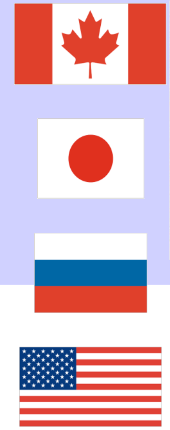
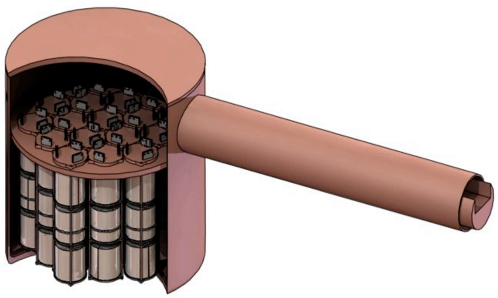
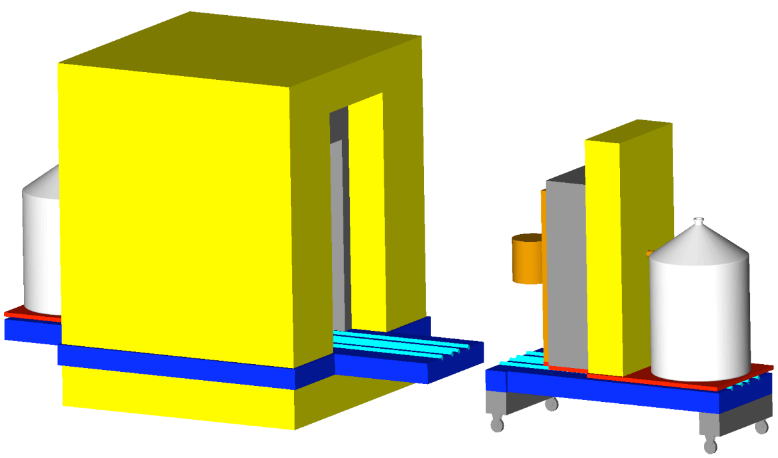
MAJORANA Status and Overview

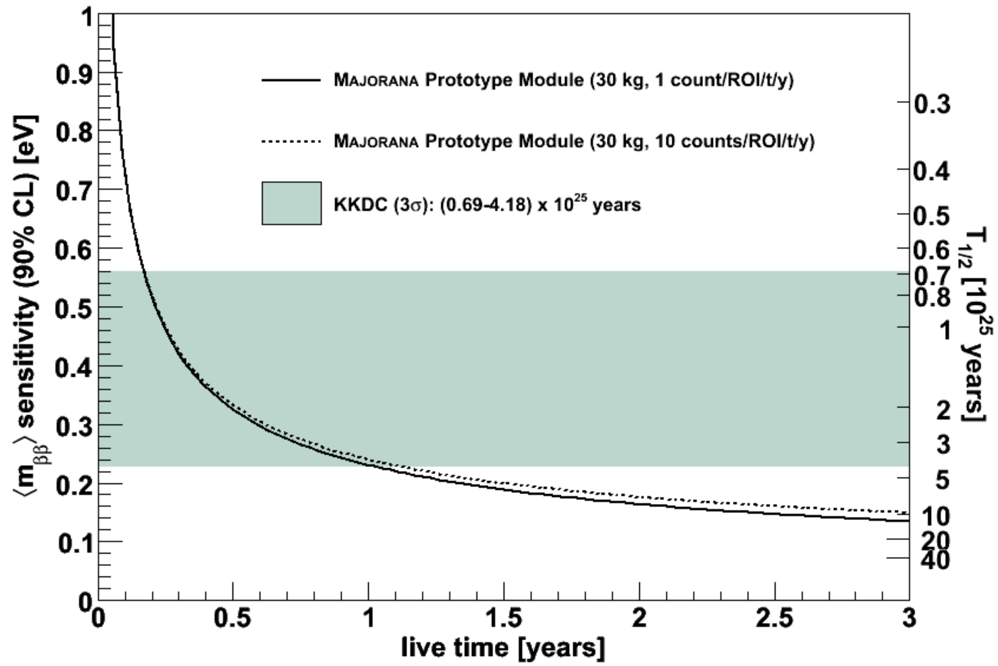


Steve Elliott

Los Alamos National Laboratory







Outline

- Double Beta Decay
  - Hope you saw summaries and overviews by Kayser, Petcov, and Hirsch
- MAJORANA overview
- Recent MAJORANA progress
- Schedule

Strengths of Ge detectors for $0\nu\beta\beta$

^{76}Ge offers a good combination of capabilities and sensitivities.

- **Favorable nuclear matrix element**
  - **e.g. $\langle M^{0\nu}\rangle$=3.9 [Rodin *et al*. 2005, erratum], 2.6 [Caurier *et al*. 2007]**
- **Slow $2\nu\beta\beta$ rate ($T_{1/2}$ = 1.4 × 10^{21} y)**
- **Demonstrated ability to enrich from 7.44% to 86%**
- **Ge is the source & detectors**
  - **Intrinsic high-purity Ge diodes**
  - **Elemental Ge maximizes the source-to-total mass ratio**
  - **Commercial Ge diodes**
  - **Well-understood technologies**
  - **Existing, well-characterized large Ge arrays (*e.g.* Gammasphere)**
  - **Excellent energy resolution — 0.16% at 2.039 MeV, 4-keV ROI**
    - **Great advantage for improving signal-to-background**
- **Powerful background rejection technologies**
  - **Segmentation, granularity, timing, pulse shape discrimination**
- **Best current limit on $0\nu\beta\beta$ used Ge**
  - **IGEX & Heidelberg-Moscow $T_{1/2}$ > 1.9 × 10^{25} y**

MAJORANA Collaboration Goals

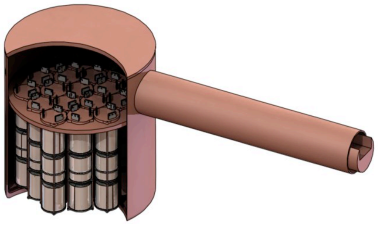
Actively pursuing the development of R&D aimed at a ~1 ton scale ^{76}Ge $0\nu\beta\beta$-decay experiment.

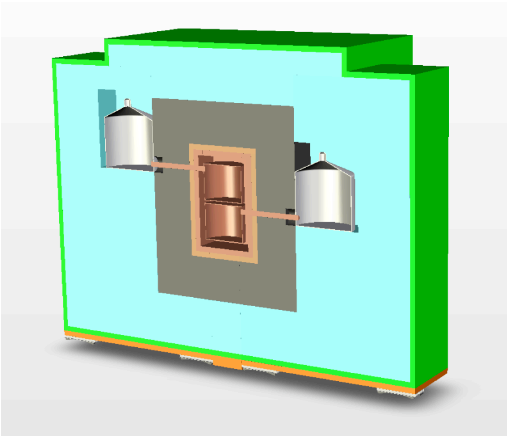
- Science goal: build a prototype module to test the recent claim of an observation of $0\nu\beta\beta$. This goal is a litmus test of any proposed technology.
- Demonstrate background low enough to justify building a 1-ton experiment.
- Prepare for a down-select between the MAJORANA and GERDA technologies for a single international ton-scale Ge-based experiment.
- Pursue longer term R&D to minimize costs and optimize the schedule for a 1-ton experiment.

Our plan has been guided by advice from NuSAG, an independent external panel review (March 06), and a DOE $0\nu\beta\beta$ pre-conceptual design review panel (Nov. 06)

The MAJORANA Demonstrator Module

- Reference Design
  - Based on 60-kg of Ge detectors.
    60-kg required for sensitivity
    to background goal.
  - At least 30-kg of 86% enriched ^{76}Ge
    crystals. Required for science goal.
  - A mix of p-type and n-type crystals.
    Required to cover range of detector possibilities
    Some crystals segmented.
  - The module design is naturally scalable,
    with independent, ultra-clean,
    electroformed Cu cryostat modules.
  - Enclosed in a low-background passive
    shield and active veto, Located deep underground (≥ 4500 mwe).





