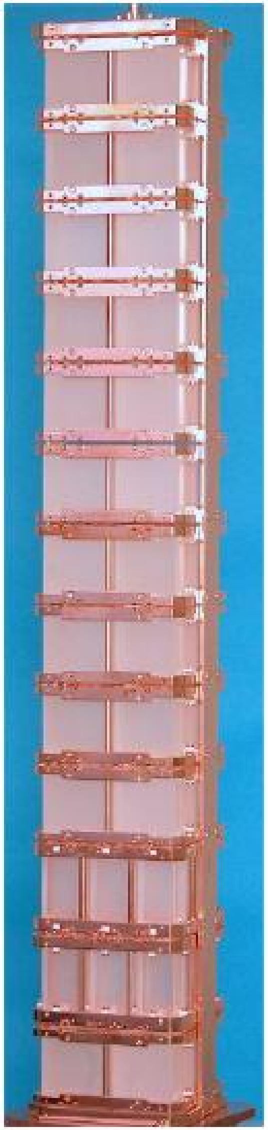
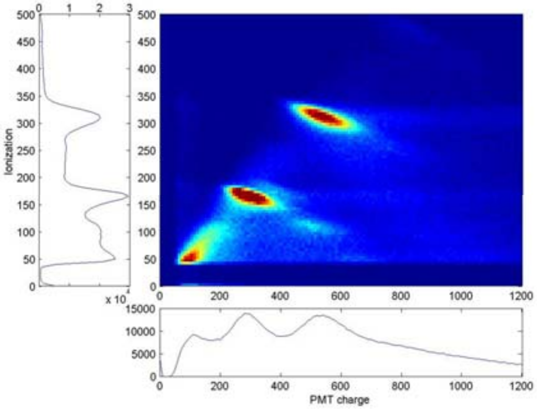
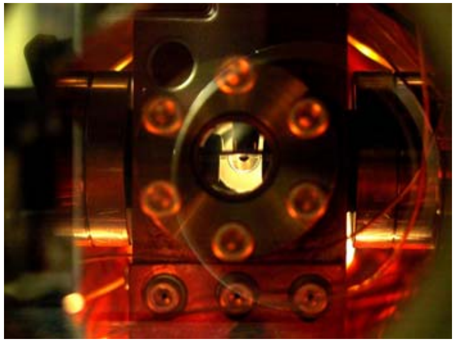
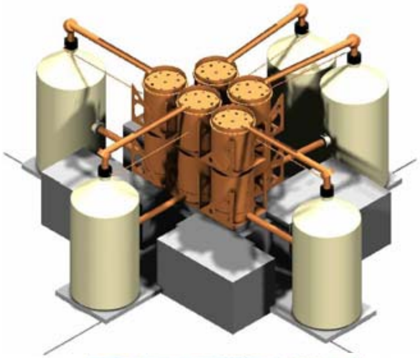


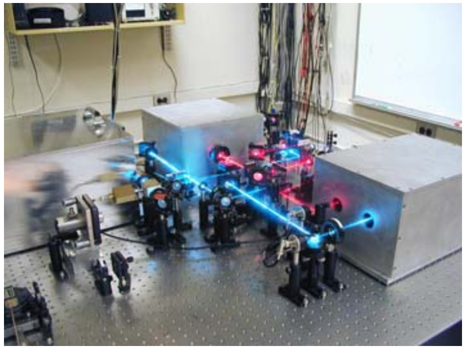


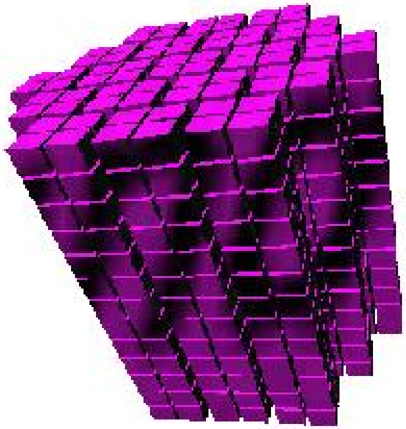




Neutrino Physics with Double Beta Decay

Carter Hall, SLAC





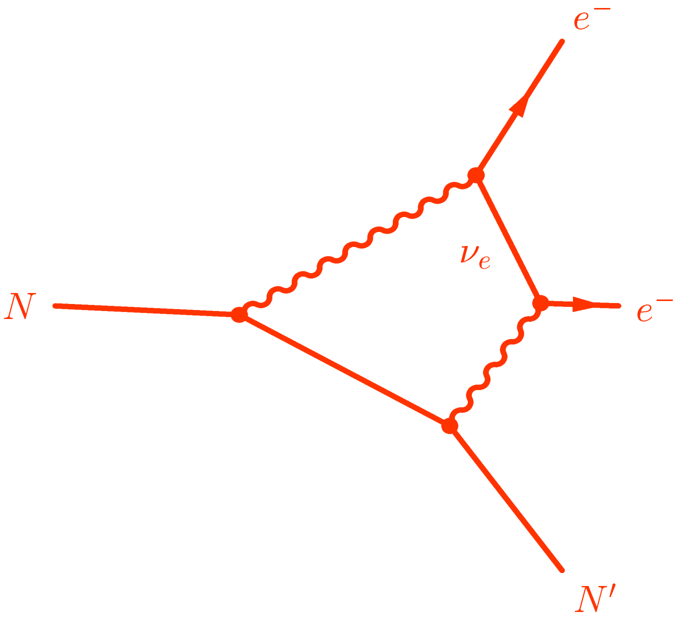
What we can learn from double beta decay:
Are neutrinos their own antiparticles (Dirac or Majorana)?

Majorana fermion: particle = antiparticle
Dirac fermion: particle and antiparticle are distinct

without caveats:

Majorana neutrinos ↔ ββ0ν

- Neutrinos must be massive (no longer a caveat).
- The neutrino mass mechanism for ββ0ν is forbidden if neutrinos carry lepton number (Dirac case).
- Many types of new physics can lead to ββ0ν (SUSY, leptoquarks, W_R, ect.), but these possibilities always imply Majorana neutrinos.
- ββ0ν is our only realistic experimental window on the Majorana/Dirac question.



"neutrino mass mechanism" for ββ0ν

What we can learn from double beta decay: Are neutrinos their own antiparticles (Dirac or Majorana)?

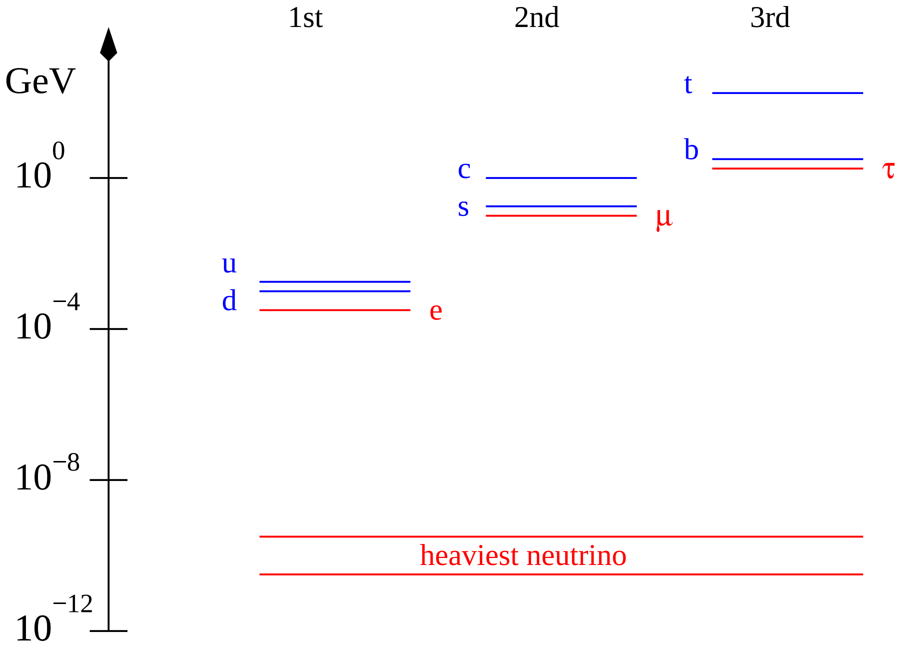
The Majorana/Dirac nature of the neutrino is determined by the mass term in the Lagrangian.

- Neutrinos are clearly an exception to the fermion mass pattern, so the Higgs cannot be the whole story.

- In many new physics models the neutrino masses are tied to the GUT scale (see-saw mechanism).

- Most models make a clear prediction for Majorana or Dirac neutrinos, so ββ0ν will constrain GUT scale physics.

Standard model fermion mass spectrum



What we can learn from double beta decay:

What are the masses and mass hierarchy of the neutrinos?

The ββ0ν decay rate depends on the absolute neutrino masses:

$$\left(T_{1/2}^{0\nu\beta\beta}\right)^{-1} = G^{0\nu\beta\beta} \cdot \left|NME\right|^2 \cdot \left|\langle m_\nu \rangle\right|^2 ,$$

phase space

Nuclear Matrix Element

effective mass

$$\langle m_\nu \rangle = \sum_i U_{ei}^2 m_i e^{i\alpha_i}$$

mixing matrix (with phases)

mass eigenvalues

Majorana phases

Two caveats: 1) we must have a reliable calculation of the nuclear matrix element
2) the neutrino mass mechanism must dominate the decay

To resolve ambiguities in $<m_\nu>$ we also need a positive result from beta spectrum endpoint measurements (KATRIN), and precise measurements of |Uei| from oscillation experiments.

