Neutrinoless double beta decay and the search for neutrino mass

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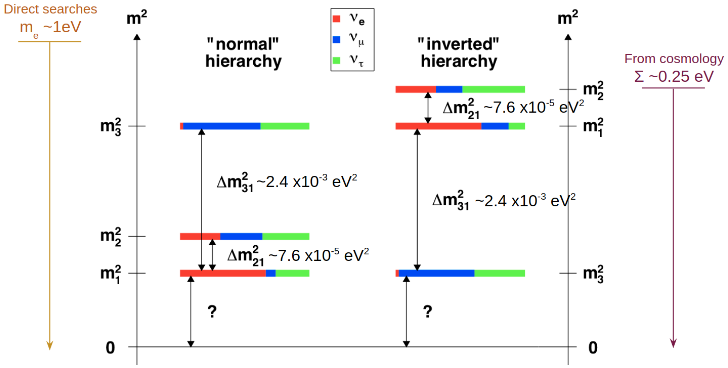
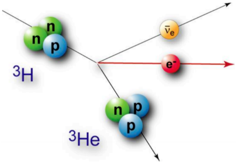
Neutrino oscillation measurements have provided extensive detail over the neutrino parameter space, but they can't measure the Majorana nature of neutrinos nor the abosolute mass scale. We need other mechanisms to access these parameters.



Adapted from PhysRevLett.123.151803

- Δm^2 from oscillation measurements
- δ_{CP} and hierarchy from beam measurements
- **but what is the absolute mass scale of the neutrino?**

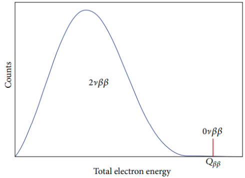
Experimental mechanisms



1. Direct searches

$$m_{ee}^2 = \left| \sum_{i=1}^{3} U_{ei}^2 m_i \right|^2$$

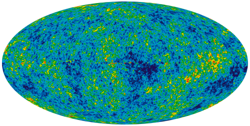
- Model-independent
- Time of flight measurements (supernovae)
- Decay spectrum endpoint $\rightarrow$ just relativistic kinematics



2. Neutrinoless double beta decay

- Model-dependent
- Majorana neutrino mass proportional to sum of mass eigenstates
- Lepton number violation

$$\langle m_{\beta\beta} \rangle = |U_{ei}^2 m_i^2|$$

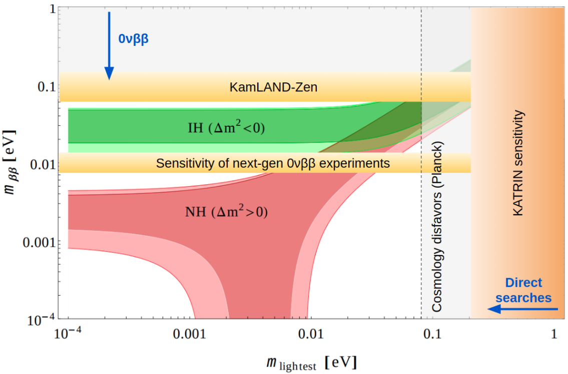


3. Cosmology

- Model-dependent
- Matter distributions & CMB influenced by Σ
- $\Sigma \leq$ 0.26eV (90% CL, Planck 2018)

$$\Sigma = \sum_{i=1}^{3} m_i$$

Current status of ν mass searches



adapted from S. Dell'Oro et al. Phys Rev D 2014

in the case of light Majorana neutrino exchange

This talk will cover only experiments which will be discussed in today's mini-symposium, sorry if your favorite is not covered!

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Neutrino Mass Searches in Tritium

Tritium undergoes beta decay, resulting in a continuum of electron energy.

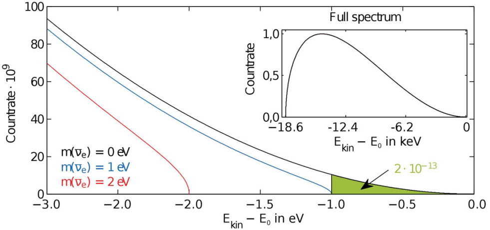
$$T_2 \rightarrow THe^{+} + e^{-} + \nu_e .$$

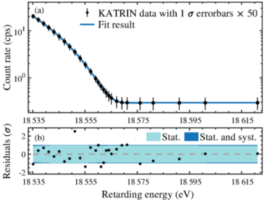
Neutrino mass $\rightarrow$ decrease in the spectrum endpoint as the neutrino carries away additional energy. Measurements of this value require

- an appropriate isotope with low endpoint and short half-life,
- high luminosity,
- high resolution, and
- low background

This measurement depends on just an understanding of relativistic kinematics of unbound nuclei.