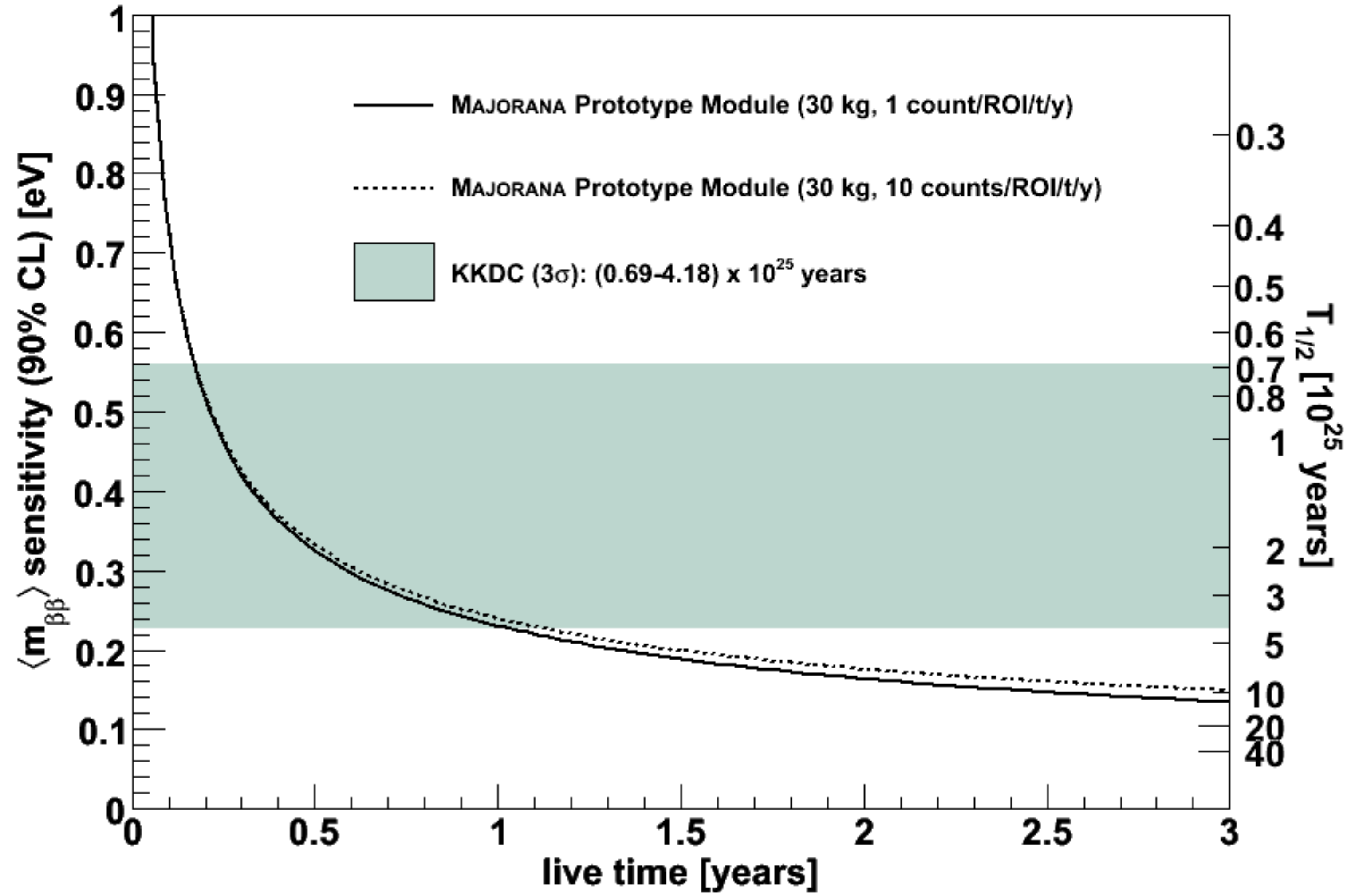
- Expected Sensitivity to $0\nu\beta\beta$
  (for 30 kg enriched material, running 3 years, or 0.09 t-y of ^{76}Ge exposure)

    $T_{1/2} \geq 10^{26}$ y (90% CL).

    Sensitivity to $\langle m_\nu \rangle$ < 140 meV (90% CL) ([Rod05,erratum] RQRPA NME).

    Able to confirm/refute KKDC 400 meV value.

MAJORANA Demonstrator Module Sensitivity



Some key questions

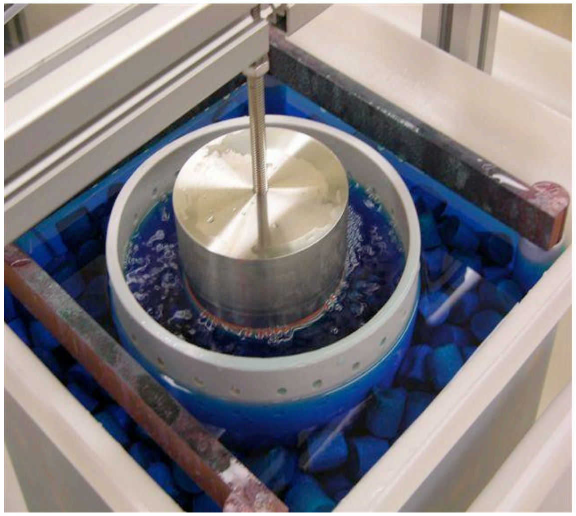
For the demonstrator module

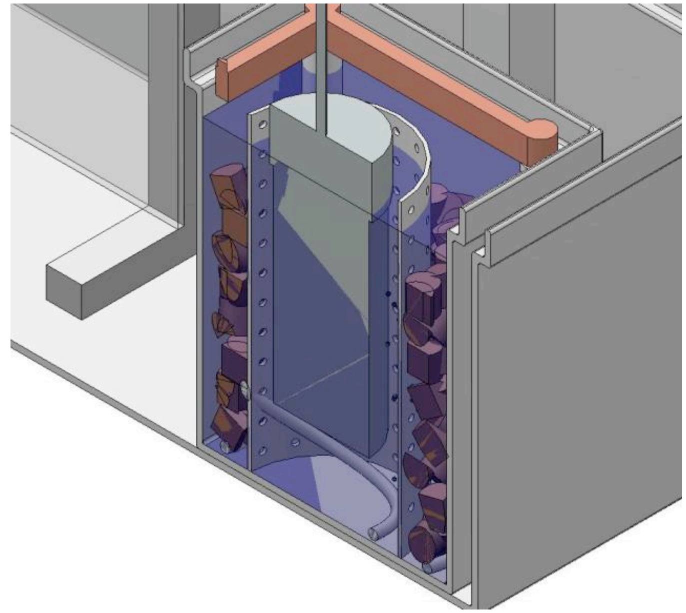
- **Is copper pure enough?**
  - **Can we electroform underground and does it help?**
- **Can large cryostats be built and operated?**
  - **Can detectors cool by radiation?**
- **What is the optimum detector configuration?**
  - **Point contact detectors, modestly segmented, highly segmented?**
  - **How well does segmentation help with background rejection?**
- **Can small parts/cables be made pure enough?**

For a 1-ton project

- **Can the cost of detectors be lowered?**
- **Can the cost of enrichment be lowered?**

Electroforming and Cu Purity - Material purity





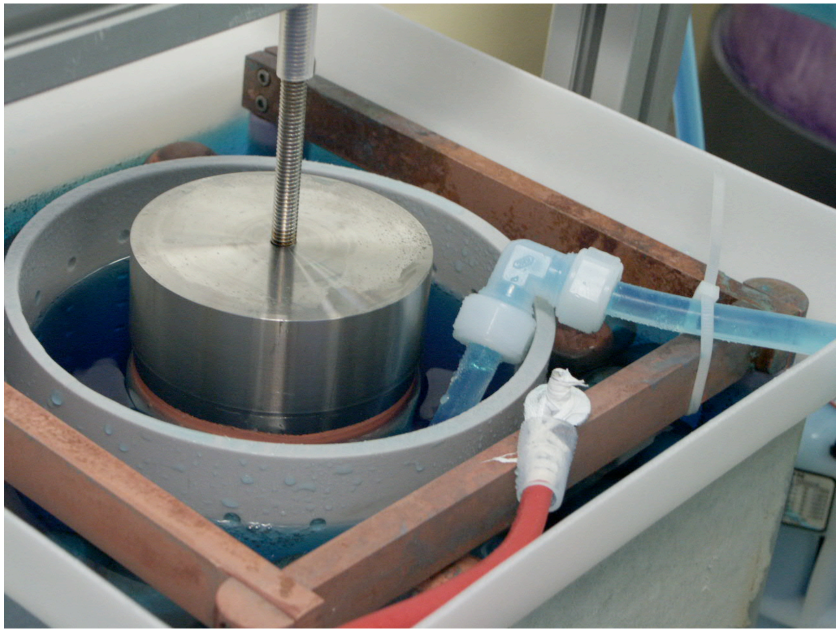
Copper Production

- Plating to several cm without machining
- Presently plating 2-5 mil/day
- Developing configurations, waveforms, recipes to improve buildup rate
- Purity limitations vs. buildup rate will come from ^{228}Th tracer studies.