Desirable properties for a ββ0ν candidate isotope: Large Q value and natural abundance

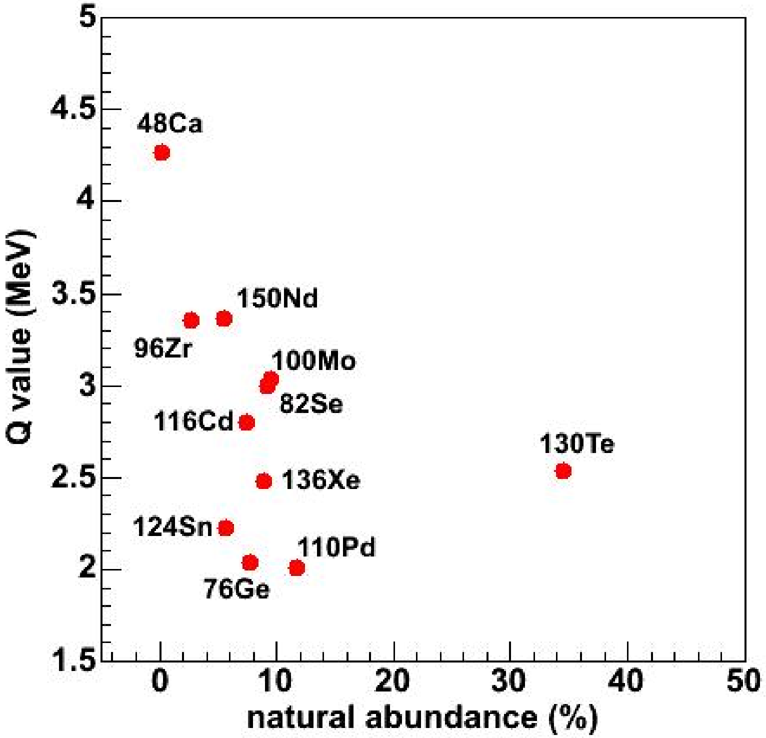
High Q value puts ββ0ν above radioactive backgrounds,
and high abundance makes the experiment cheaper.

- ^{48}Ca: fantastic Q, but only 0.2% natural abundance

- ^{130}Te: moderate Q, but no enrichment needed

- ^{76}Ge: low Q, moderate abundance, yet currently has the best sensitivity

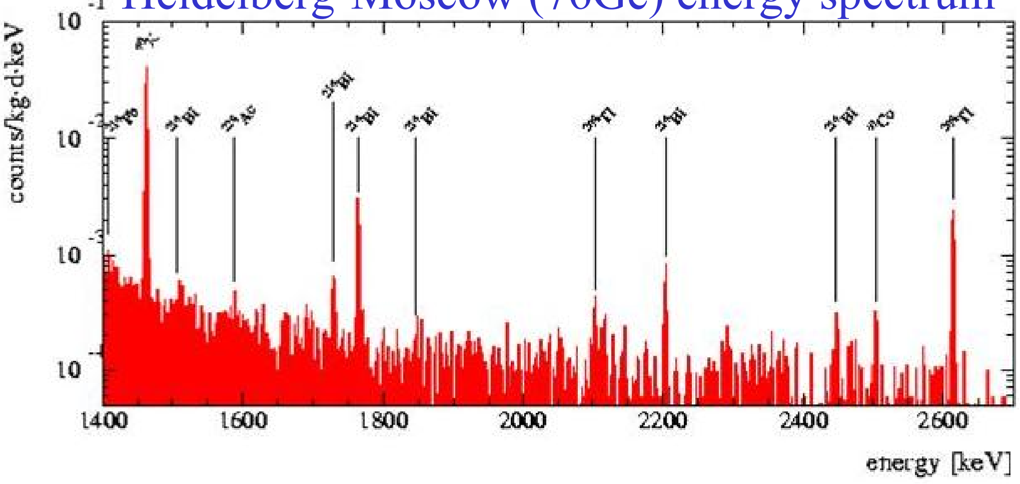
- ^{136}Xe: moderate abundance, but enrichment is relatively cheap (noble gas)



Desirable properties for a ββ0ν candidate isotope:
Good energy resolution

The ββ0ν signature is a line at the Q value – so energy resolution is critical.

Heidelberg-Moscow (76Ge) energy spectrum

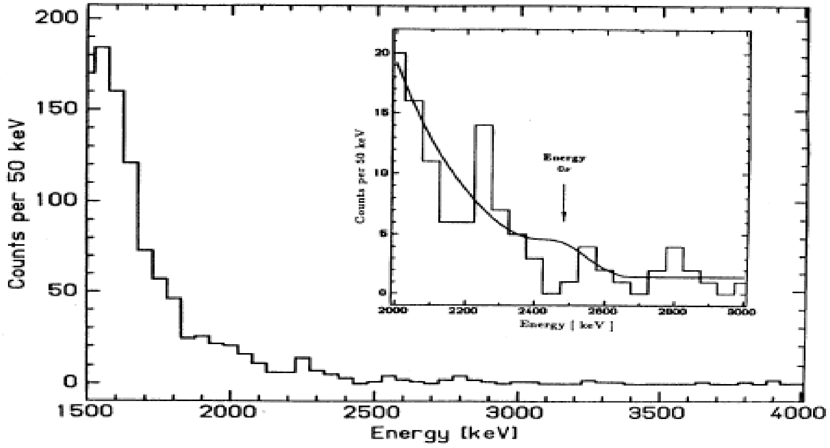


Superb energy resolution:
76Ge (diode): 0.2% FWHM
130Te (bolometer): 0.4% FWHM

Modest energy resolution:
136Xe (liquid TPC): 3.3% FWHM
100Mo, 82Se (plastic scintillator): ~14% FWHM

If resolution is very poor ββ2ν overwhelms ββ0ν.

Gotthard TPC (136Xe) energy spectrum



Current status of ββ0ν searches

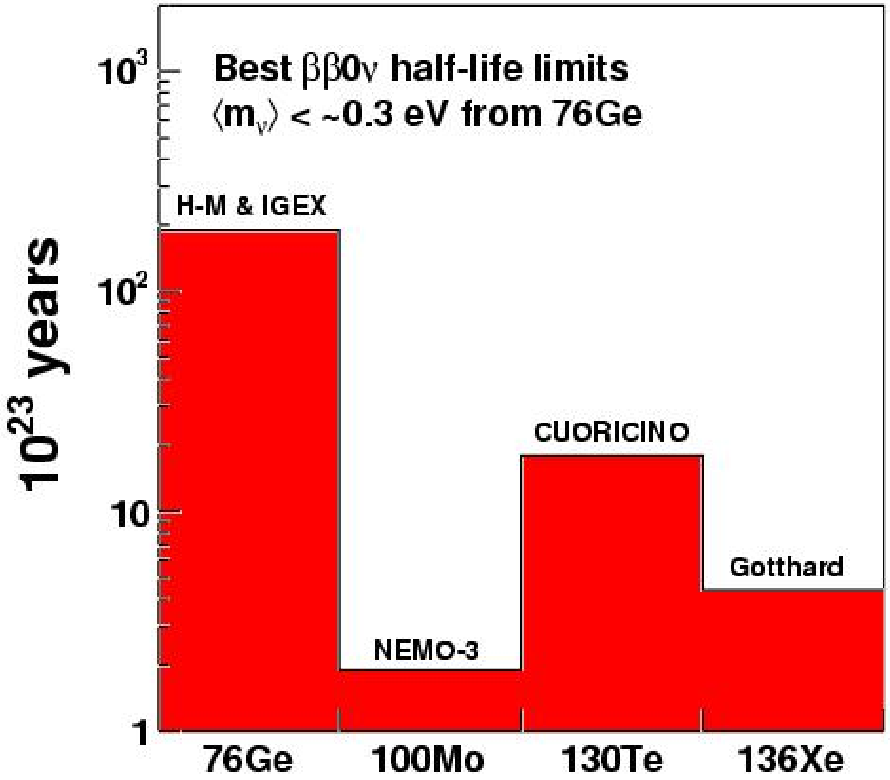
ββ0ν has not been observed(!)

Four isotopes have $<m_\nu>$ sensitivity from 0.3 to 3.0 eV.

Best sensitivity is currently from 76Ge (Heidelberg-Moscow and IGEX), but 130Te is rapidly closing the gap (CUORICINO).

Tritium beta endpoint searches give $m(\nu_e) < 2.2$ eV (Mainz and Troitsk).

WMAP data give $\Sigma m\nu < 0.75$ eV (model dependent).



Germanium Basics

An IGEX Ge diode
in its copper cryostat

Detectors are solid state diodes typically 2-3 kg enriched to ~80% in 76Ge.

Fantastic energy resolution (4 keV FWHM) due to low ionization potential (2.9 eV) and good Fano factor (0.05).

Operated at LN temperature to suppress thermal noise.

