper surface and crystal surface was reduced by a factor of 6.5 thanks to the new detector surface treatment.
- Demonstrate CUORE sensitivity goal is within reach.

Background paper in preparation!
Fit to the Unblinded ROI

Simultaneous unbinned extended ML fit to range [2470,2570] keV

Fit function has 3 components:
1. Calibration-derived lineshape modeling posited fixed at 2527.5 keV
2. Calibration-derived lineshape modeling Co peak floated around 2505 keV
3. Continuum flat background
We find no evidence for $0\nu\beta\beta$ of $^{130}\text{Te}$ (report the Bayesian limits)

$$\Gamma^{0\nu\beta\beta}(^{130}\text{Te}) < 0.25 \times 10^{-24} \text{ yr}^{-1} \ (90\% \ C.L., \ stat.+sys.)$$

$$T_{1/2}^{0\nu\beta\beta}(^{130}\text{Te}) > 2.7 \times 10^{24} \text{ yr} \ (90\% \ C.L., \ stat.+sys.)$$
Combining the CUORE-0 result with the Cuoricino result from 19.75 kg-yr of $^{130}$Te exposure yields the Bayesian lower limit:

$$T_{1/2}^{0
u \beta \beta}(^{130}\text{Te}) > 4.0 \times 10^{24} \text{ yr (90\% C.L., stat.+sys.)}$$

Effective Majorana Mass

\[ \langle m_{\beta\beta} \rangle < 270 - 650 \text{ meV} \]
1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

\[ \langle m_{\beta\beta} \rangle < 270 - 760 \text{ meV} \]
1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015))
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME
The 2015 Long Range Plan for Nuclear Science

Reaching for the Horizon

devices, and new computing techniques are themselves great achievements (see Sidebar 5.1). Several experiments are currently operational or about to come online with half-life sensitivities for the neutrinoless decay mode in the range of $10^{25} - 10^{26}$ years; they will also provide us with critical guidance about how best to take the next steps.

Next-generation neutrinoless double beta decay experiments have enormous potential to discover this process. With masses of isotope on the scale of tons, expected improvements in half-life sensitivity are two orders of magnitude or more over existing limits (i.e., $10^{27} - 10^{28}$ years). Results from solar, reactor, and atmospheric neutrino oscillation experiments have shown that there must be a neutrino mass state of at least 50 meV. When interpreted within the simplest lepton-number-violating mechanism (i.e., the exchange of light Majorana neutrinos), such “ton-scale” experiments can discover neutrinoless double beta decay if the lightest neutrino mass is above 50 meV or if the spectrum of neutrino masses is “inverted” (see Figure 5.2). Even if neither condition is realized in nature, a discovery is possible if other mechanisms beyond the simplest one contribute to the decay.

Well motivated alternative mechanisms involving new super-heavy particles more than 10 times heavier than weak force carriers (the W and Z particles) provide additional strong motivation for next-generation experiments.

Within the simplest mechanism (light Majorana neutrino exchange), the measurement of the decay half-life of the neutrinoless mode combined with input from nuclear theory allows a determination of the effective neutrino mass. This effective neutrino mass is a special quantum mechanical sum of all of the neutrino masses and is distinct from the individual neutrino masses. In this context, then, the search for neutrinoless double beta decay not only tests the fundamental law of lepton-number conservation but also provides quantitative information about the absolute scale of neutrino mass, complementing direct neutrino mass and cosmological measurements. In combination with these probes, the absence of a signal in the ton-scale search for neutrinoless double beta decay would imply the presence of a Dirac component of the neutrino masses, with significant ramifications for our understanding of the origin of neutrino masses.

Figure 5.2: Effective average neutrino mass from neutrinoless double beta decay vs. the mass of the lightest neutrino. Current limits and expected limits from ongoing experiments are shown as gray and blue horizontal bands. The green (for inverted hierarchy) and red (for normal hierarchy) bands show the expected ranges within the light Majorana neutrino exchange mechanism. Next-generation ton-scale experiments aim to probe effective Majorana neutrino masses down to 15 meV, shown as the horizontal dashed line.

Where is the field going?
Outline

- Neutrinoless double-beta decay ($0\nu\beta\beta$) search
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Summary:
Exponentially Falling Tiny Rates

- Large total mass
- Stable detector operation
- Low energy threshold
- Very low background
Status of the WIMP Direct Detection Searches

![Graph showing the status of WIMP direct detection searches with various data points and curves indicating different experiments like PandaX-I 2015, XENON100, 2012, LUX 2013, SuperCDMS 2014, DarkSide50, CRESST-II, CDEX 2014, CoGeNT 2014, CDMS-II Si, and DAMA 3 sigma.](image)
- Total target mass of 741 kg
- Stable detector operation expected with pulse tube and dilution refrigerators
- Bolometer offers low energy threshold and good energy resolution
- Quenching factor ~ 1 benefits detection of nuclear recoil events
- First dark matter search to test DAMA with Te
WIMP Search with CUORE: Energy Threshold

- Continuous Data Acquisition provides access to the low energy events
- Optimal Filter can identify low energy events

3 keV signal

Detection Efficiency

![Graph showing ADC counts and efficiency vs. energy](image)

- Raw Pulse
- Optimal Filtered Pulse

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Kyungeun E. Lim (Yale University)
Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from $^{210}$Po, $^{218}$Po, $^{222}$Rn decays.