Copper Cleanliness

- Assay data indicates that $CuSO_4$ in bath is source of Th in part
- Producing our own $CuSO_4$ from pure starting materials has been more successful in producing clean Cu then re-crystalizing the $CuSO_4$.
- Initial ICPMS study in 2005
  - 5-10 μBq/kg, limitation in materials, prep
  - Improved to 2-4 μBq/kg
  - Goal <1 μBq/kg

Underground electroforming at WIPP - Cu purity



Electroform a part underground

Electroformed Cu is extremely pure, very little Th/U. By electroforming UG, the cosmogenic isotope Co-60 should be eliminated also

1. Demonstrate that one can safely form a part underground in a highly regulated environment
2. WIPP follows a strict safety protocol directed by DOE and MSHA
3. Low voltage system to plate Cu from 1.2 M acid solution onto SS mandrel

<u>Test Part</u>

Copper "Beaker" fabricated

660 gm

160 mm high, 110 mm diameter

Wall thickness ~1 mm

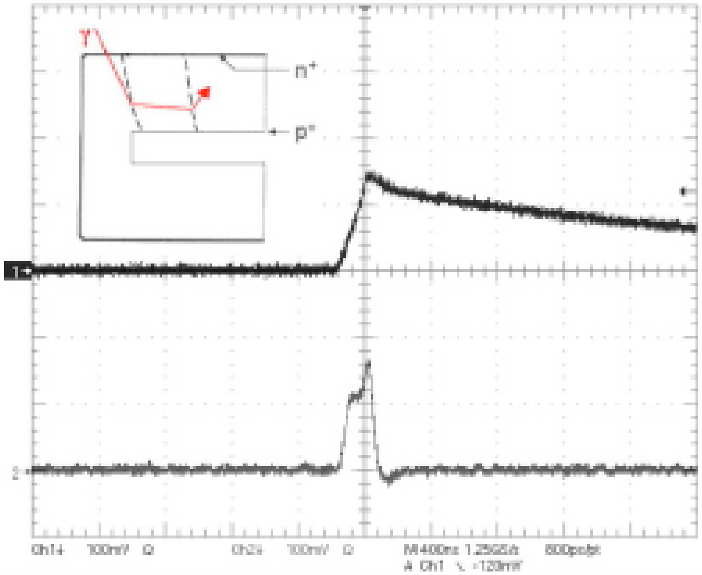
~10 days of UG electroforming in two stretches

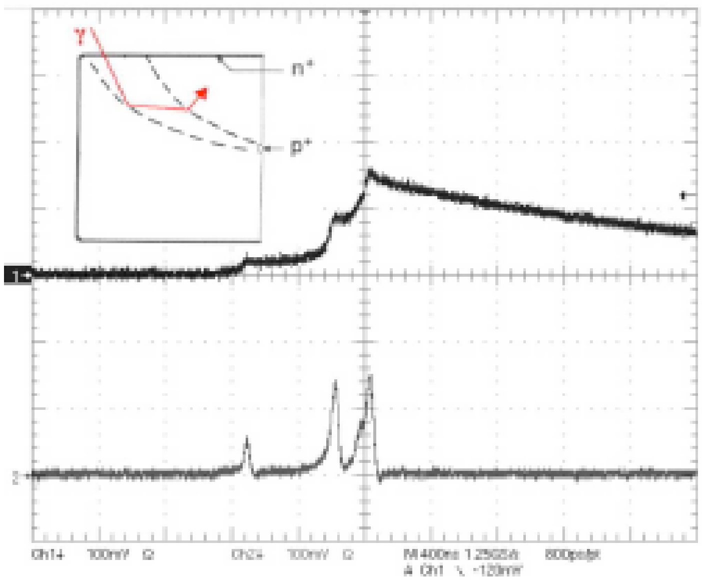
Solution is 1.5 kg copper sulfate dissolved in 16 L 1.2M sulfuric acid

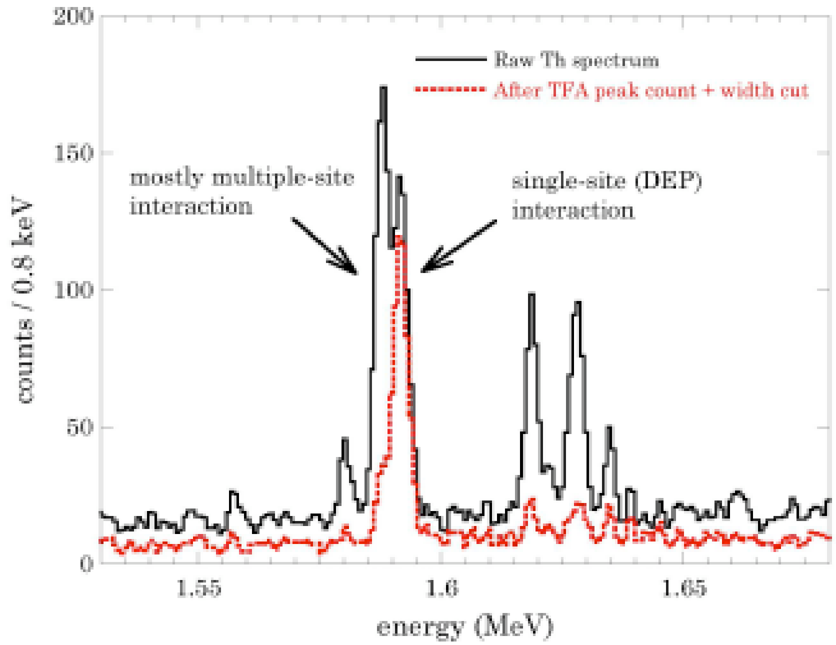
Part removed from mandrel by successive dunks in boiling water and liquid nitrogen

Point-Contact Detectors - Detector optimization

Barbeau et al., JCAP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36 , 926(1989)



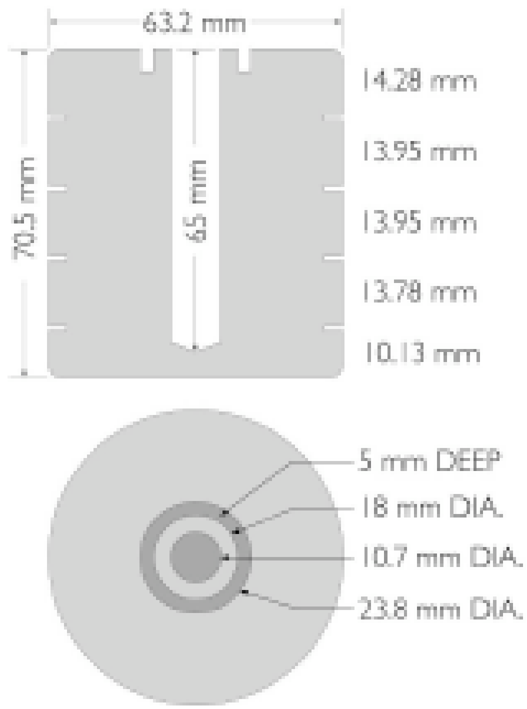


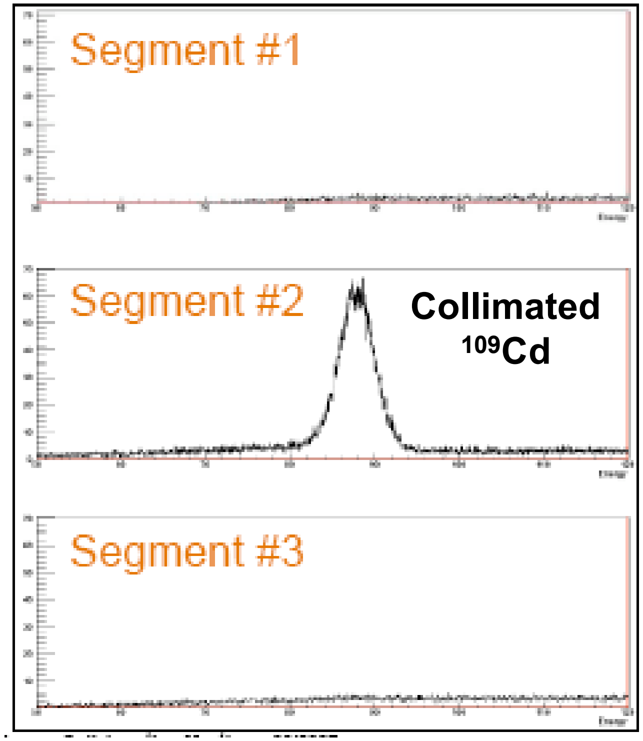


- The longer drift distance in the PPC stretches the pulse leading to a clear indication of a multiple site event.
- A solid p-type detector: easier to handle, instrument.
- But achieves much of advantage of segmented detectors.