Four crystals with LN service and Pb shield

Pulse shape analysis rejects multiple site events within a single crystal.

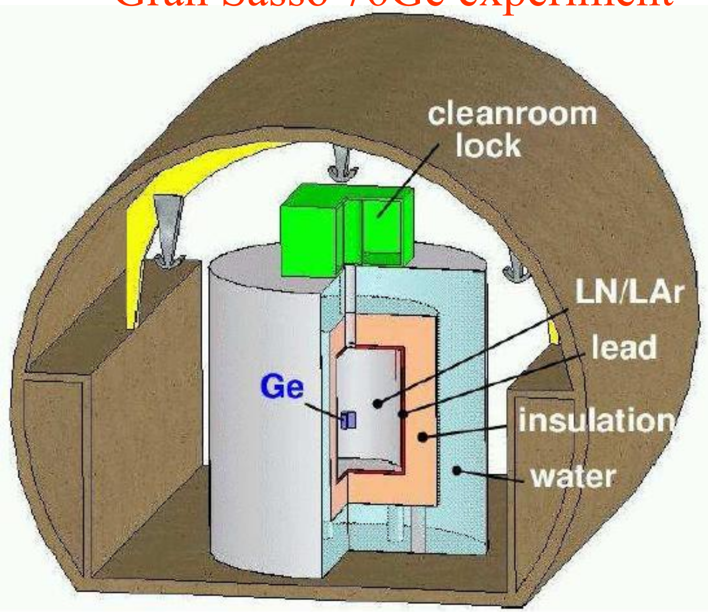
Suffers from low Q value (2039 keV) and cosmogenics in the germanium (68Ge, 60Co) and copper cryostats.

Next generation 76Ge experiments

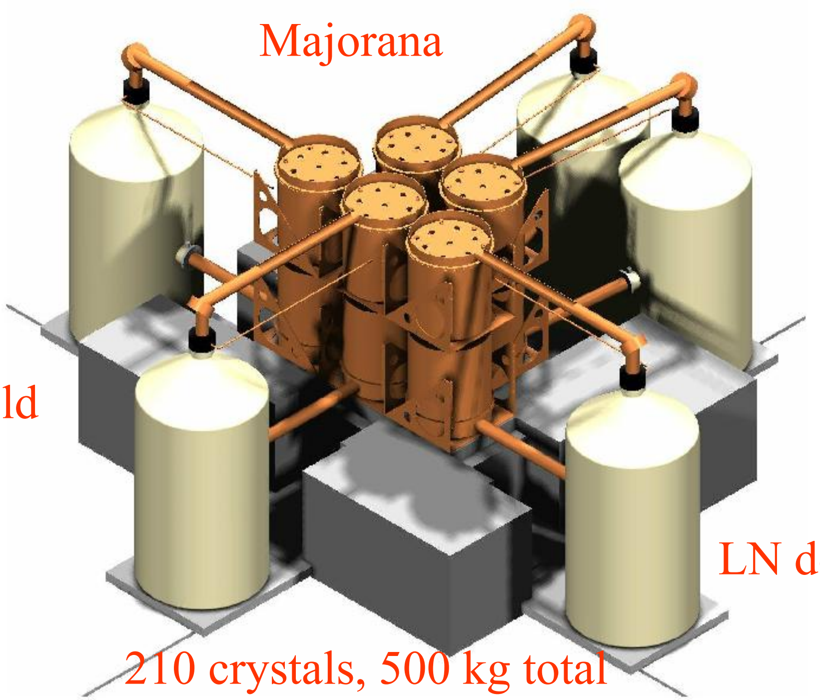
Majorana is a successor to IGEX, whose dominant backgrounds were cosmogenics in the germanium.

A Gran Sasso proposal calls for the elimination of 238U and 232Th in the cryostats by operating the diodes directly in LN or LAr, away from the copper.

Gran Sasso 76Ge experiment



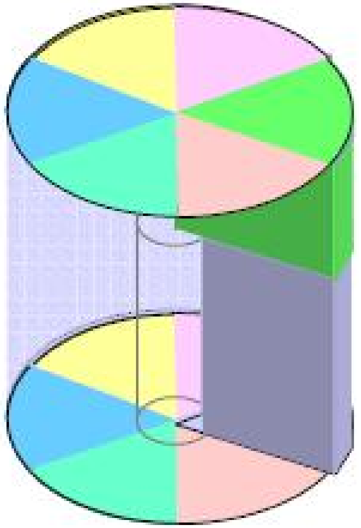
Majorana



Pb shield

LN dewar

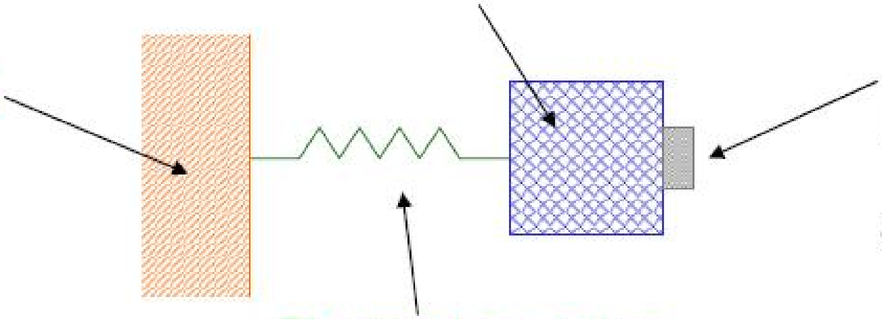
210 crystals, 500 kg total



Segmentation (6x2) results in 2500 individual 200g segments

Tellurium basics: low temperature bolometers

Diamagnetic and dielectric crystals have tiny heat capacities at low temperature. Cool them down to 10 mK, and you can see energy deposition with a thermometer .



C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK

Heat sink
T ≅ 10 mK

Thermometer
NTD Ge-thermistor
R ≅ 100 MΩ
dR/dT ≅ 100 kΩ/μK

Thermal coupling
G ≅ 4 nW / K = 4 pW / mK

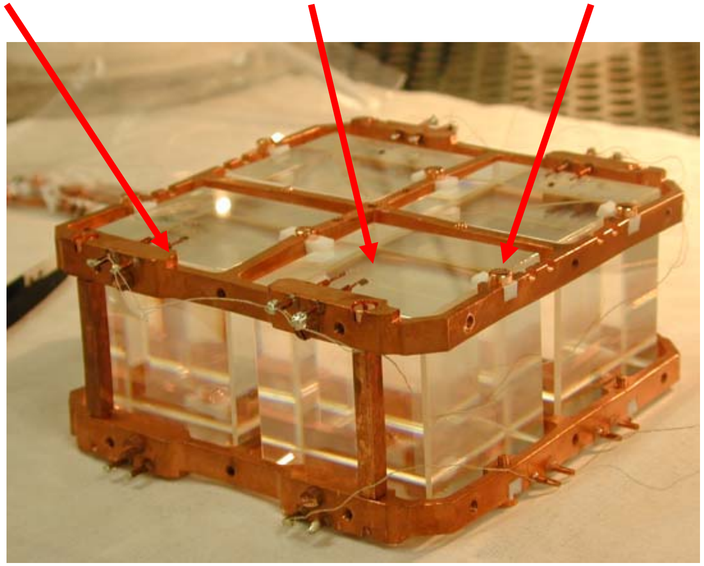
This technique is applicable to many isotopes – currently 130Te is used to take advantage of its high isotopic abundance (30%).

Outstanding energy resolution is possible (1 keV). Drawbacks: no information beyond energy, like particle ID (alpha vs beta), event location, or event topology.

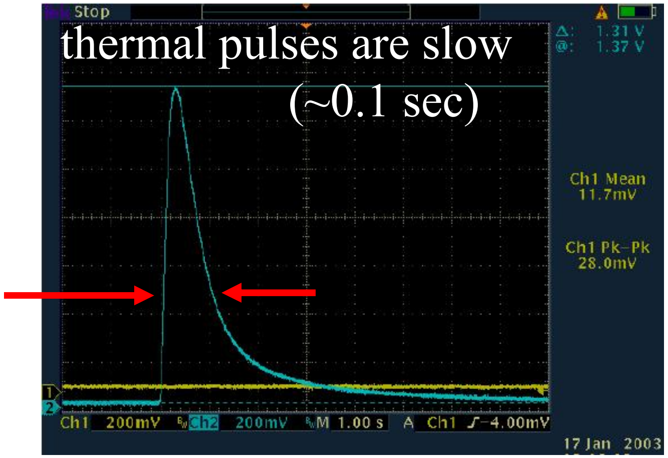
130Te : CUORICINO

Italy, US, Netherlands, Spain

heat sink thermometer thermal link



CUORICINO - is a 40.7 kg tower of TeO2 crystals in operation at Gran Sasso.



thermal pulses are slow (~0.1 sec)