THe-TRAP Project



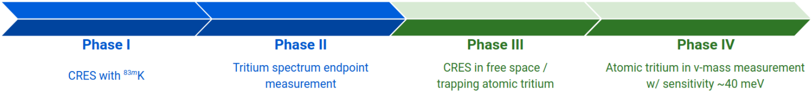


KATRIN 2019

$$m^2(\nu_e) = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$$
$$m(\nu) < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{CL})$$

PRL 123, 221802 (2019)

Project 8 — Phase II

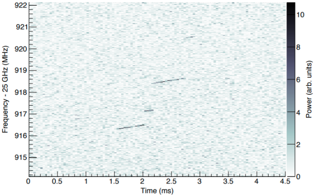


Cyclotron Radiation Emission Spectroscopy (CRES) of electrons from β-decay of T_2 — measurements of the kinetic energy of the electron using the relativistic shift in frequency.

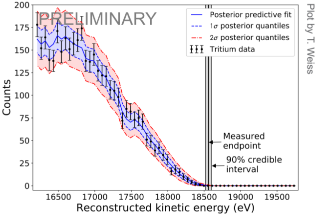
- Phase I demonstrated CRES on single electrons from ^{83m}Kr
- Started data-taking with T_2 source in Oct 2018
- Phase II measured tritium spectrum endpoint

2018 preliminary result:

$$T_2 \text{ endpoint: } E_0 = (18559.4^{+24.9}_{-24.7}) \text{ eV}$$
$$\text{Bkgd} \leq 3 \times 10^{-10} \text{ eV}^{-1}\text{s}^{-1} \text{ (90\% CI)}$$



Nu2020, First T_2 e^- event



Nu2020, 2018 T_2 e^- energy spectrum

Project 8 — Phase III

Phase I	Phase II	Phase III	Phase IV
CRES with ^{83m}K	Tritium spectrum endpoint measurement	CRES in free space / trapping atomic tritium	Atomic tritium in ν-mass measurement w/ sensitivity ~40 meV

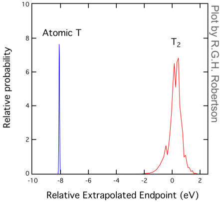
Cyclotron Radiation Emission Spectroscopy (CRES) of electrons from β-decay of T_2 — measurements of the kinetic energy of the electron using the relativistic shift in frequency.

Phase III

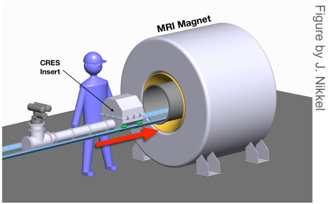
- preparation and trapping of atomic tritium
- CRES in large volumes

Phase IV

- measurement of tritium endpoint with atomic tritium
- sensitivity $\sim$40 meV

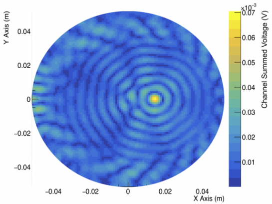


Nu2020: tritium final state atomic (blue) vs molecular (red)



Nu2020, scaling up to 200 ccm w/ MRI magnet

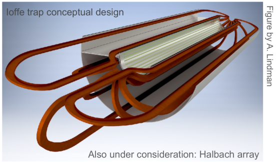
Project 8 — R&D



Reconstructed electron signal using *Locust*

Modeling RF CRES signals using *Locust*

- Adds electron radiation fields and antenna response
- Simulated datasets with realistic distributions of event properties
- Systematic studies of detection efficiency and frequency precision.