Segmented p-type detectors - Detector optimization

King *et al.* arXiv:0706.0034

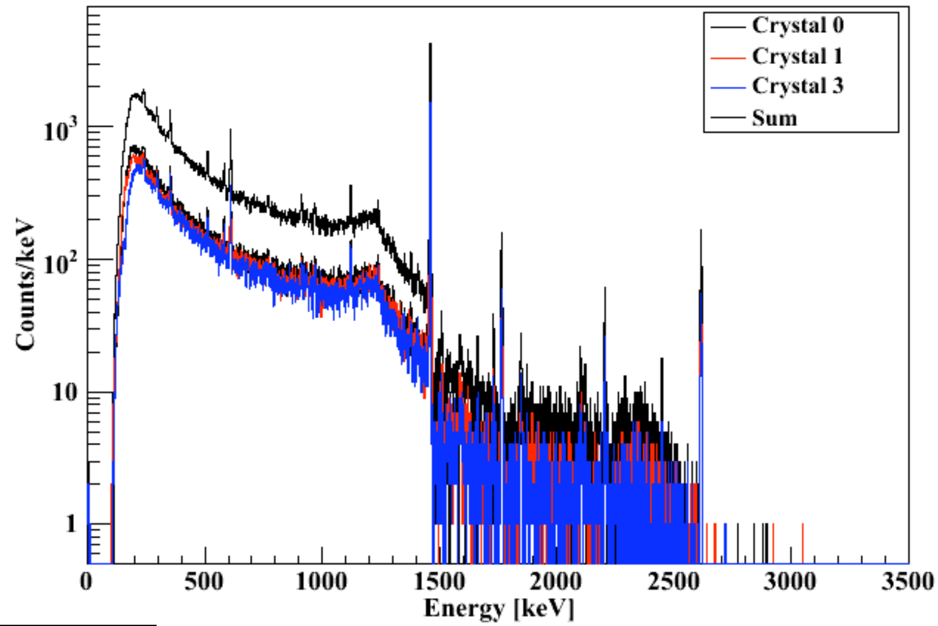




- Closed end, p-type semi-coaxial has been segmented by cutting groves through the Li-diffused dead layer and etching the groves
- The degree of segmentation has been tested with a collimated Cd source focused on 1 segment

- The efficacy of reducing background due to the ^{208}Tl 2.6-MeV γ ray near 2038 keV by a segmentation cut was measured
- Segmentation eliminated 59% of such events
- The shapes of the current pulses were unaffected preserving the ability to use PSD

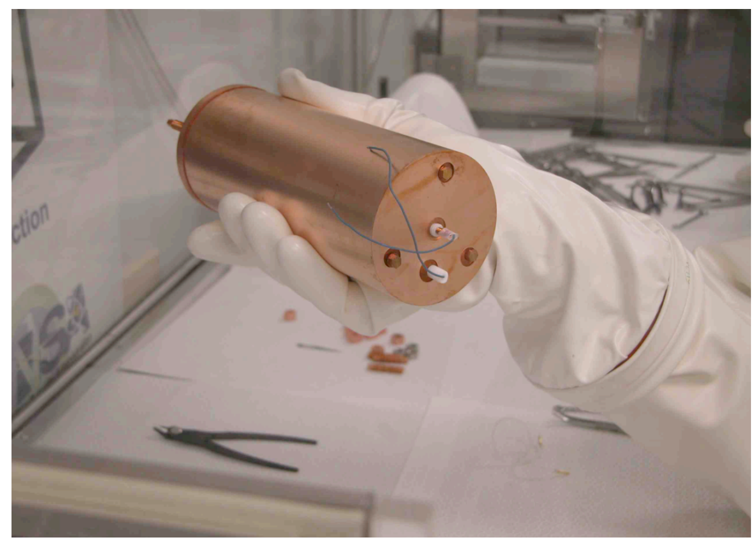
Low-background cryostat testing at WIPP - Large cryostats



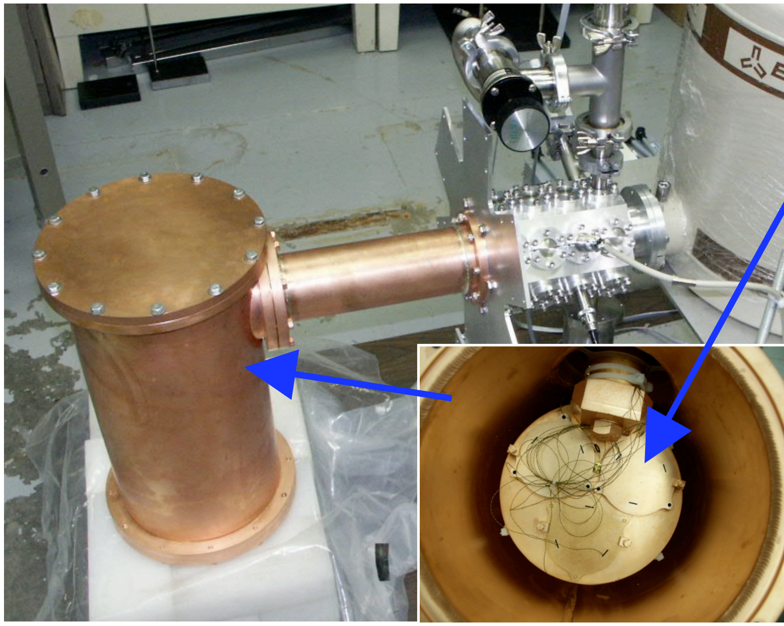
Progress in the MEGA cryostat

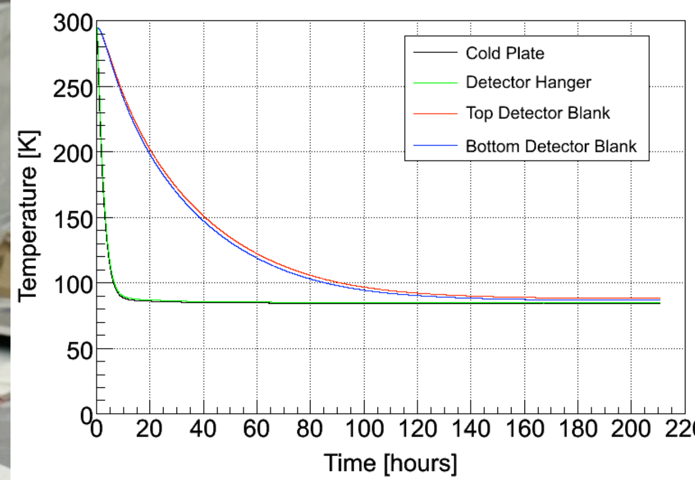
Installed and operated Ge detectors underground at WIPP in low-background apparatus

1. Installed Ge detectors in clean room environment
2. Connected and tested associated electronics
3. Brought system to vacuum and cooled with LN
4. Collected 17-hour background run from three Ge detectors



Test Cryostat for String Design - Large cryostats





Detector String

- Cryostat holds 3 strings - Each string holds 3 detectors
- Strings hang inside detector hanger

Goals

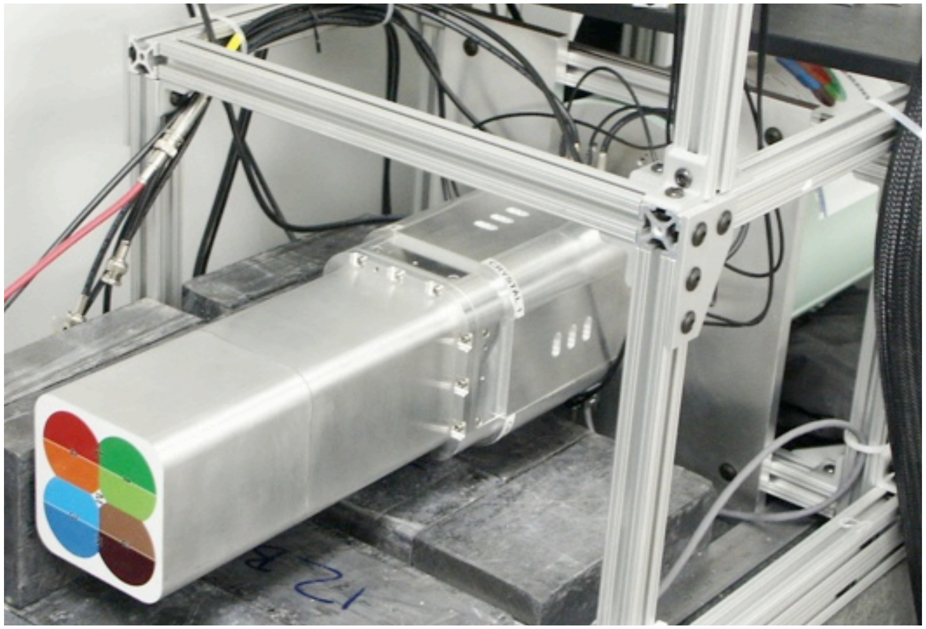
- Study thermal properties of the Majorana crystal cooling design
- Explore detector string design and mounting options
- Operate a string of cooled detectors under vacuum