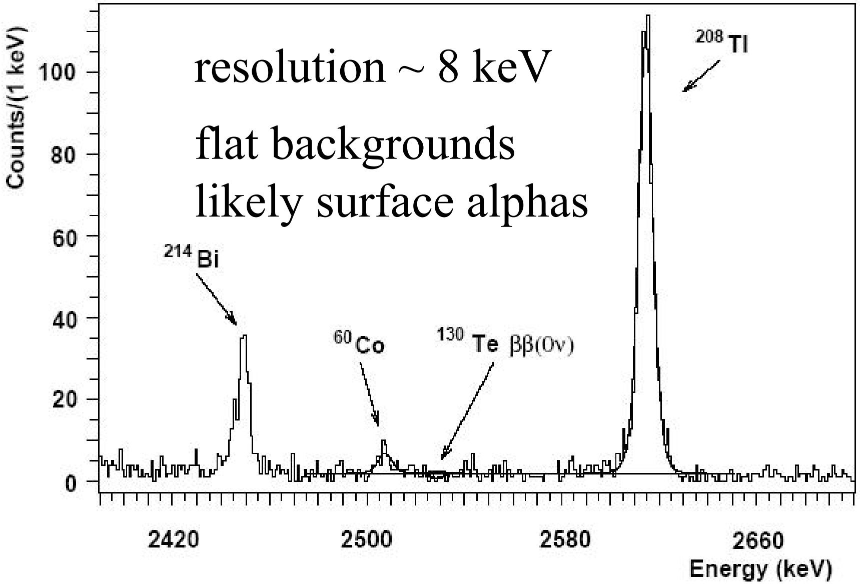
TeO2 tower under construction

130Te: CUORICINO and CUORE

CUORICINO: exposure to date = 10.85 kg yr (~20% of Heidelberg-Moscow) Live time ~ 75%, so exposure should surpass H-M soon.

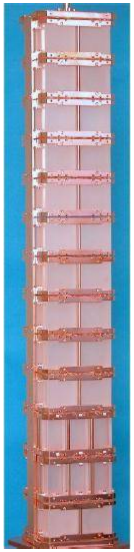
Current result: $\langle m_\nu \rangle < 0.2 - 1.1$ eV

CUORICINO energy spectrum

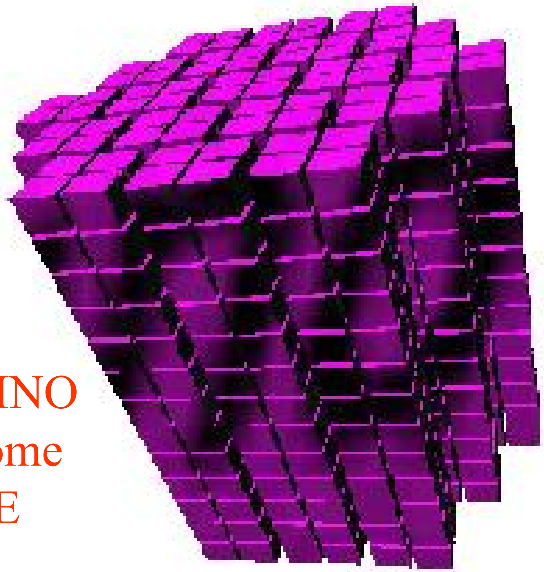


resolution ~ 8 keV

flat backgrounds
likely surface alphas



CUORICINO will become CUORE

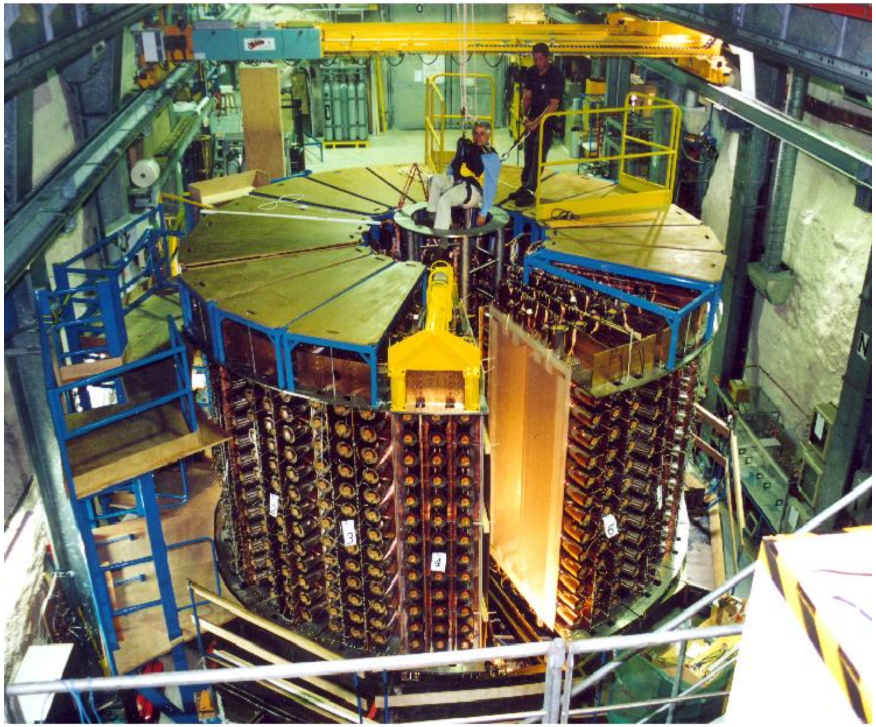


CUORE will consist of multiple CUORICINO-type towers.

Total mass = 741 kg (34% 130Te)

Neutrino mass sensitivity ~ 30 meV

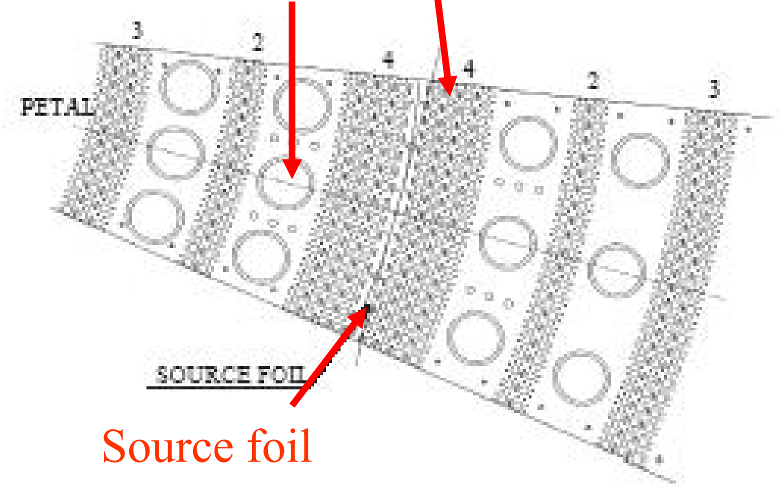
100Mo and 82Se: NEMO-3



France, Russia, Japan, US, Czech Republic, currently taking data in Frejus, France.

NEMO is designed to investigate the ββ0ν mechanism: multiple isotopes and electron angular distribution.

Passive isotope on thin foils surrounded by Geiger mode drift cells for electron tracking and plastic scintillator for energy measurement.



Source foil

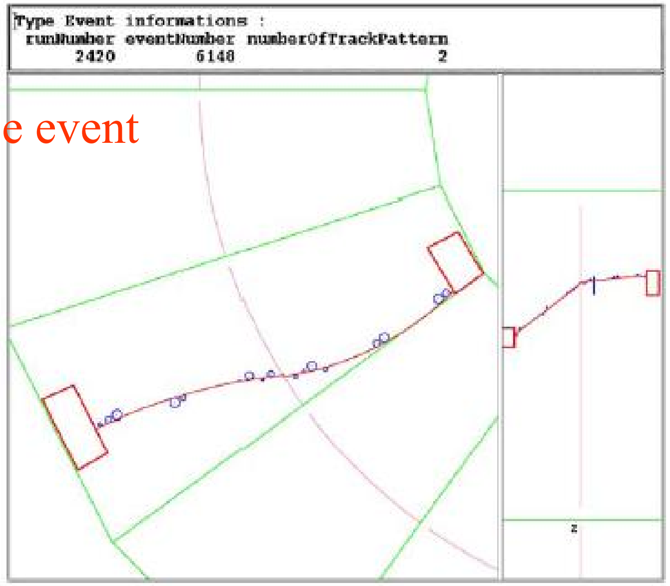
25 Gauss magnetic field measures β charge.

Tracking provides powerful background rejection, but thin foil sources are more difficult to scale up. (NEMO-3 has 10 kg of isotope). Moderate energy resolution: FWHM = 150 keV for 1 MeV electrons.

100Mo and 82Se: NEMO-3

6.9 kg of 100Mo and 0.93 kg of 82Se for ββ0ν search.

Other isotopes for ββ2ν measurements and background studies.