<table>
<thead>
<tr>
<th>Energy [keV]</th>
<th>dN/dE [cts/2keV]</th>
</tr>
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<tbody>
<tr>
<td>3000</td>
<td>$10^2$</td>
</tr>
<tr>
<td>3500</td>
<td>$10^3$</td>
</tr>
<tr>
<td>4000</td>
<td>$10^2$</td>
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<tr>
<td>4500</td>
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CUORE-0 Preliminary

210Po
218Po
222Rn

Single crystal
Double crystal coincidences
Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from $^{210}$Po, $^{218}$Po, $^{222}$Rn decays.

Nuclear quenching factor of phonon detector is expected to be 1.

The largest deviation from 1 measured by $^{206}$Pb was integrated as uncertainty on the nuclear recoil energy scale.

Double crystal coincidence (Energy Sum is $^{210}$Po Q-Value)
Nuclear Recoil Quenching

- Using surface alpha events, it is possible to measure nuclear quenching of recoiling nuclei from $^{210}$Po, $^{218}$Po, $^{222}$Rn decays
- Nuclear quenching factor of phonon detector is expected to be 1
- The largest deviation from 1 measured by $^{206}$Pb was integrated as uncertainty on the nuclear recoil energy scale

CUORE-0 Preliminary

Double crystal coincidence (Energy Sum is $^{210}$Po Q-Value)
CUORE is expected to test the DAMA WIMP observation claim with 5 years of data accumulation
Outline

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Status of the WIMP Direct Detection Searches

Unresolved tension exists

WIMP-nucleon cross section (cm$^2$)

WIMP mass (GeV/c$^2$)

PandaX-I 2015
XENON100, 2012
LUX 2013
SuperCDMS 2014
DarkSide50
CRESST-II new
CDEX 2014
CoGeNT 2014
CDMS-II Si
DAMA 3 sigma

PandaX collaboration: arXiv:1505.00771
DAMA Modulation Signal

- 243 (25x9.7) kg of NaI(Tl), operated at LNGS in Italy
- Observe annual modulation only at the low energies

- Modulating signal w/ 9.3σ C.L.
- Spanning 15 cycles


Bernabei et al., arXiv:1412.6524
DM-Ice17 at the South Pole

- 2x 8.5kg NaI(Tl) modules
- Data from June 2011 to present
- Demonstrated the feasibility of deploying and operating NaI(Tl) detectors in the Antarctic Ice
- Studied environment stability and the capability of IceCube to veto muon events
- *In situ* measurement of the radio purity of the surrounding ice
Operating newly-grown NaI(Tl) crystals (2x 18.3kg) at Boulby Lab in UK

- 2850 m.w.e overburden
- Low Rn background (2.5 Bq/m^3, ~ x10-50 lower than other labs)
- Housed in the copper lined lead castle
COSINE

An International Consortium of Sodium Iodide Experiments

- **ANAIS**
  - 113 kg
  - External Muon Veto

- **DM-Ice**
  - 55 kg in Yangyang
  - Crystal R&D Boulby

- **KIMS**
  - 52 kg
  - Liquid Scintillator Veto

- Cross-collaboration data analysis effort
- Start data-taking by June 2016, Test DAMA in 2.5 years
The figure shows the SI WIMP-nucleon cross section in units of cm$^{-2}$ as a function of the WIMP mass in GeV. The graph includes lines representing DAMA allowed regions, DM-Ice17 exclusion limits, and COSINE sensitivity projections. The strongest limit from the Southern Hemisphere is highlighted.

Key points:
- DAMA allowed regions (90% C.L., 3σ, 5σ)
- DM-Ice17 Exclusion Limit (90% C.L.)
- COSINE, 2 years of data
- Median Projected Sensitivity (90% C.L.)
- Preliminary
Summary

- $0\nu\beta\beta$ and WIMP dark matter discovery, which require new physics beyond the Standard Model would have a major impact on our understanding on the Universe.

- As experiments are getting bigger, addressing common challenges in $0\nu\beta\beta$ and WIMP dark matter searches can greatly benefit both fields.

- CUORE will be one of the most sensitive $0\nu\beta\beta$ searches world wide, using well-established and competitive techniques offered by TeO$_2$ bolometers.

- WIMP analysis of CUORE will be complementary to the other dark matter experiments using different target materials.

- COSINE, an international consortium of Sodium Iodide Experiments, will definitely test the DAMA claim within two and half years of data-taking starting in 2016.