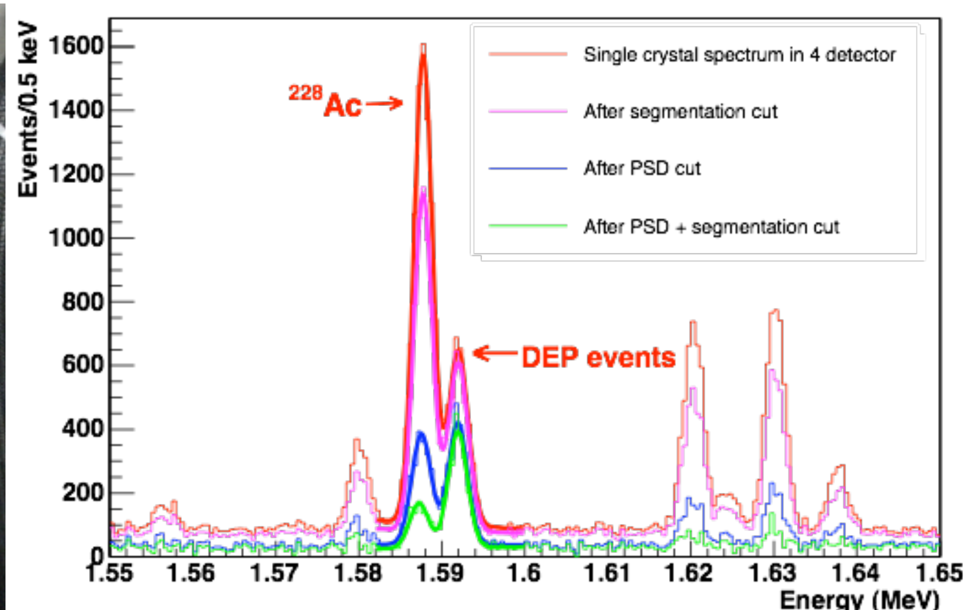
Thermal Test

1. Stainless steel “detector blanks” (above) similar thermal mass and emissivity of Ge crystals
2. Thermocouples mounted on blanks and copper parts show temperature response when cooled (above)
3. Successful cooling of blanks by radiation

PSA/Segmentation Independence - background rejection

Reference: NIM-A 558 (2006) 504





Pulse shape analysis and detector segmentation individually, are powerful ways to tag and reject multi-site backgrounds in HPGe detectors

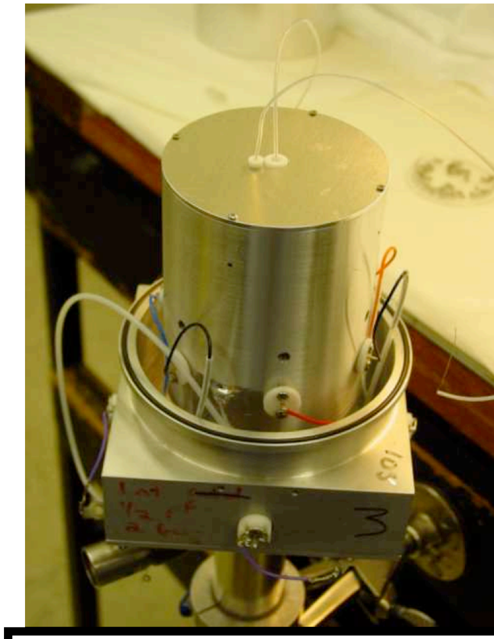
What is their affect when used in combination?

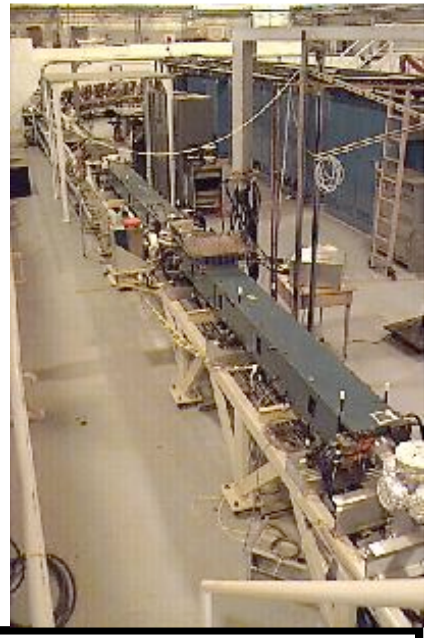
- Used experimental and Monte Carlo data to demonstrate ability to recognize energy depositions separated by 3-4 mm along field lines in CLOVER detectors with PSA
- Demonstrated <1.9 mm width for segmentation borders
- Combined pulse shape and segmentation analysis resulted in factor of 10 reduction in γ-ray lines and factor of 3 reduction in continuum events near $\beta\beta$ ROI

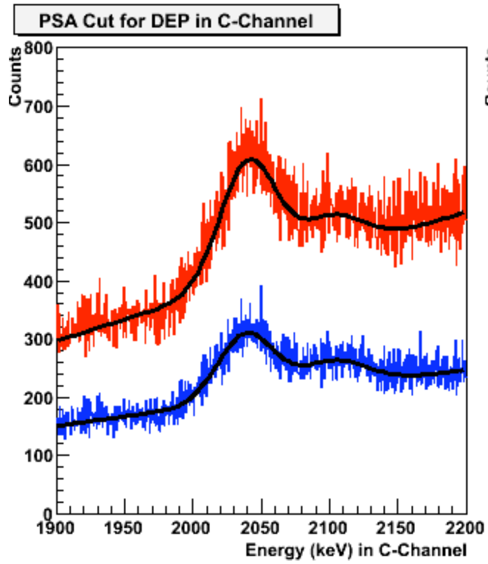
Survival Probabilities:

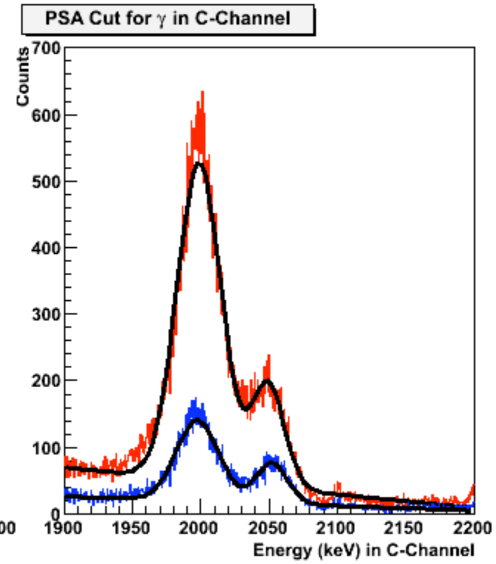
1588 keV γ-ray		
66 ± 1.4% (Segmentation)	20 ± 1.1% (PSA)	7 ± 0.5% (Combined)
1592 keV double-escape peak		
97 ± 2.7% (Segmentation)	20 ± 2.9% (PSA)	73 ± 4.5% (Combined)
2.0-2.1 MeV continuum		
81 ± 2.6% (Segmentation)	43 ± 3.1% (PSA)	30 ± 2.1% (Combined)

HIγS FEL Runs to Characterize SEGA - background/detectors









2 MeV DEP Survival: 59.7 ± 7.8%

2 MeV γ-Ray Survival: 27.9 ± 1.1%

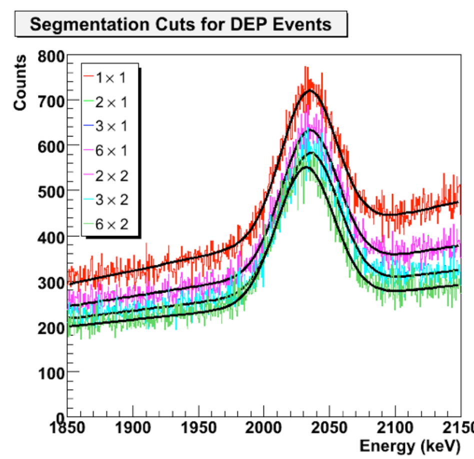
3 MeV γ-Ray Survival: 28.5 ± 0.4%

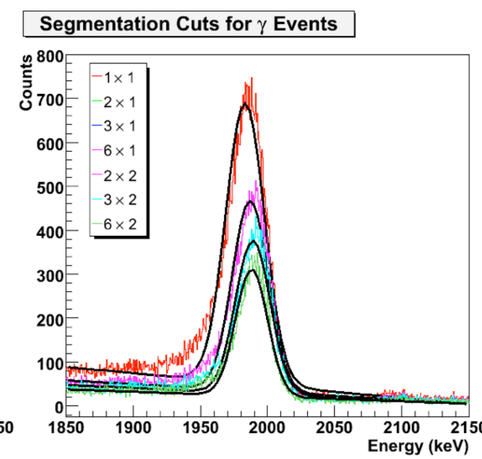
SEGA is the first segmented detector in the world made from enriched ^{76}Ge

The FEL can be used as a tunable energy γ-ray source to get γ-rays and DEPs at $Q_{\beta\beta}$

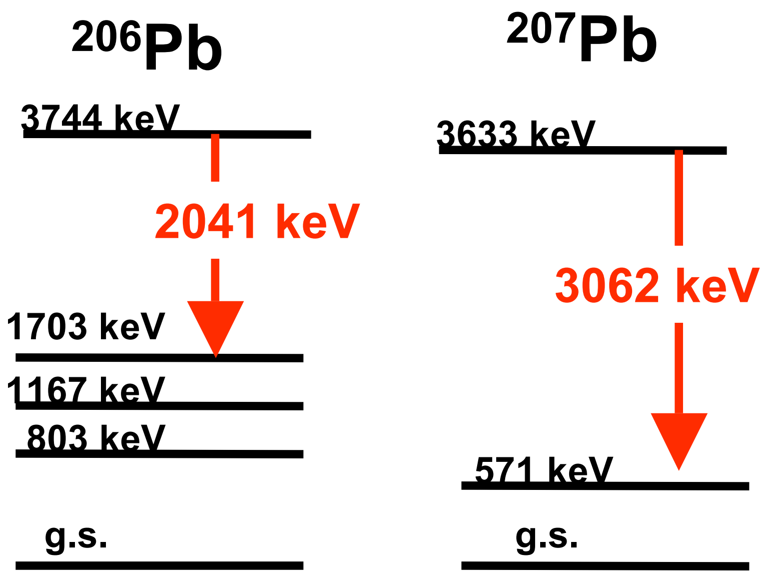
What is the background discrimination power of PSA and segmentation for γ-ray and DEP events at $Q_{\beta\beta}$?