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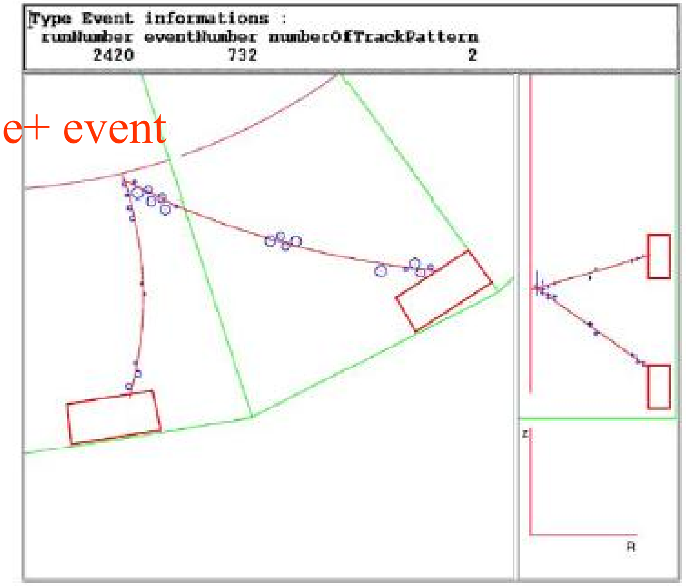
e-e event



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Type Event informations :
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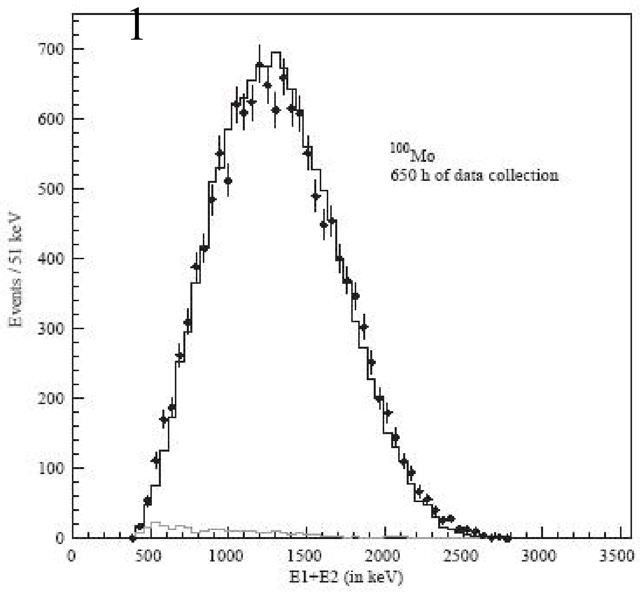
e-e+ event

100Mo and 82Se: NEMO-3

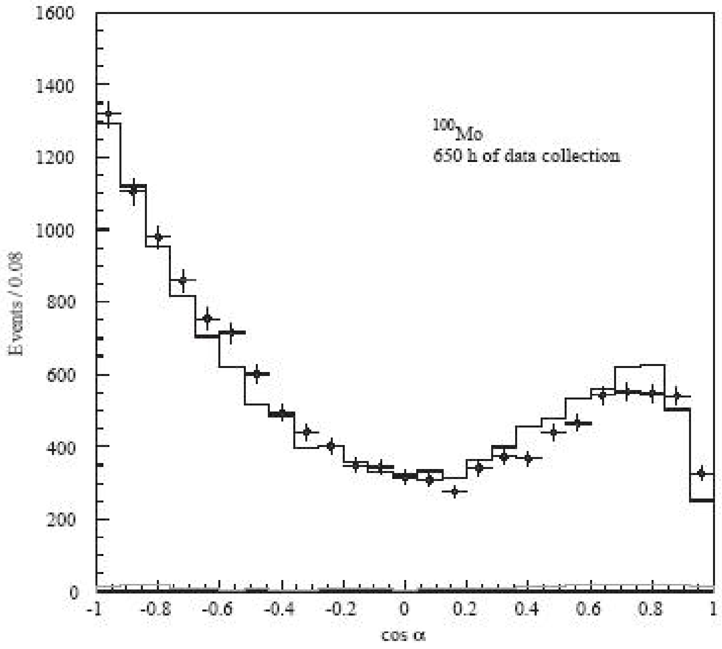
Energy spectrum and angular distribution agrees beautifully with ββ2ν expectation for 100Mo.

NEMO-3 is the world’s most sensitive 100Mo experiment, and has also measured ββ2ν half lives for 82Se, 116Cd, and 150Nd

100Mo ββ2ν energy spectrum



100Mo ββ2ν angular distribution



The NEMO collaboration has proposed a 100 kg experiment called Super-NEMO, with neutrino mass sensitivity of 30 meV.

136Xe: Enriched Xenon Observatory (EXO)

200 kg of isotope: 80% 136Xe

US, Canada, Switzerland, Italy, Russia

Noble gas - easy to enrich and purify.
Monolithic detector – minimal surface area.
Good rejection for Compton scatters, alpha decay.
No long lived isotopes to activate.
Drawbacks: moderate energy resolution,
new technology.

EXO clean rooms at Stanford

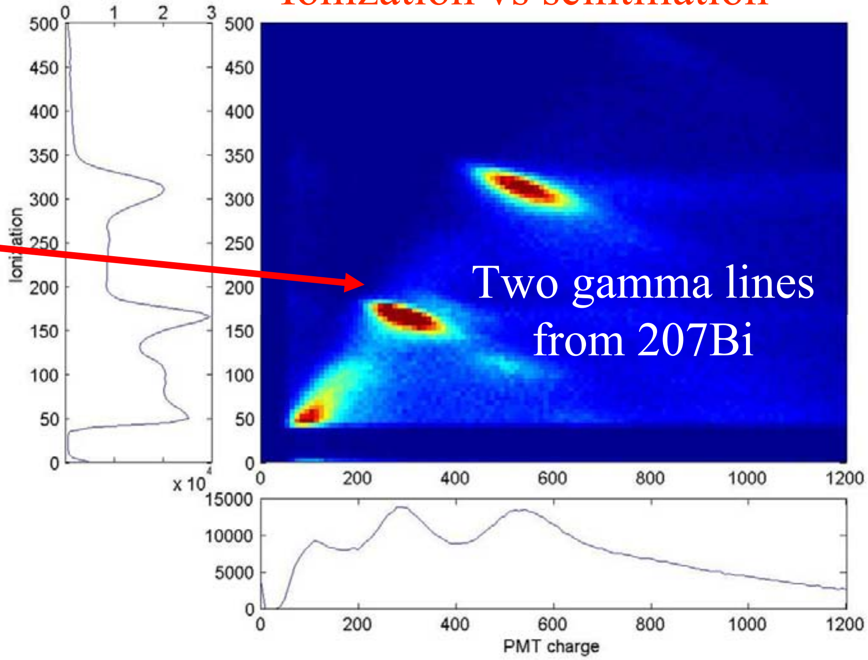
EXO is constructing a 200 kg liquid Xe TPC to be located underground at WIPP in Carlsbad, NM.

Experiment will be assembled and commissioned inside the clean rooms at Stanford, then the clean rooms will move to WIPP for physics data taking.

136Xe: EXO 200 kg prototype

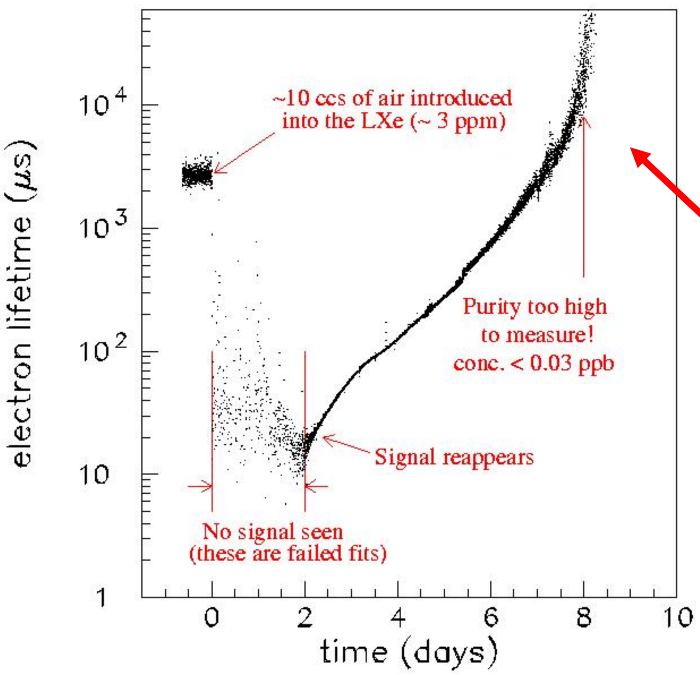
EXO R&D has shown that xenon energy resolution can be improved from 120 keV to 80 keV FWHM using the anti-correlation of scintillation and ionization, with further improvement expected.