Nu2020 Ioffe trap conceptual design

Atomic Tritium Demonstrator

- Produce and store atomic T at scale, reusing recombined T_2
- Multiple test stands ongoing testing each component of the ATD
- Running in parallel with Free-Space CRES Demonstrator

- Free space antenna array for spatial tracking
- Phase IV sensitivity — improved understanding of effects from density, $\vec{B}$ field homogeneity, energy resolution

Tritium Recoil-Ion Mass Spectrometer (TRIMS)

PRL 124.222502 (2020)

- Measure branching ratio of molecular tritium source to the bound molecular ion using time-of-flight mass spectrometry.
- TT or HT sample
- Coincidence of β & ion
  H^+, He^+, He^{++}, & HHe^+ from HT,
  T^+ & THe^+ from TT.

Kinematics: ion mass-to-charge ratio given by

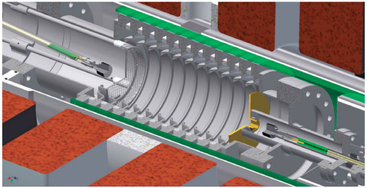
$$\frac{m}{q^2} = t^2 \frac{E^2}{2K_{\text{ion}}}$$

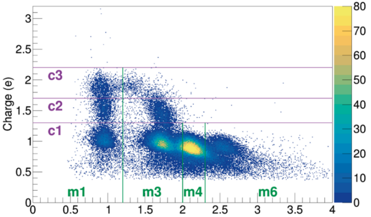
t = flight time, K_{ion} = final kinetic energy

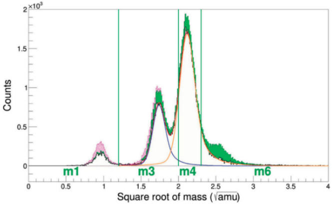
TRIMS 2020 results

- HT $\rightarrow$ $HeH^+ + e^-$: 56.51(55)%
- TT $\rightarrow$ $HeT^+ + e^-$: 50.3(15)%

$\rightarrow$ *decrease syst. in KATRIN + Project 8.*

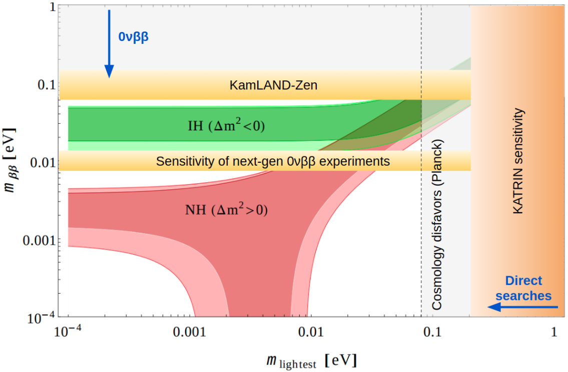






Direct ν mass searches

- Project 8 Phase IV is expected to have sensitivity of ∼40 meV, pushing in from the left
- TRIMS is expected to help decrease systematic errors in KATRIN and molecular tritium measurements from Project 8.



adapted from S. Dell'Oro et al. Phys Rev D 2014

in the case of light Majorana neutrino exchange

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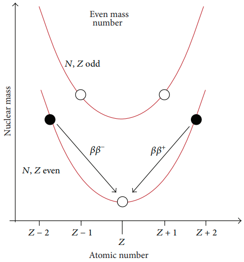
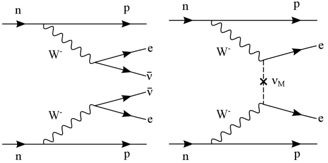
Double Beta Decay



Rare radioactive decay, found in even-even nuclei where single-beta decay is energetically forbidden (e.g. ^{130}Te)

- Two-neutrino ($2\nu\beta\beta$) $\Rightarrow$ Observed, $T_{1/2} > 10^{18}$ years
  $(A, Z) \rightarrow (A, Z+2) + 2e^- + 2\bar{\nu}_e$
- Neutrinoless ($0\nu\beta\beta$) $\Rightarrow$ Expected $T_{1/2} > 10^{25}$ years
  $(A, Z) \rightarrow (A, Z+2) + 2e^-$



Observation of $0\nu\beta\beta$ is a critical tool to study neutrinos:

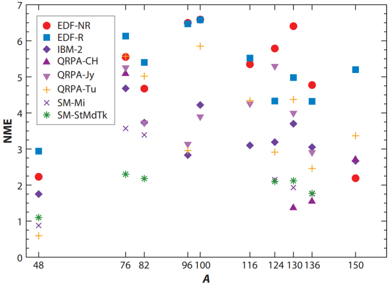
- Majorana ($\nu = \bar{\nu}$) or Dirac ($\nu \neq \bar{\nu}$) nature
- Lepton number violation ($\Delta L = 2$)
- ν mass scale and ordering