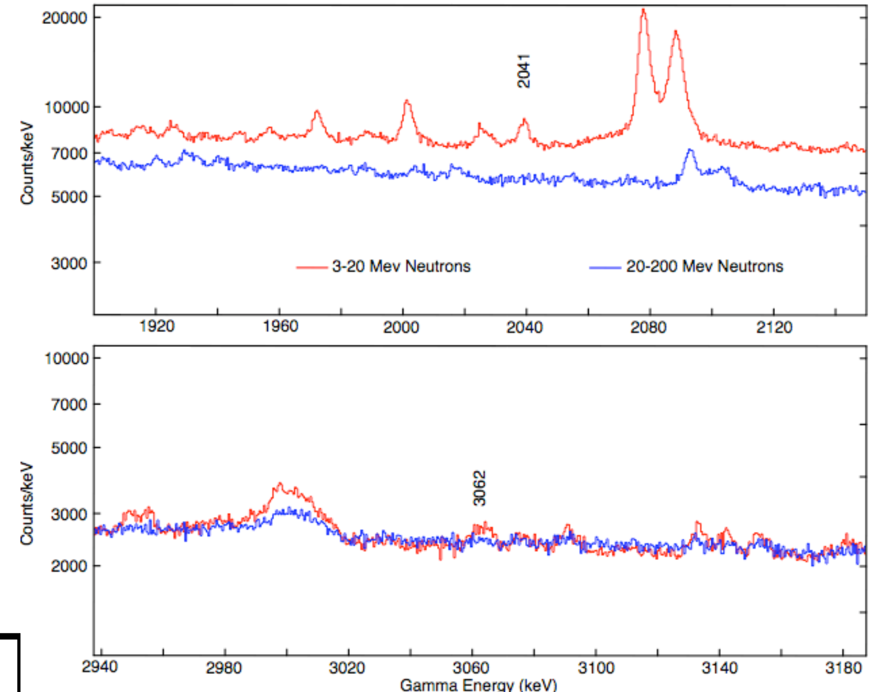
1. **Demonstrated PSA in SEGA detector for the first time**
2. **Used 6 x 2 (ϕ x z) segmentation to examine survival probabilities for several segmentation schemes for DEP and γ-ray events**
3. **Performance should improve after electronic and cryogenic upgrades**





New Levels of Sensitivity - New Backgrounds





Specific Pb γ rays are problematic backgrounds

^{206}Pb has a 2040-keV γ ray, and ^{207}Pb has a 3062-keV γ ray, backgrounds very close to the 2039-keV of 0νββ in ^{76}Ge

1. Neutron interactions in Pb excite these levels
2. The DEP of the 3062 is a single-site energy deposit similar to 0νββ, hard to reject
3. Cross sections are poorly known and hence simulation codes poorly describe them

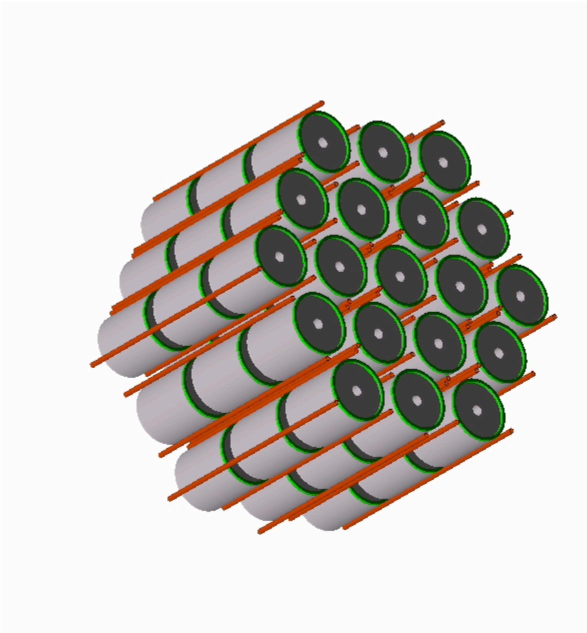
Neutron reaction studies

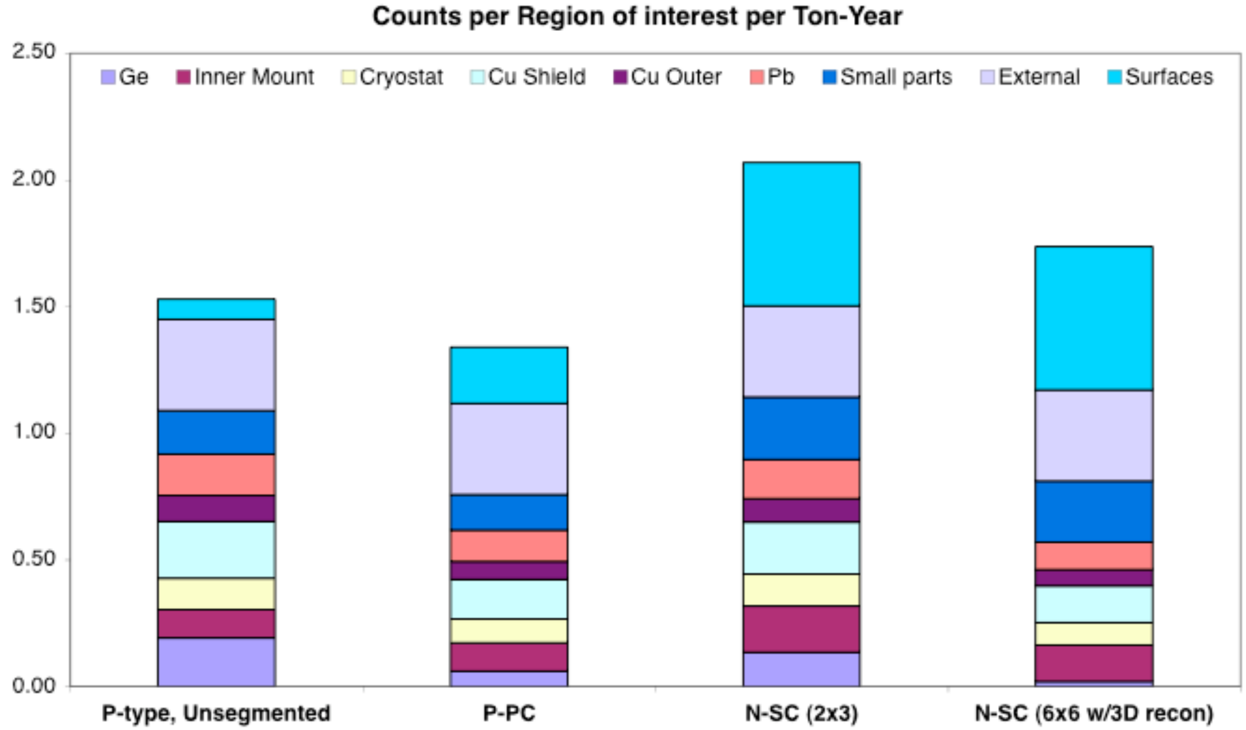
We discovered the lines and recognized their potential for creating background (arXiv:0704.0306)

We estimated the cross section

We initiated studies at LANSCE and TUNL to measure the cross sections with neutrons up to ~200 MeV in Pb, Cu and enriched Ge

Reference Design Backgrounds





- **Background modeling**
  - **Simulated major background sources for detector components in a 57-cystal array + shield using MaGe**
  - **Calculated total backgrounds individually for each detector technology under consideration**
- **Results**
  - **Cu purity of ~0.3 mBq/kg is required; sizeable contribution from ^{208}Tl in the cryostat and shield.**
  - **Higher rejection of segmented designs is roughly balanced by introduction of extra readout components.**
  - **P-PC appears to achieve the best backgrounds with minimal readout complexity.**