Ionization vs scintillation



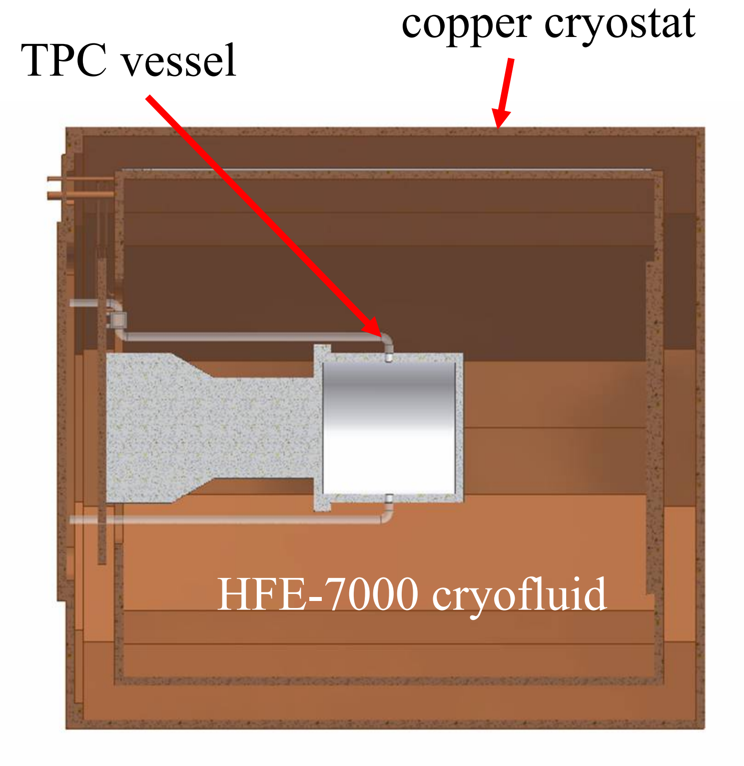
Two gamma lines from 207Bi

LXe purity with recirculation, May 17-25

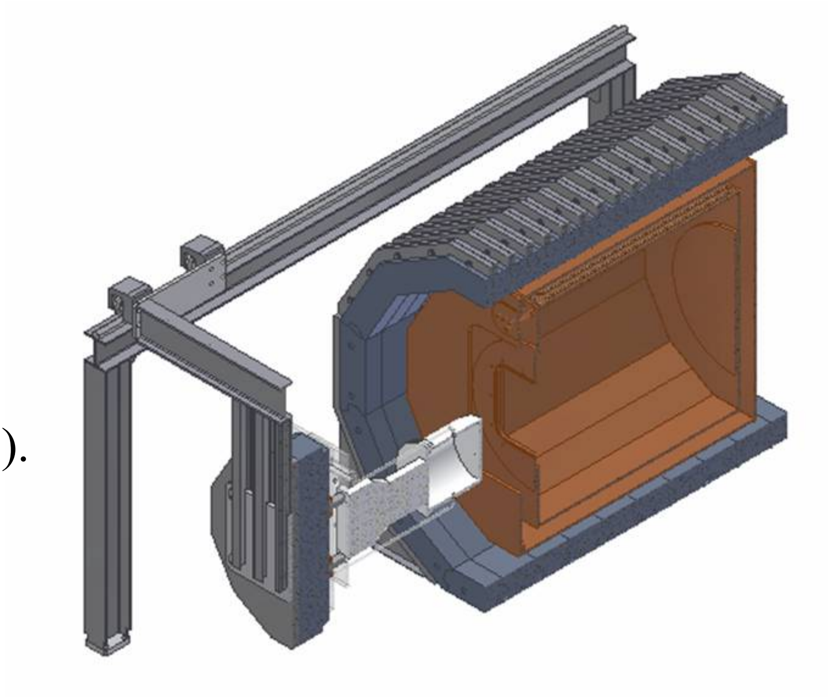


Re-purification of xenon works well – purity recovers completely within one week from an intentional poisoning with 10 ccs of air.

136Xe: EXO 200 kg prototype



LXe TPC to be contained in low background vessel, surrounded by 50 cm of ultra-pure cryofluid inside a copper cryostat and shielded by 25 cm of lead.

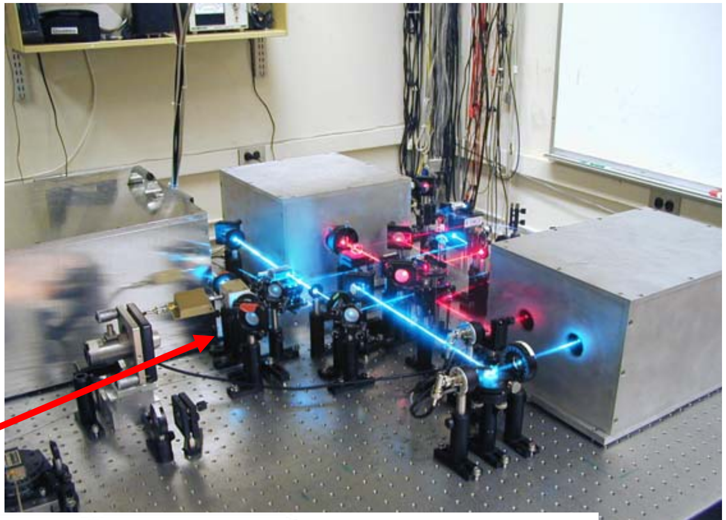


Cryostat fabrication begins next month (France). Design of lead shielding, electronics, and TPC electrostatics is in advanced stages.

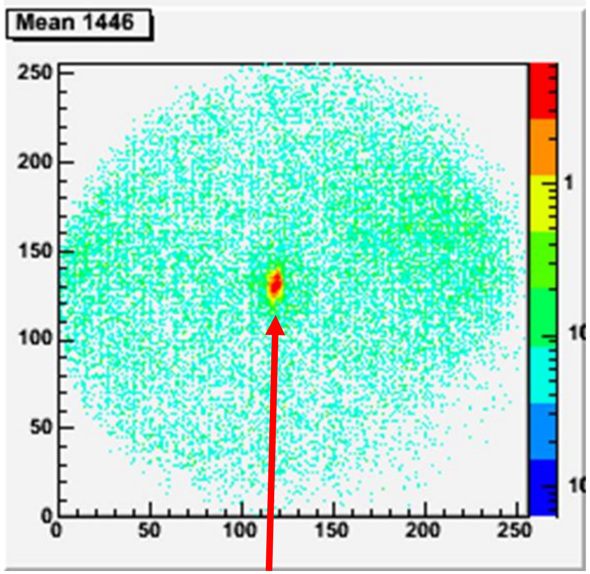
136Xe: Ton-scale EXO with barium tagging

EXO intends to build a ton-scale background free $\beta\beta0\nu$ experiment by tagging the final state barium ion event-by-event.

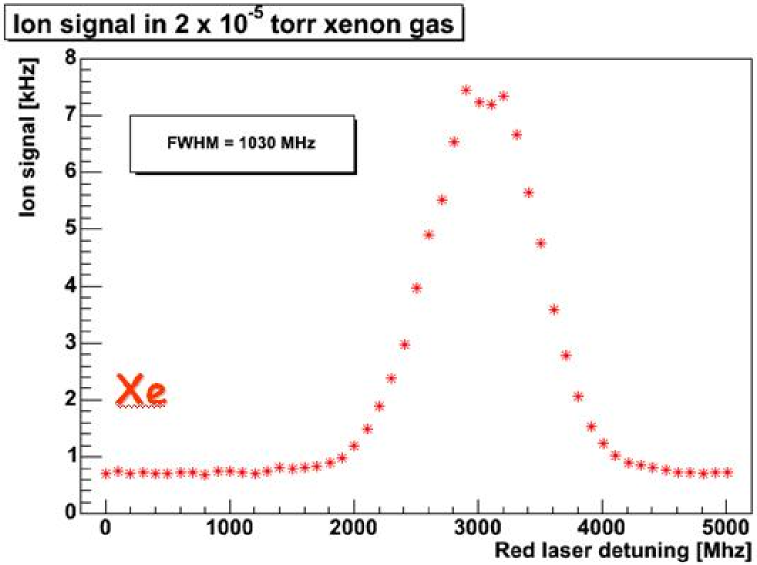
Barium unique atomic spectroscopy makes it possible to “see” a barium ion with the naked eye.



blue and red lasers needed for the spectroscopy

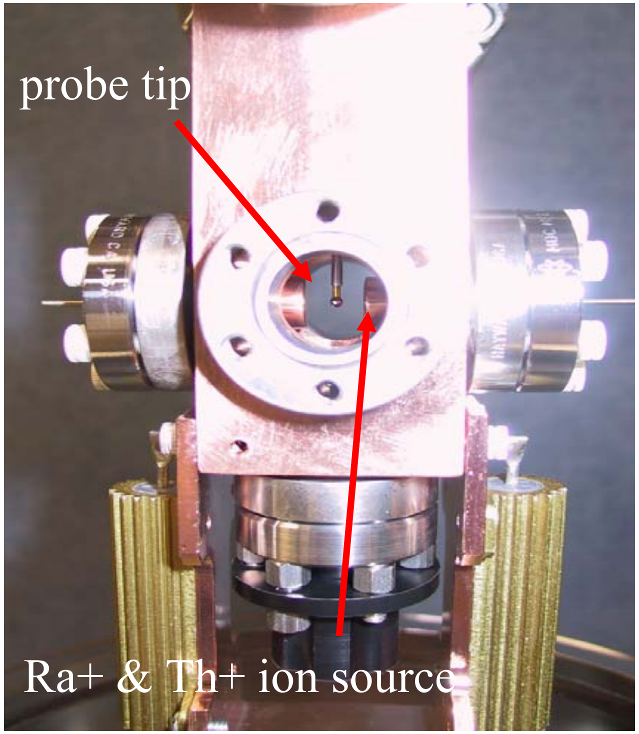


A photo of a single Ba+ ion in vacuum



Ba+ ion resonance in a Xe buffer gas

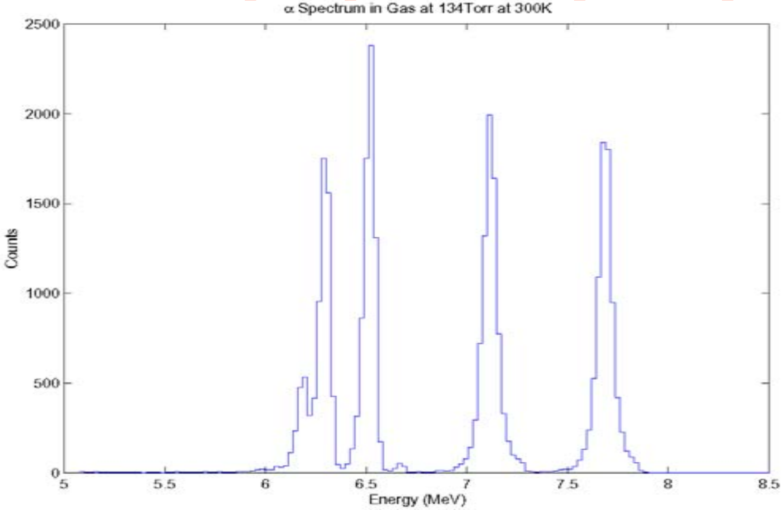
136Xe: Ton-scale EXO with barium tagging