Measuring neutrino mass with $0\nu\beta\beta$

$$\Gamma_{0\nu} = (T_{1/2}^{0\nu})^{-1} = G_{0\nu}\ |M_{0\nu}|^2\ \langle m_{\beta\beta}\rangle^2$$

$$\langle m_{\beta\beta}\rangle = |U_{ei}^2 m_i^2|$$

Nuclear matrix elements (M) are a major source of uncertainty



Ann. Rev. Nucl and Part.Sci. 69 (2019)

KamLAND-Zen:
$T_{1/2} > 10.7 \times 10^{25}$ yr
$m_{\beta\beta} < 61$ - 165 meV

Other mechanisms for $0\nu\beta\beta$ like heavy neutrino exchange with right-handed currents have different parameter spaces (so ruling out the IH with light-majorana exchange isn't the end of this path)

Measurements of $2\nu\beta\beta$ and $0/2\nu\beta\beta$ to excited states contribute to understanding of NME, which in turn contributes to neutrino mass measurements

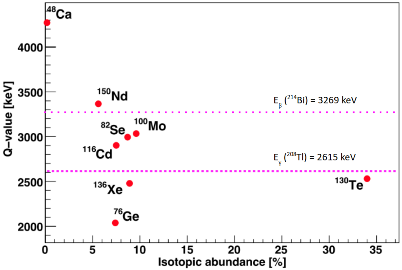
A Better $0\nu\beta\beta$ Detector

Sensitivity to $0\nu\beta\beta$ for an experiment with non-zero background:

$$F_{T_{1/2}} \propto \epsilon \cdot \eta \sqrt{\frac{M \cdot T}{b \cdot \Delta E}}$$

or for an experiment with zero background ($\mathcal{O}(1)$ compared to exposure)

$$F_{T_{1/2}} \propto \epsilon \cdot \eta \cdot M \cdot T$$



- ϵ = signal efficiency
- η = abundance or enrichment
- $M \cdot T$ = exposure ("ton-year")
- b = background index in ROI
- ΔE = energy resolution at Q-value

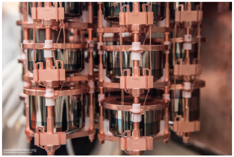
Fundamental requirements for modern experiments searching for $0\nu\beta\beta$:

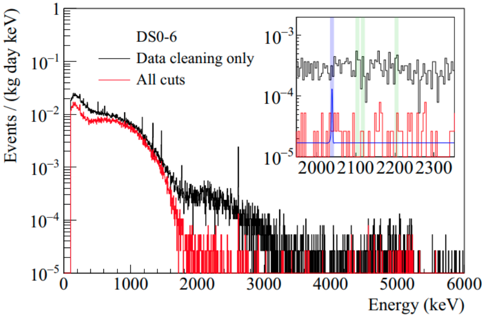
- Ultra-low background materials
- Underground location
- Large amount of candidate isotope
- Excellent signal/background discrimination

Majorana Demonstrator

$$^{76}\text{Ge} \rightarrow {}^{76}\text{Se} + 2e^-$$

- Since 2015 in Sanford Underground Research Facility
- Array of Ge crystals: 29.7 kg 88% enriched ^{76}Ge
- Shielding & active muon veto with ultra-clean materials.
- Recent improvements in discriminating parameters for multi-site and surface α events.
- 2020 hardware upgrade to signal & HV connections



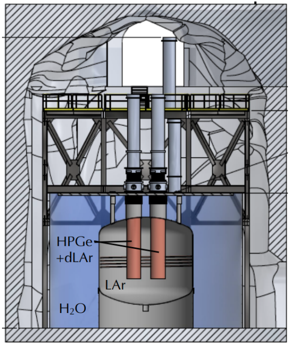


Phys Rev C 100, 025501 (2019)

ΔE = 2.5 keV FWHM at Q-value (2039 keV)
$b = 11.9 \pm 2.0$ cts/FWHM/t/yr
Limit $T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Above: 26 kg-yr. New result with $\sim$ 50 kg-yr exposure expected soon.

LEGEND

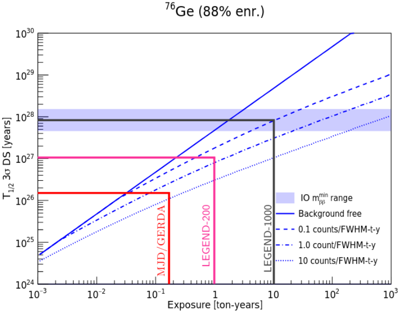


LEGEND-1000:

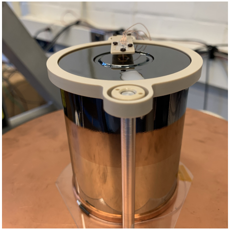
- Ton-scale 90% enriched ^{76}Ge in detector array
- Combines components from MJD (clean materials & low-noise electronics) and GERDA (active LAr veto)
- Background goal: <0.03 cts/FWHM/t/yr

Discovery sensitivity to $T_{1/2} \sim 10^{28}$ yr ($m_{\beta\beta} \sim 10 - 20$ meV)

LEGEND-200 (2021):
Under construction in GERDA infrastructure, 200 kg scale, expected sensitivity to $T_{1/2} \sim 10^{27}$ yr

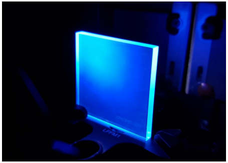


LEGEND Ongoing Research and Development



Scanning cryostats for surface event analysis

Studying surface effects on HPGe detectors in vacuum. CAGE-S is designed to scan passivated surfaces at varying angles to study effects from α,β, & γ sources with <3mm positional resolution.



(Photo: F. Fischer/MPP)

Scintillating PEN as an active veto material

A common plastic, PEN can be used in the design of the experiment in and around the detector array. Scintillation from escaping gammas can be measured as an active veto, reducing background from Compton scatters and partial depositions.

- Xe-doped LAr to increase light yield of veto
- ASIC front-end electronics
- New HPGe detector geometries & sizes

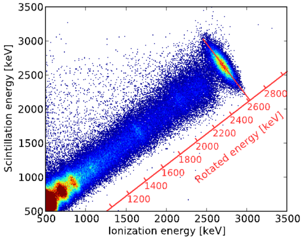
EXO-200 results

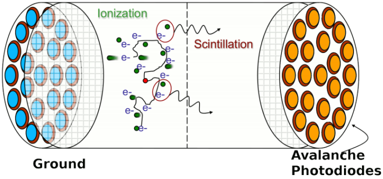
- ran at WIPP from 2011 to 2018*
- LXe TPC, using linear combination of scintillation and ionization signals for event reconstruction
- DNN for background discrimination

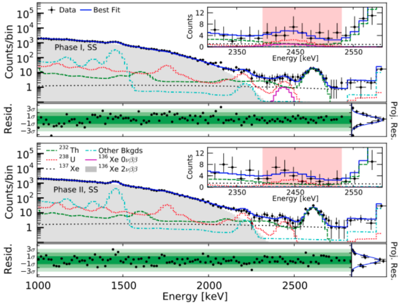
$$^{136}\mathrm{Xe} \rightarrow\ ^{136}\mathrm{Ba} + 2e^-$$

PRL 123,161802 (2019)

$T_{1/2} > 3.5 \times 10^{25}$ yr (90%CI)
234.1 kg yr exposure
$\Delta E = 1.15\pm0.02\%$ at Q-value

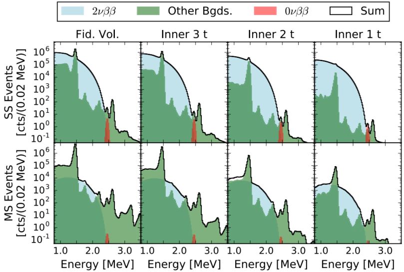


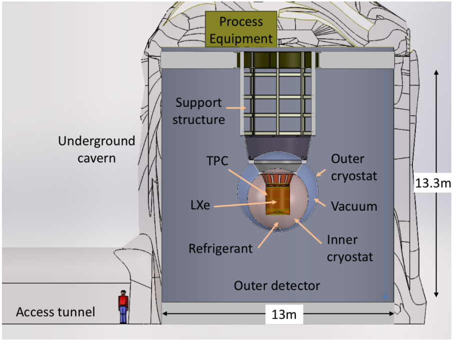




nEXO

- 5 ton single-phase LXe TPC
- Enriched to 90% in ^{136}Xe
- 1.3m x 1.3m cylindrical detector with single drift region
- Based on the success of the EXO-200 detector, including an extensive radioassay campaign.





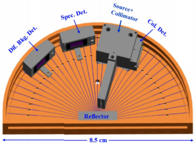
PRC 97 065503 (2018)

Expected sensitivity to $T_{1/2}$ of $0\nu\beta\beta$ in ^{136}Xe:
9.2×10^{27} yr (90% CL)
($m_{\beta\beta} \leq$ (45-211) meV)

nEXO ongoing work

Updated sensitivity projections

- Updates to event reconstruction based on EXO-200 results
- Optical simulation projections of light response
- DNN for signal/background discrimination
- Interactions in the "skin" outside the optically-open TPC field cage.



LIquid Xenon OPtical Characterization (LIXO)

- Measurement of VUV4 SiPM candidates in LXe
- Use scintillation in LXe from ^{252}Cf source
- Specular reflectivity measured as $\sim$30%
- Reflectivity decreases as function of angle

Recent and Upcoming Papers

- Measurement of the scintillation and ionization response of LXe (PRC 101 065501 (2020))
- Event reconstruction with optically-open field cage (arXiv:2009.10231)

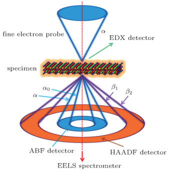
Radon as an injected calibration source

- End-of-run calibration campaign on EXO-200 demonstrated first Rn injection in single-phase LXe
- Demonstrated capability to track population decay
- Complementary to external γ calibration plans

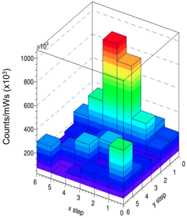
Barium Tagging

$$^{136}\text{Xe} \rightarrow {}^{136}\mathbf{Ba}^{++} + 2e^{-}$$

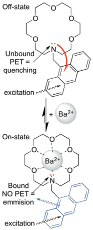
Tagging the daughter Ba ion could eliminate all but $2\nu\beta\beta$ backgrounds in a xenon experiment.



Scanning Transmission Electron Microscopy
Small volume of LXe is extracted and the Ba ion is imaged and identified using STEM. Demonstrated single atom Ba ID in $BaCl_2$ molecule.

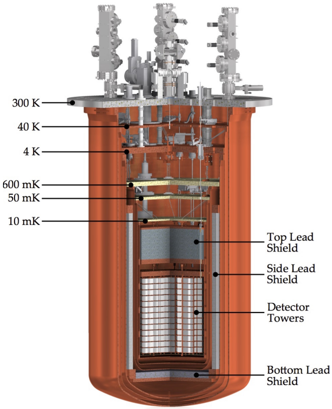


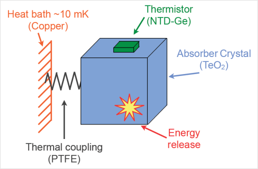
SXe fluorescence
Extract daughter Ba^{+} by freezing ion in solid xenon using a cryoprobe. Resultant window is then probed with a laser, expecting fluorescence. Demonstrated counting of single barium atoms in solid xenon (Nature 569 2019)

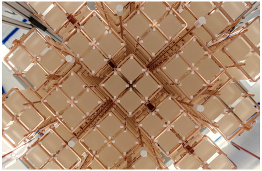


Chemical fluorescence
Sample expected to contain Ba ion combined with a dry-phase barium chemosensor molecule, which allows for identification using TIRFM (Nature Sci Rep 9, 15097 2019)

Cryogenic Underground Observatory for Rare Events (CUORE)





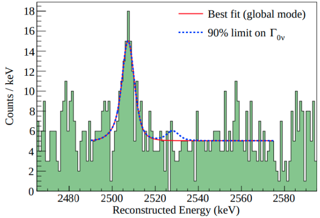


$$^{130}\mathrm{Te} \rightarrow \ ^{130}\mathrm{Xe} + 2e^-$$

- 988 TeO_2 bolometers (206 kg ^{130}Te) instrumented with NTD thermistors
- Detector array cooled to operating temp of ~10mK.
- Stringent radiopurity control on materials and assembly
- Target $\Delta E = 5$ keV at Q-value
- Target $b = 10^{-2}$ ct/keV/kg/yr

Expected sensitivity to $T_{1/2}$ of $0\nu\beta\beta$ in ^{130}Te:
9.5×10^{25} yr (90% CL)
($m_{\beta\beta} \lesssim$ (50-130) meV)

CUORE



PRL 124 122501 (2020)

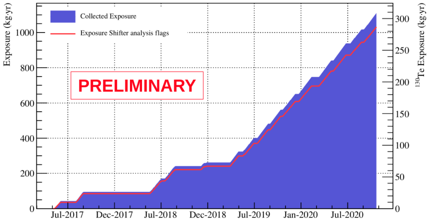
$T_{1/2} > 3.2 \times 10^{25}$ yr (90%CI)

($m_{\beta\beta} \leq$ (75-350) meV)

372.5 kg yr exposure

ΔE = 7.0 keV FWHM at Q-value (2528 keV)

b = (1.38 $\pm$ 0.07) ct/keV/kg/yr



- Bayesian Analysis using BAT
- Likelihood model: flat continuum (BI), posited peak for $0\nu\beta\beta$(rate), peak for ^{60}Co(rate+position)
- Systematics: repeat fits with nuisance parameters, allow negative rates (<0.4% impact on limit).

Background Exposure: 1031.43 kg yr

Background Collected Exposure: 1110.3 kg yr

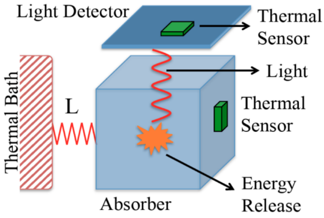
* does not take into account analysis efficiency

CUPID: CUORE with Upgraded Particle IDentification

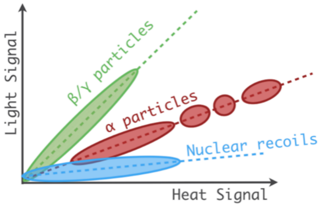
$$^{100}\text{Mo} \rightarrow {}^{100}\text{Ru} + 2e^-$$

Secondary bolometer reads out scintillation light for signal/background discrimination.

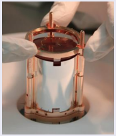
- 1500 Li_2MoO_4 crystals hosting 250 kg of ^{100}Mo
- CUORE infrastructure
- $\Delta E \sim 5$ keV FWHM at $Q_{\beta\beta} = 3034$ keV
- Background goal: 0.5 cts/FWHM/t/yr



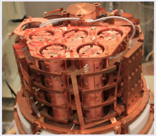
$\boxed{\text{Discovery sensitivity to } T_{1/2} \sim 10^{27} \text{ yr } (m_{\beta\beta} \sim 12-20 \text{ meV, 10 yr})}$



CUPID-0



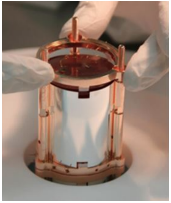
CUPID-Mo



CUPID pre-CDR arXiv:1907.09376

CUPID

CUPID-0



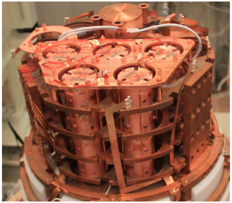
26 ZnSe crystals enriched with 5.17 kg of ^{82}Se and equipped with a Ge light detector for PID.

- 20.05±0.34 keV FWHM at the Q-value
- 99% α rejection

$0\nu\beta\beta$ of ^{82}Se
$T_{1/2} > 3.5 \times 10^{24}$ yr
$m_{\beta\beta} < [0.31 - 0.64]$ eV
90% CI , 5.29 kg·yr

PRL 123, 032501 (2019)

CUPID-Mo



20 ~0.2kg enriched Li_2MoO_4 crystals. 20 Ge wafers coated with SiO instrumented with NTDs acted as light detectors for PID.

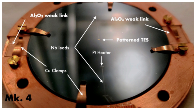
- 7.7(7) keV FWHM at the Q-value
- Excellent α rejection

$0\nu\beta\beta$ of ^{100}Mo
$T_{1/2} > 1.4 \times 10^{24}$ yr
$m_{\beta\beta} < [0.31 - 0.54]$ eV
90% CI , 2.17 kg·yr

Neutrino 2020
(Paper in prep)

(Selection of) CUPID Ongoing R&D

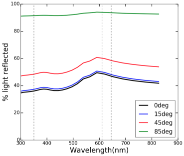
TES-based large area photon detectors

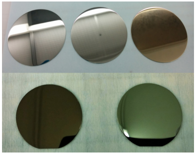


square Ir/Pt bilayer TES in the middle with Au pads on both sides

- Need high photon collection efficiency, very low threshold ($\sim$100eV) and excellent timing resolution
- Ir/Pt bilayer transitions at $\sim$37mK
- Au pads improve signal-to-noise
- Timing resolution of $\Delta t \sim 5\ \mu$sec
- $\Delta E_{\mathrm{FWHM}}/E \ \sim 0.3$ at 71 keV
  (most probable deposition energy during muon calibration)

AR coatings for light collection





JINST 12, no. 09, P09018 (2017)

- Bare Ge naturally reflects 600nm scint. light, up to 85% at high incidence angles.
- Light yield directly ties to α discrimination
- CUPID plans to use 75nm SiO AR coating like CUPID-Mo, but other thicknesses and materials are under investigation.

Recent and Upcoming Papers

- CUPID rejection of pile-up events (*in prep*)
- Characterization of LMO crystals (*in prep*)
- CUPID-Mo new $0\nu\beta\beta$ results in ^{100}Mo (*in prep*)
- CUPID-Mo pulse shape discrimination using PCA (arXiv:2010.04033)
- Ir-based TES fabrication and characterization (JAP 128, 154501 (2020))

- Direct neutrino mass measurements are entering an exciting phase, gearing up for Project 8 Phase IV.
- Neutrinoless double beta decay experiments are making great strides on a variety of R&D fronts, including updates to existing simulation and analysis techniques as well as tabletop measurements of materials for use in next-generation detectors.

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Welliver, B. [LM] New Results in the search for $0\nu\beta\beta$ decay in ^{100}Mo from CUPID-Mo

Wagaarachchi, S. [KG] Searching for Neutrinoless Double Beta Decay in CUORE using Multi-Site events

Singh, V. [KN] Performance and optimization of transition-edge sensor based photon detectors for CUPID

Vetter, K. [SK] Noise Correlation with Acoustic Signals in CUORE

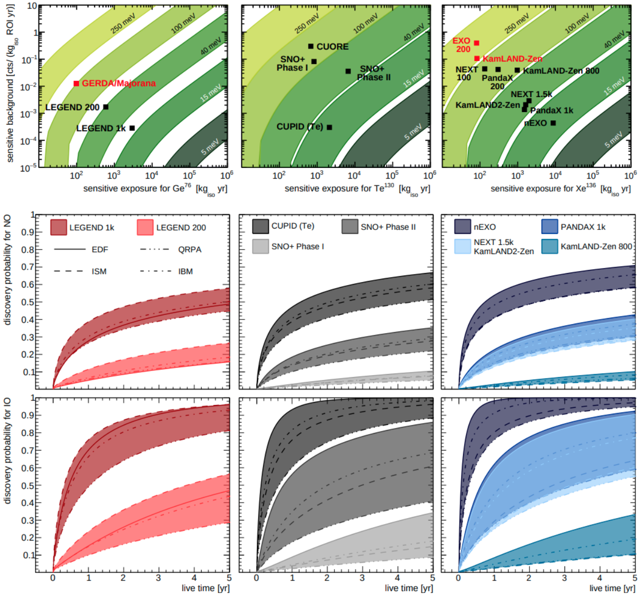
Dixon, T. [FG] A detailed background model for the CUPID-Mo $0\nu\beta\beta$ experiment

Beretta, M. [FG] Mock data production for pileup rejection studies in CUPID

Huang, R. [FG] Studying CUORE Pulses with Principal Component Analysis

Pagan, S. [FG] Projected Backgrounds and Mitigation Techniques for the CUPID Experiment

Surukuchi, P.T. [FG] Analysis Techniques for Background Reduction and Event Identification in the Search for Neutrinoless Double Beta Decay with CUORE



PhysRevD.96.053001