MAJORANA Schedule

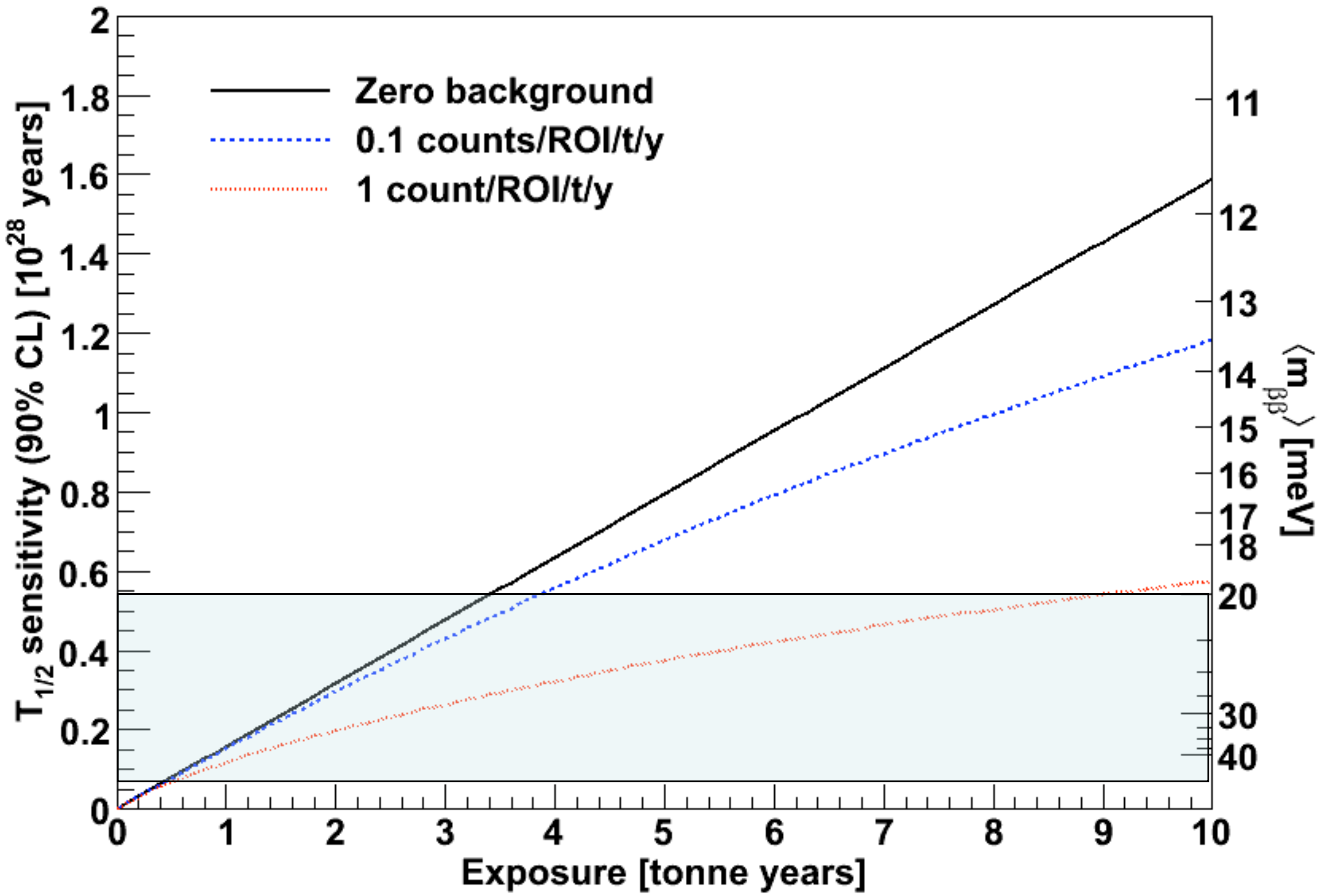
R&D Demonstrator

- **2008: finalize detector choice/cryostat design**
- **2008-09: installation of UG labs, begin e-forming Cu**
- **2009: purchase isotope**
- **2010-11: fabricate detectors, cryostats**
  - **Estimated cost ~$20M with most funding requested 09-11**
- **2011-12: begin data taking**
- **2013: technology down-select decision**
  - **Need for 1-ton experiment determined**

1-ton Detector

- **2013-14: develop final plan for 1-ton expt.**
- **2015-18: build 1-ton expt.**
- **2018-24: operate experiment, Steve Retires**

1-ton ^{76}Ge Sensitivity vs. Background

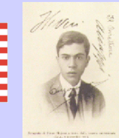


Recent Majorana technical progress

- Material studies
  - Development of improved techniques to electroform large, ultra-clean Cu cryostats (Hoppe *et al.*)
  - Electrofromed test part underground at WIPP
  - Progress on pushing ICP-MS assay sensitivities to the sub μBq/kg level (Hoppe et al. paper)
  - Developed Copper cleaning and passivation techniques
  - Investigation of alternative enrichment technologies
- Specific signal and background studies
  - Understanding sensitivity to neutron induced backgrounds underground (Mei and Hime)
  - Identification of specific Pb(n,n'γ) lines problematic for Ge (paper in press)
  - Studies of sensitivity to surface contaminations (paper in preparation)
  - Sensitivity of Ge detectors to neutron backgrounds using an AmBe source (paper in press)
  - Studies on potential (n, n'γ) backgrounds at TUNL and LANSCE. (Pb, Cu and Ge-76)
  - Study of sensitivity of two neutrino and neutrinoless double-beta decay to excited states in ^{76}Ge (Kazkaz diss. and paper in prep.)
- Detector studies
  - Effectiveness of background cuts using a Clover detector (Elliott *et al.*)
  - Studies of segmented detectors and background reduction methods using the MSU detector (36) and the LLNL (40) Ge detector (LLNL(40) paper submitted)
  - Constructed enriched segmented detector and characterized its initial performance
  - Studies of effectiveness of background reduction using SEGA and the TUNL HIGs facility (paper in preparation)
  - Exploration of an improved modified electrode Ge detector (Collar *et al.* papers submitted)
  - Studies of segmented p-type detector
- Simulation
  - Development of MaGe simulation framework (paper in preparation with GERDA)
  - Extensive study of backgrounds for the Majorana reference design (paper in preparation)
  - Quantitative study comparing sensitivities for different detector configurations and segmentation schemes
  - Geant4 validity for simulations of muon-induced neutrons (paper submitted and accepted)
  - Pulse shape simulation studies in point-contact detectors
  - Development of an improved Geant4 surface sampling routine (paper in preparation)
- Cryostat and system studies
  - Constructed large prototype electroformed cryostat (MEGA) and operated with multiple crystals
  - Support of Gretina digitizing card in ORCA
  - Constructed test cryostat for studying string design options and cooling performance
  - Developed initial prototype of calibration system
  - Large cryostat cooling: comparison between modeling and measurement, emissivity measurements

The MAJORANA Collaboration

Note: Red text indicates students



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Summary

An initial prototype ^{76}Ge module with 30-60 kg of 86% enriched ^{76}Ge and backgrounds on the order of or less than 1 count/ROI/t-y will allow us to demonstrate the feasibility of Ge for a 1-ton scale experiment capable of reaching a sensitivity to the "inverted hierarchy" neutrino mass scale (30-40 meV).