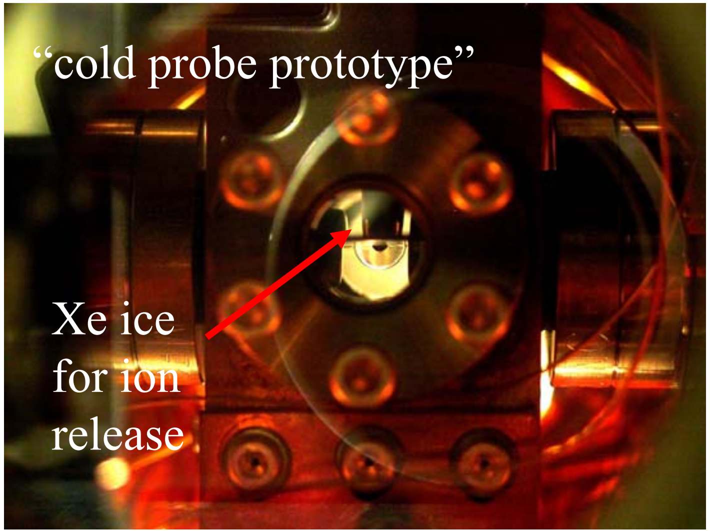


The biggest remaining hurdle to barium tagging is the delivery of the Ba+ ion from liquid Xe to the spectroscopy trap.

Our prototype electrostatic probe has shown that the we can ‘grab’ ions in liquid xenon. Must now demonstrate efficient ion release and trap loading.

Observed alpha spectrum on probe tip





Collaborations around the world are forming to build ambitious experiments with a wide variety of techniques.

Degenerate hierarchy (100 – 300 meV): 3 to 5 years with 100 kg scale experiments

Inverted heirarchy (~50 meV): 5 to 10 years with one ton experiments

Normal heirarchy (~ 5 meV): 10+ years with ten ton experiments.

Future looks bright for double beta decay.

The neutrino physics of double beta decay (in red):

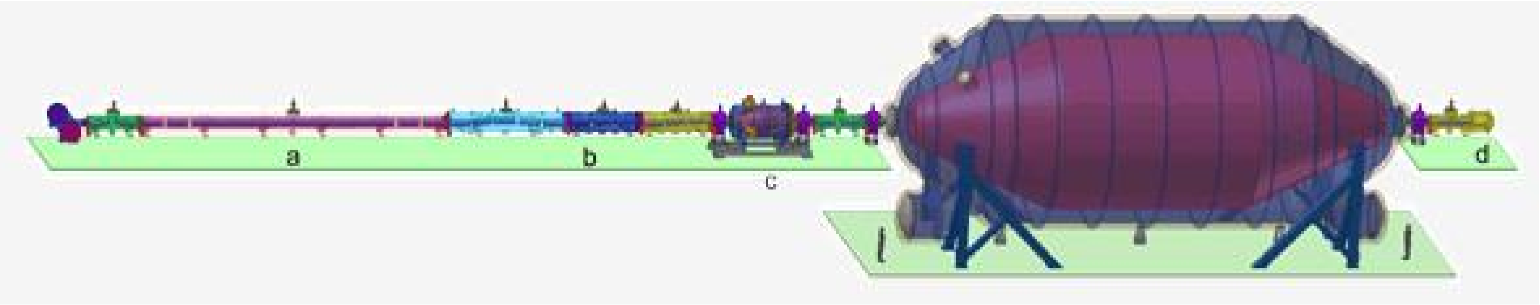
1. What are the masses of the neutrinos?
2. What is the pattern of mixing among the different types of neutrinos?
3. Are neutrinos their own antiparticles?
4. Do neutrinos violate the symmetry CP?
5. Are there sterile neutrinos?
6. Do neutrinos have exotic properties (dipole moments, neutrino decay, ect.)?
7. What do neutrinos have to tell us about the intriguing proposals for new models of fundamental physics?
8. What is the role of neutrinos in shaping the universe?
9. Are neutrinos the key to the understanding of the matter-antimatter asymmetry of the universe?
10. What can neutrinos disclose about the deep interior of astrophysical objects and the mysterious sources of very high energy cosmic rays?

Recommendation #1: "We recommend, as a high priority, a phased program of sensitive searches for neutrinoless nuclear double beta decay."

*APS Multidivisional Neutrino Study, November 2004

What we can learn from double beta decay:
(1) Are neutrinos their own antiparticles (Dirac or Majorana)?

We must search for ββ0ν even if neutrinos are Dirac:
Observation of ββ0ν = Majorana neutrinos
Observation of neutrino mass kinematically + non-observation of ββ0ν = Dirac neutrinos



The KATRIN experiment is a next generation (2008) beta endpoint spectrometer,
and is expected to be sensitive to neutrino masses > 0.2 eV.

What we can learn from double beta decay:
(2) What are the masses and mass hierarchy of the neutrinos?

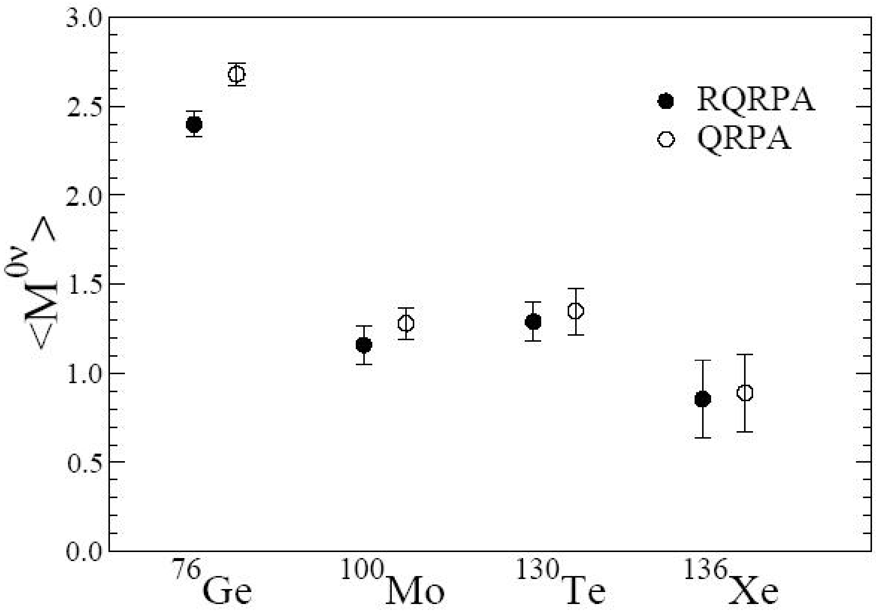
ββ0ν matrix element calculations are known for having large errors (~300%), but we have reason to be optimistic.

*PRC **68** 044302 (2003)

Rodin, *et. al.* *:

- fix the strength of the particle-particle interaction to reproduce the observed ββ2ν decay rates

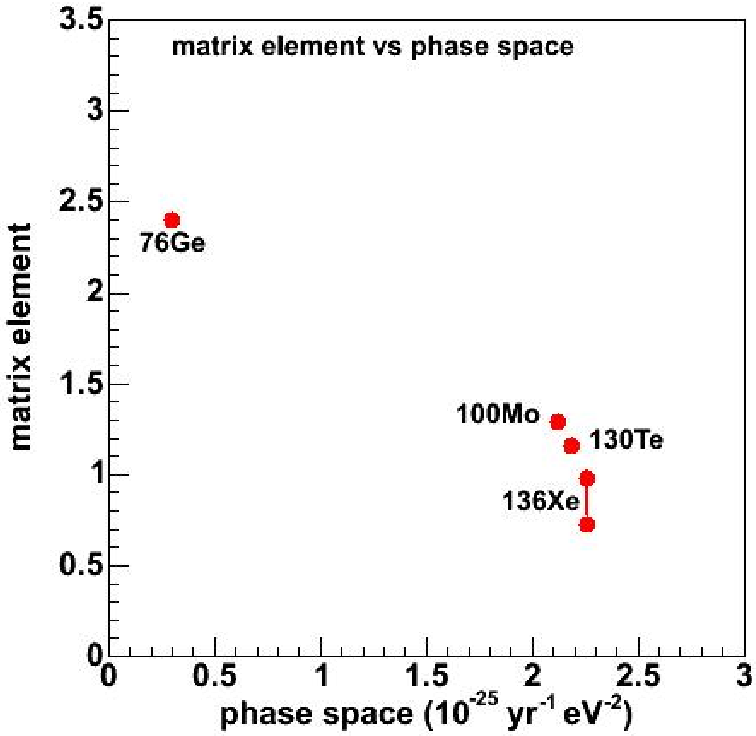
- then the ββ0ν matrix element depends weakly on the number of the single particle states used, and weakly on the calculation method (QRPA or RQRPA).

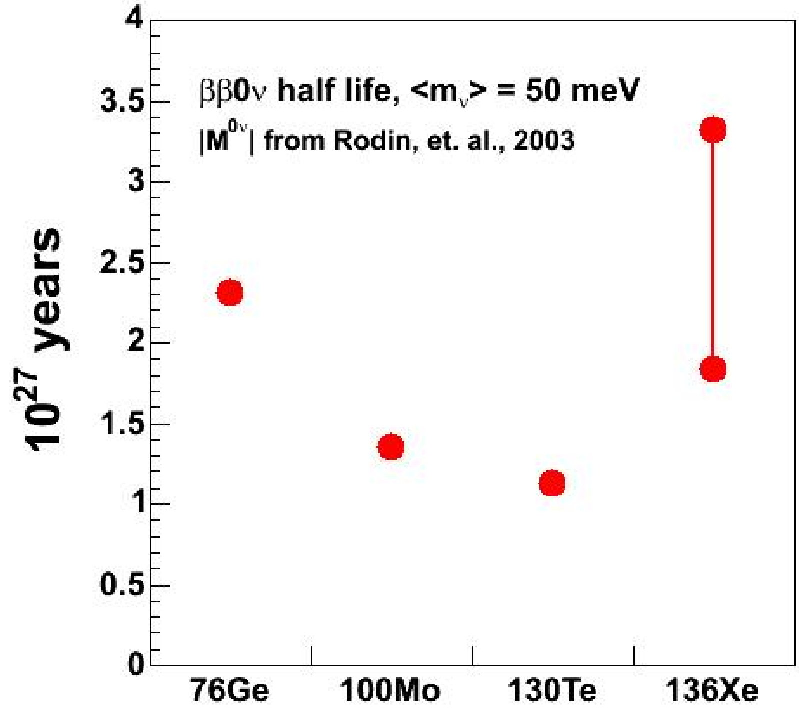


Such a prescription can only be confirmed by observing ββ0ν in multiple isotopes.

Desirable properties for a ββ0ν candidate isotope: Large matrix element and phase space

Decay rate = phase space × |nuclear matrix element|^2 × |effective neutrino mass|^2

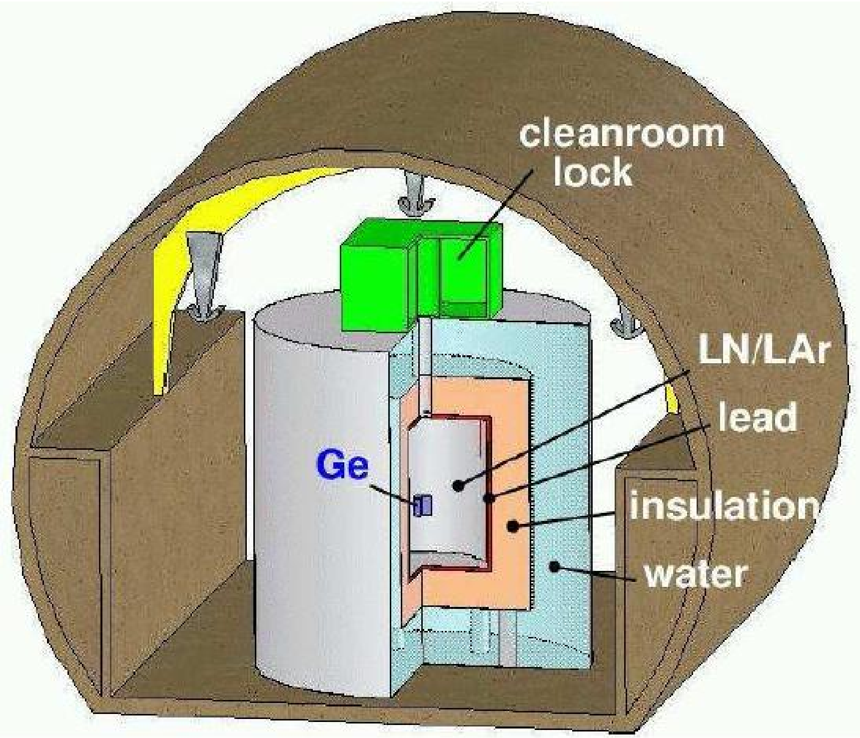




Note that different matrix element calculations can alter this picture.

Next generation 76Ge experiments: Heidelberg-Moscow successor at Gran Sasso

Italy, Russia, Germany



H-M backgrounds were mostly 238U and 232Th in the copper cryostats. A European collaboration proposes to reduce them by operating the crystals directly in LN or LAr, which can be high purified of radioactivity.

The Gran Sasso and Majorana collaborations will likely merge to build a single global 500 kg germanium experiment.

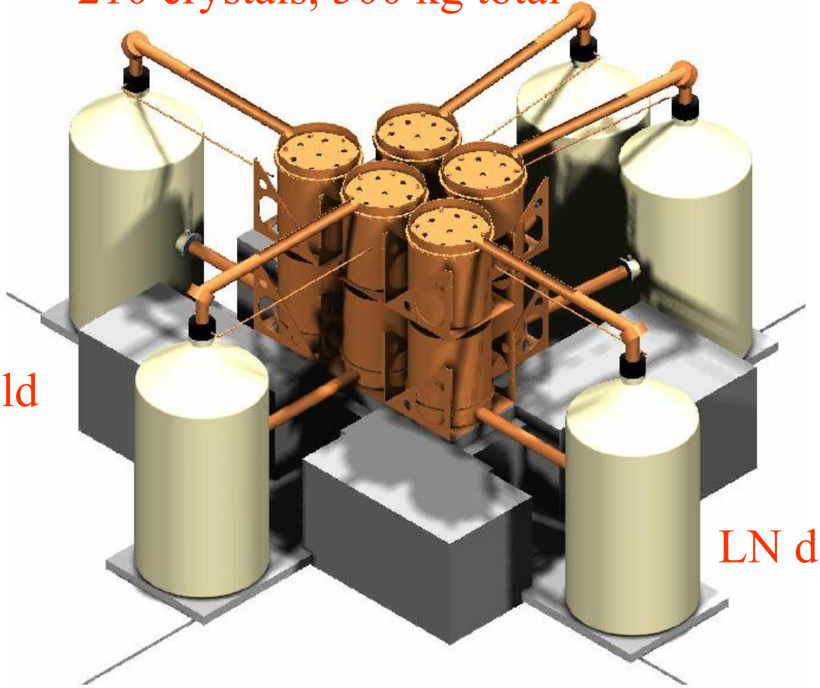
Next generation 76Ge experiments: Majorana

US, Russia, Japan

Majorana is a successor to IGEX, whose dominant backgrounds were cosmogenics in the germanium.

Majorana aims to suppress cosmogenics through crystal segmentation and underground diode production.

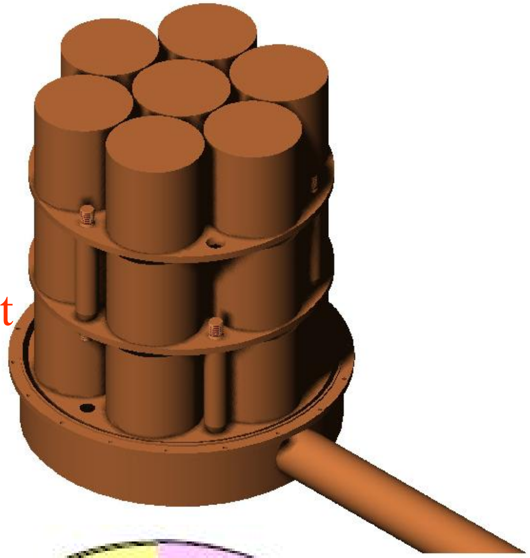
210 crystals, 500 kg total



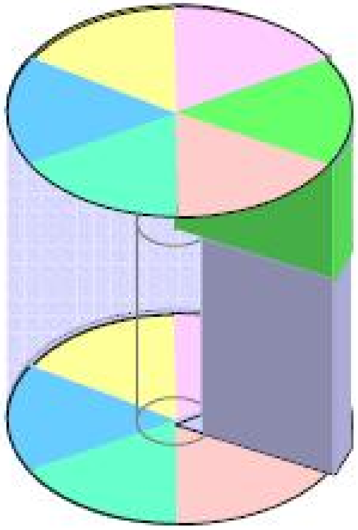
Pb shield

LN dewar

21 Ge diodes,
2.35 kg each



copper cryostat



Segmentation (6x2) results in 2500 individual 200g segments