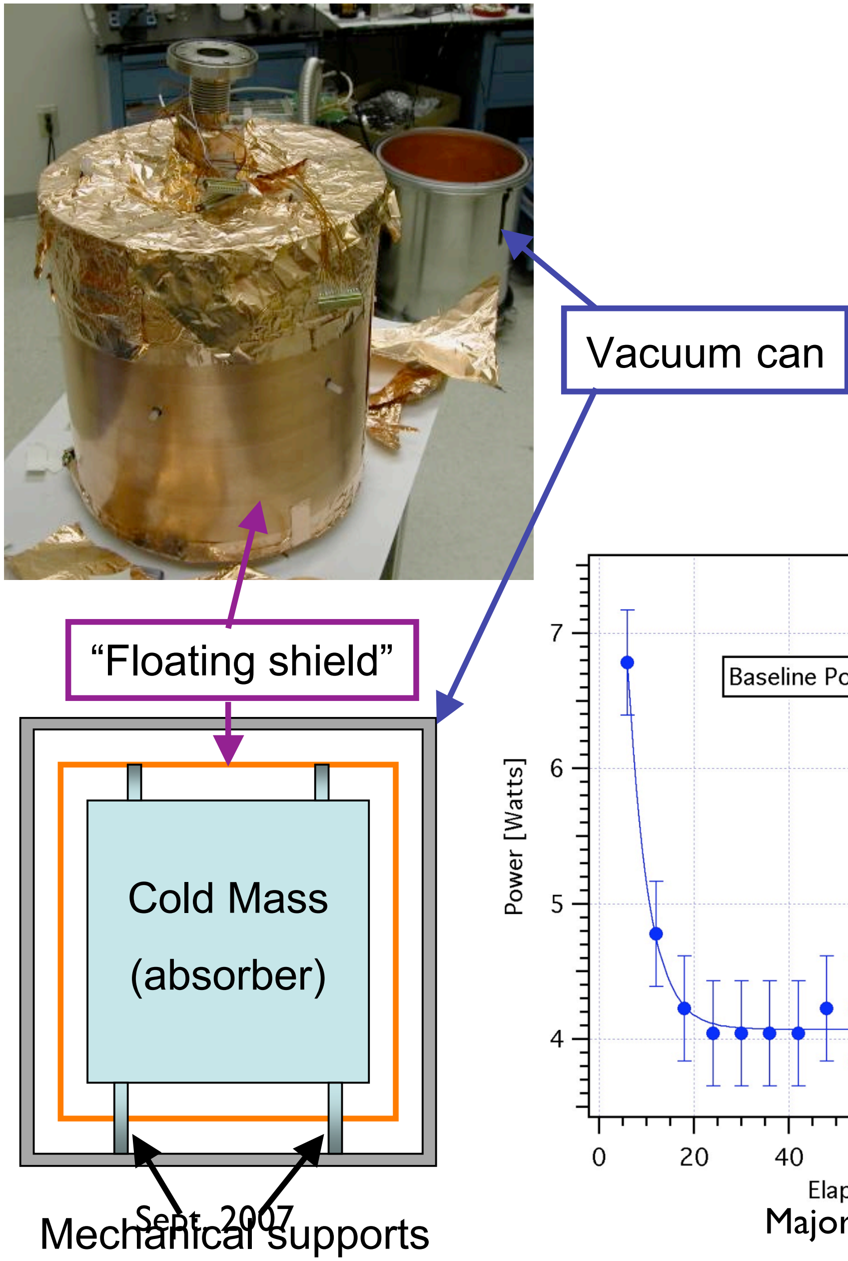
- **Our technical reference plan has been reviewed and deemed feasible**
- **The remaining Majorana R&D is aimed at reducing risks**
  - **Demonstrating electroformed Cu that meets the low-activity requirements**
  - **Investigating new detector concepts**
  - **Producing low-background, low-mass cables**
  - **Examining options to avoid potential detector fabrication & schedule delays**
- **We have to continue to explore ways to "*aggressively pursue the construction of the first 60 kg module*"**
  - **Prototype using existing ^{nat}Ge detectors and realistic cryostat, small parts and strings**
  - **Alternative detector technologies**
  - **Mixed deployment of different detector technologies**
  - **Early deployment of smaller numbers of crystals - module may include 2-3 cryostats**

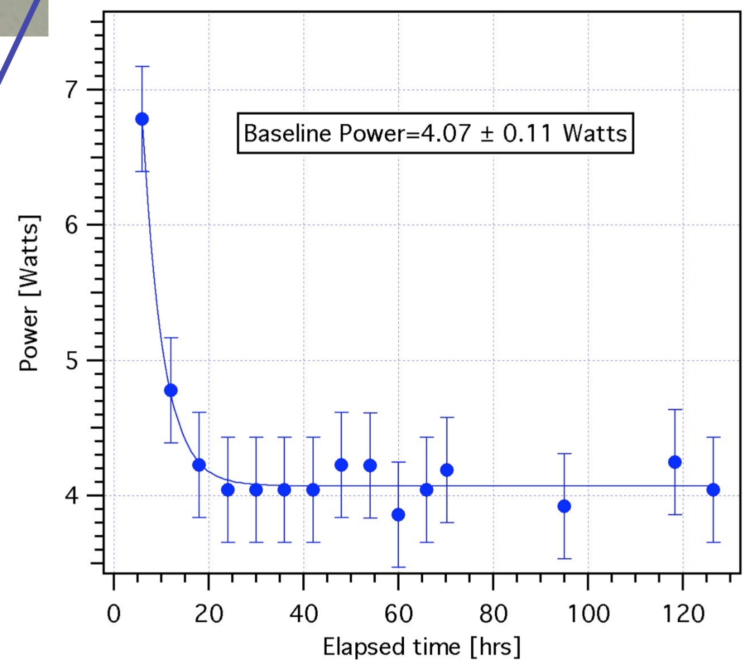
Extra Slides

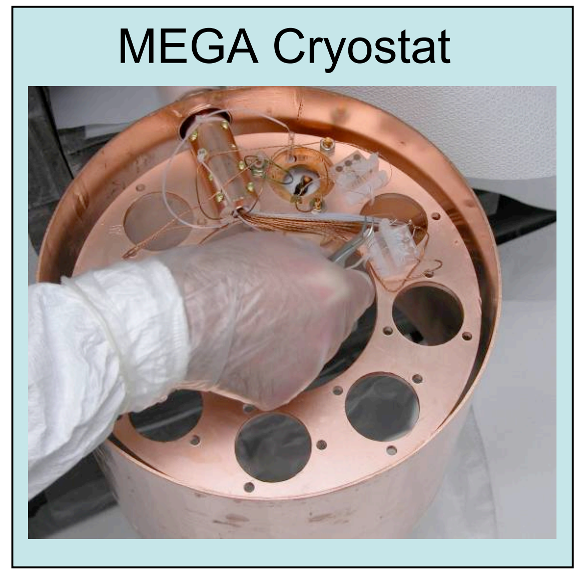
Large cryostat cooling tests - Large cryostats

Demonstrated cool down of a large copper cryostat and quantitative evaluation of the emissivity following peroxide cleaning and passivation

1. **Initial cooling of MEGA cryostat indicated excellent performance of a MAJORANA-scale cryostat**
2. **MEGA heat load estimated at 9 Watts; implied ε_{Cu}~3%**
3. **Quantitative measurements made with large-scale test cryostat shown schematically to left**
4. **Test cryostat heat load of only 4 Watts; implied ε_{Cu}=2.5(5)%**
5. **Demonstrated effectiveness of single "floating shield" rather than conventional multi-layer insulation (MLI)**

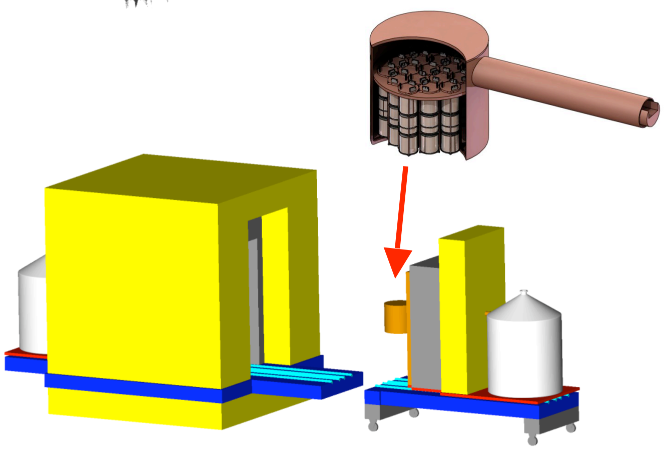




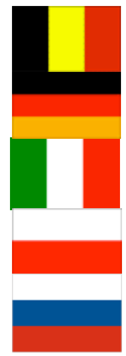


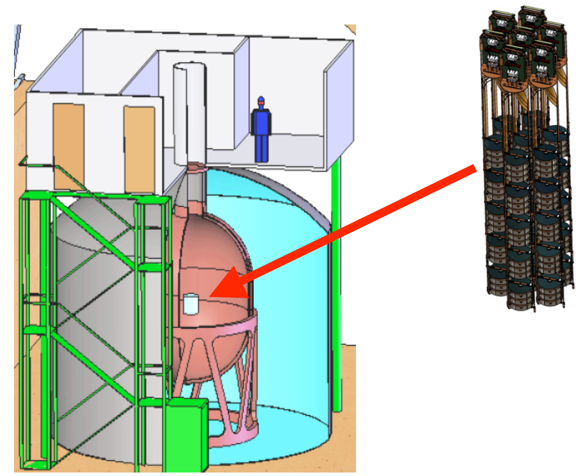
MAJORANA - GERDA

MAJORANA



GERDA





- **Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat**
- **Shield: electroformed copper / lead**
- **Initial phase: R&D demonstrator module: Total ~60 kg (30 kg enr.)**

- **'Bare' ^{enr}Ge array in liquid argon**
- **Shield: high-purity liquid Argon / H_2O**
- **Phase I (mid 2008): ~18 kg (HdM/IGEX diodes)**
- **Phase II (mid 2009): add ~20 kg new detectors - Total ~40 kg**

Joint Cooperative Agreement:

• Open exchange of knowledge & technologies (e.g. MaGe, R&D)

• Intention is to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA