THE MAJORANA $^{76}Ge\ 0\nu\beta\beta -$ DECAY EXPERIMENT

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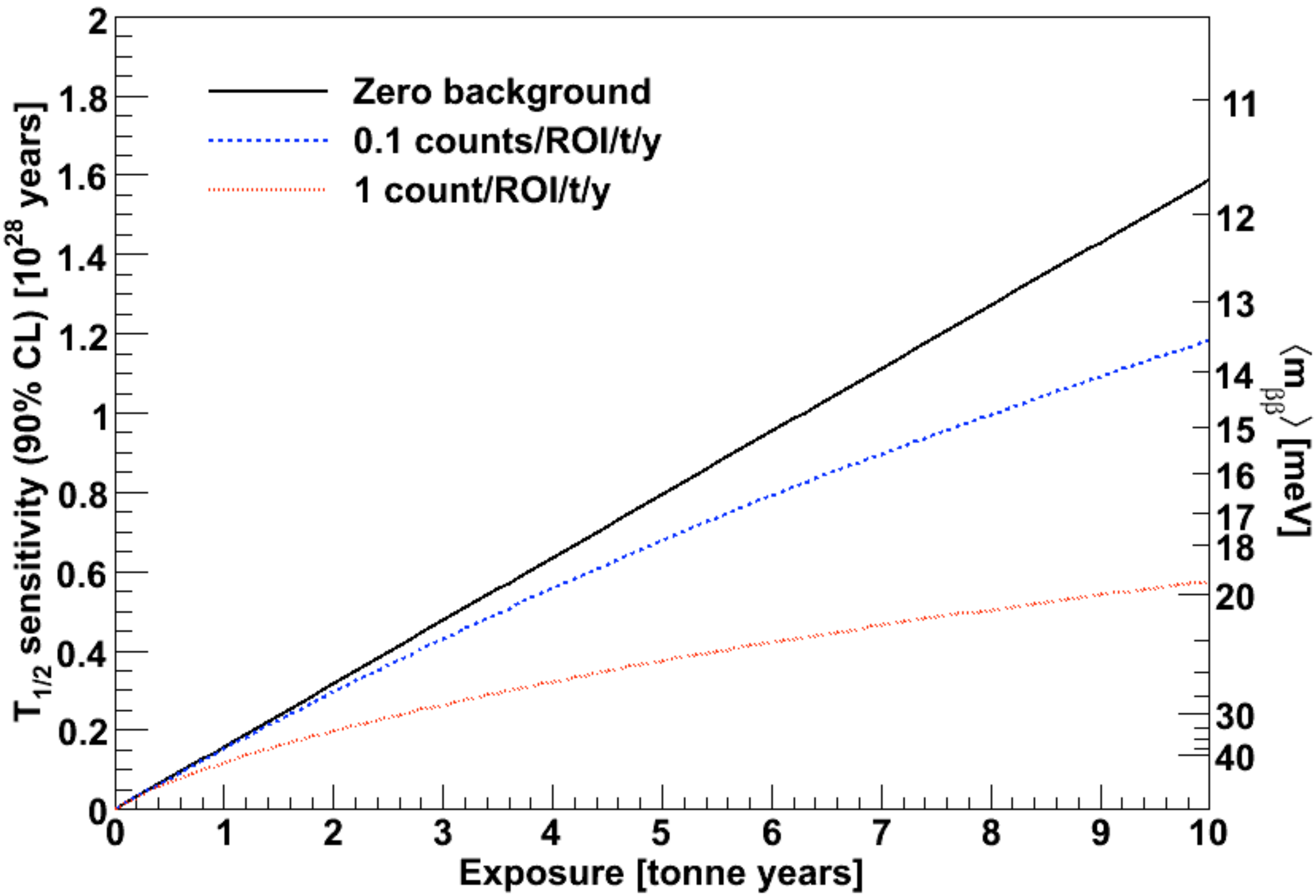
FOR
THE MAJORRANA COLLABORATION

MAJORANA R&D Program Goals

Perform a "near background-free" search for neutrinoless double-beta decay in ^{76}Ge as an R&D program to develop a 1-tonne experiment

- **Demonstrate background levels that would justify scaling up to a 1-ton or larger experiment.**
- **Probe the quasi-degenerate neutrino mass region above 100 meV.**
- **Confirm or refute the Klapdor-Kleingrothaus claim of an observation of $0\nu\beta\beta$ in ^{76}Ge.**
- **Show long-term operation of crystals, scalability, and feasibility of cost & schedule**
- **Make a technology down-select in collaboration with GERDA (bare Ge detectors in liquid cryogen) for the optimum 1-tonne configuration.**

1-tonne ^{76}Ge Sensitivity



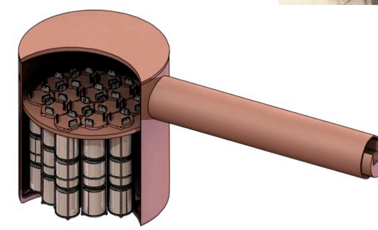
MAJORANA R&D

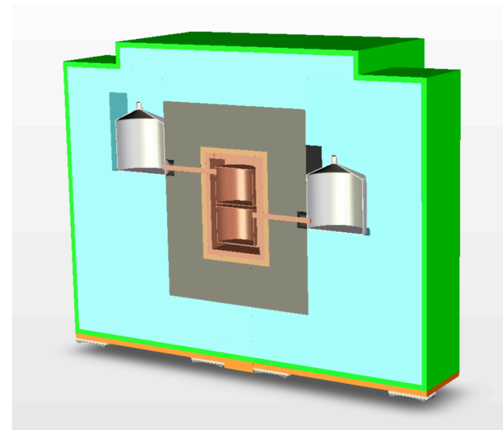
Towards a 1-tonne experiment

- Phase I: Construct 60 kg R&D Module
- Mixed detector types, enrichment levels
- Goals:
  - Selection of optimal detector design:
    - Highly/modestly segmented n-type detector
    - Point Contact p-type detector
  - Verification of background simulation.
  - Ultra-low Background Materials, in particular cable and copper shielding.
- Continued cooperation with GERDA collaboration (MaGe, materials, LAr Shield)

The MAJORANA Prototype Module

- R&D Reference Design
  - Based on 60 kg of Ge crystals
  - Planned for a mix of p-type and n-type crystals
    - p-type: point-contact (40 kg)
    - n-type: modest to highly segmented (20 kg)
  - 30 kg of 86% enriched ^{76}Ge crystals
    30 kg of natural Ge or depleted in ^{76}Ge.
  - Scalable, with independent, ultra-clean, electroformed Cu cryostat modules
  - Enclosed in a low-background passive shield and active veto
  - Located deep underground (≥ 4500 mwe)





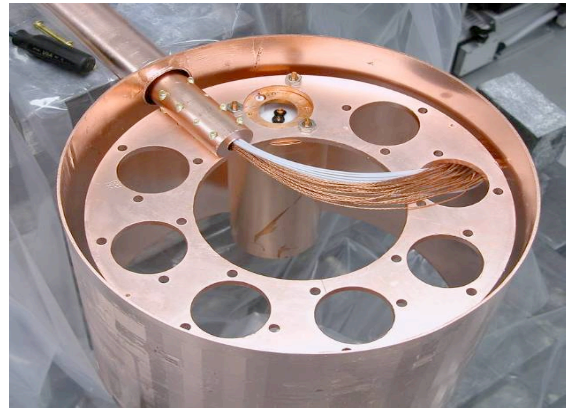
- Background Specification Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
  ~ ≤**1 count/ROI/t-y** (after analysis cuts)
- Expected Sensitivity to $0\nu\beta\beta$
  (for 30 kg enriched material, running 3 years, or 78 kg-y of ^{76}Ge exposure)
  $T_{1/2} \geq 1.0 \times 10^{26}$ y (90% CL)
  Sensitivity to $<m_\nu>$ < 140 meV (90% CL) ([Rod06 erratum] RQRPA NME)
  Able to confirm/refute KKDC 400 meV value (20% measurement).

Background Identification

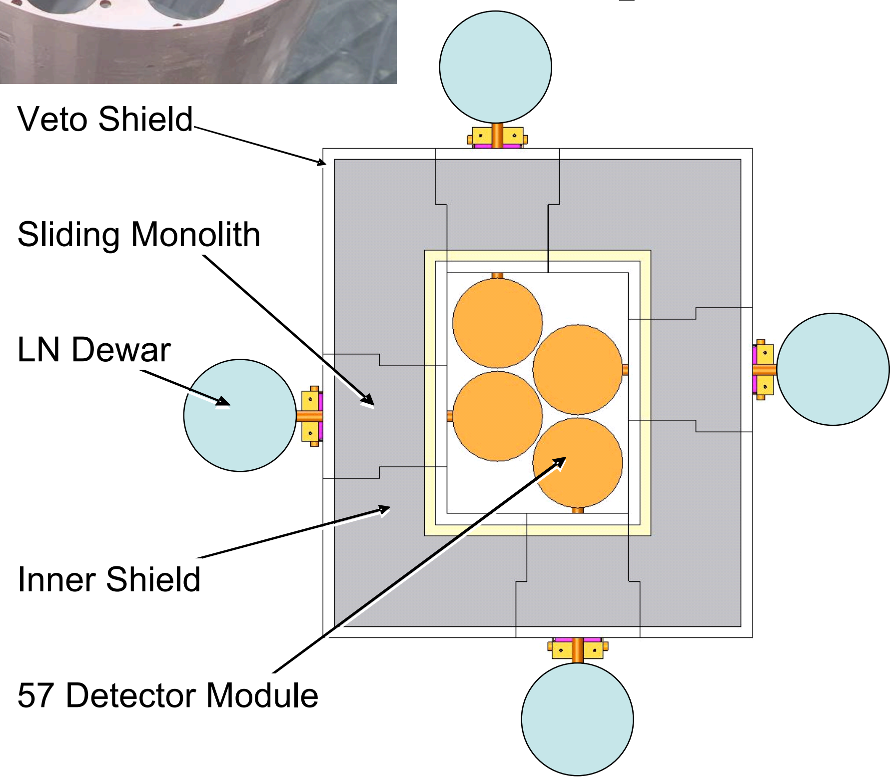
- Goal: ≤1 event / ton-year in 4 keV ROI
- Backgrounds:
  - Natural isotope chains: ^{232}Th, ^{235}U, ^{238}U, Rn
  - Cosmic Rays:
    - Activation at surface creates ^{68}Ge, ^{60}Co.
    - Hard neutrons from cosmic rays in rock and shield.
  - $2\nu\beta\beta$-decays.
- Need factor ~100 reduction over what has been demonstrated.
- Monte Carlo estimates of acceptable levels
- Most backgrounds are multi-site. Signal is single-site

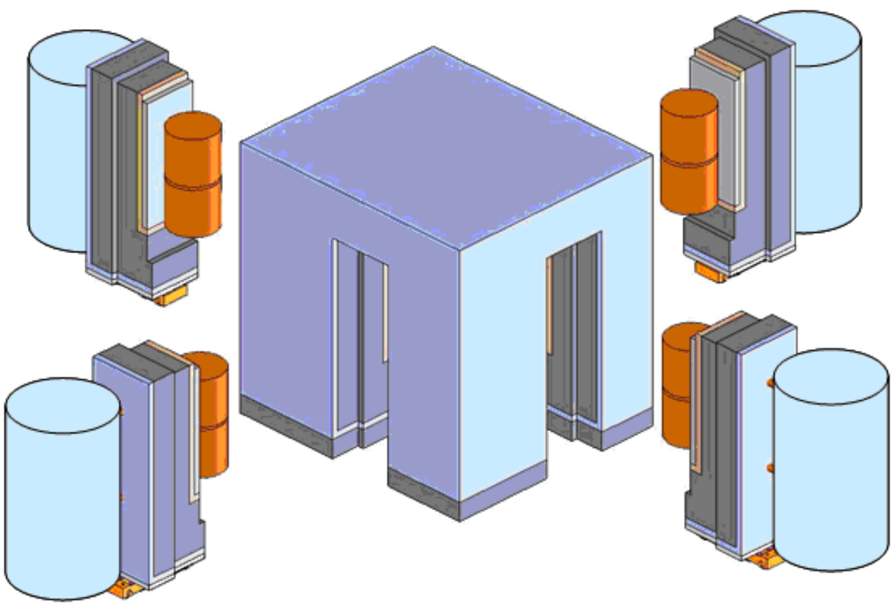
Materials and Shielding

- Ultra-radiopure materials
- Deep underground: >5000’
- Modular deployment.
- 40 cm bulk Pb, 10 cm ultra-low background shield
- Active 4π veto detector

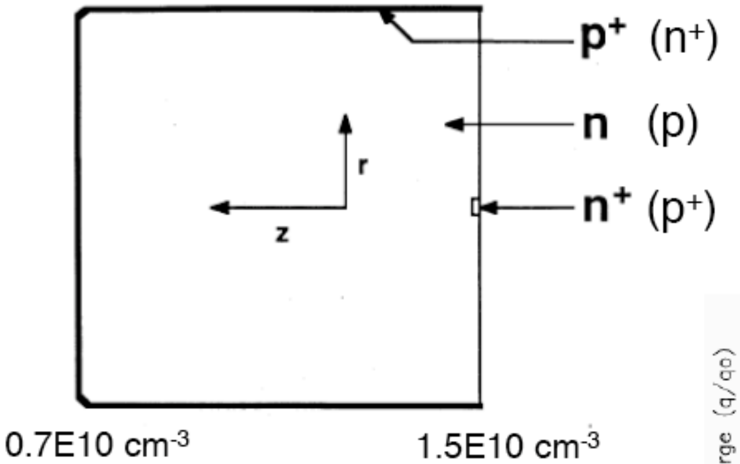


Top view

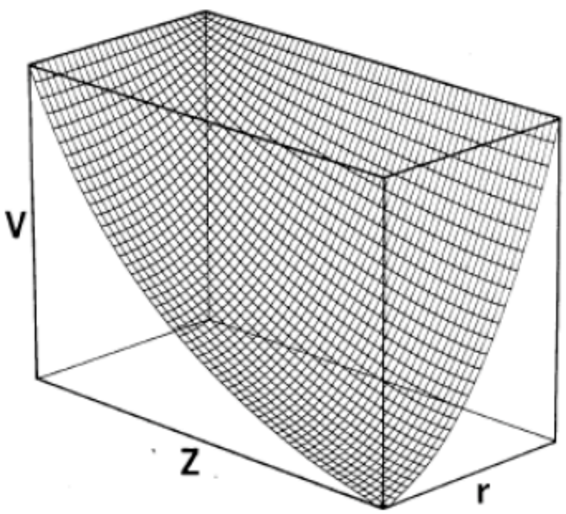


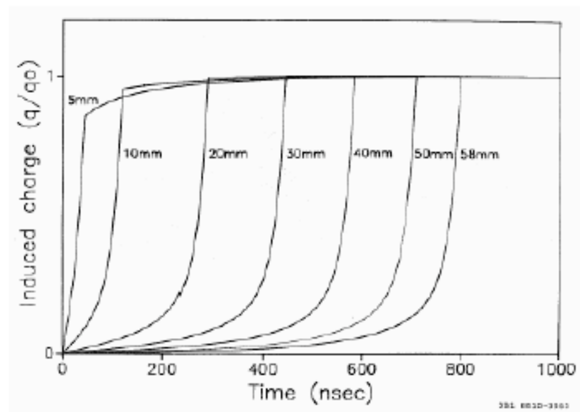


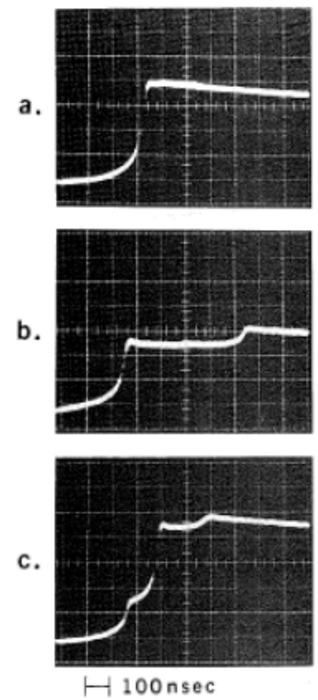
Point Contact Detector



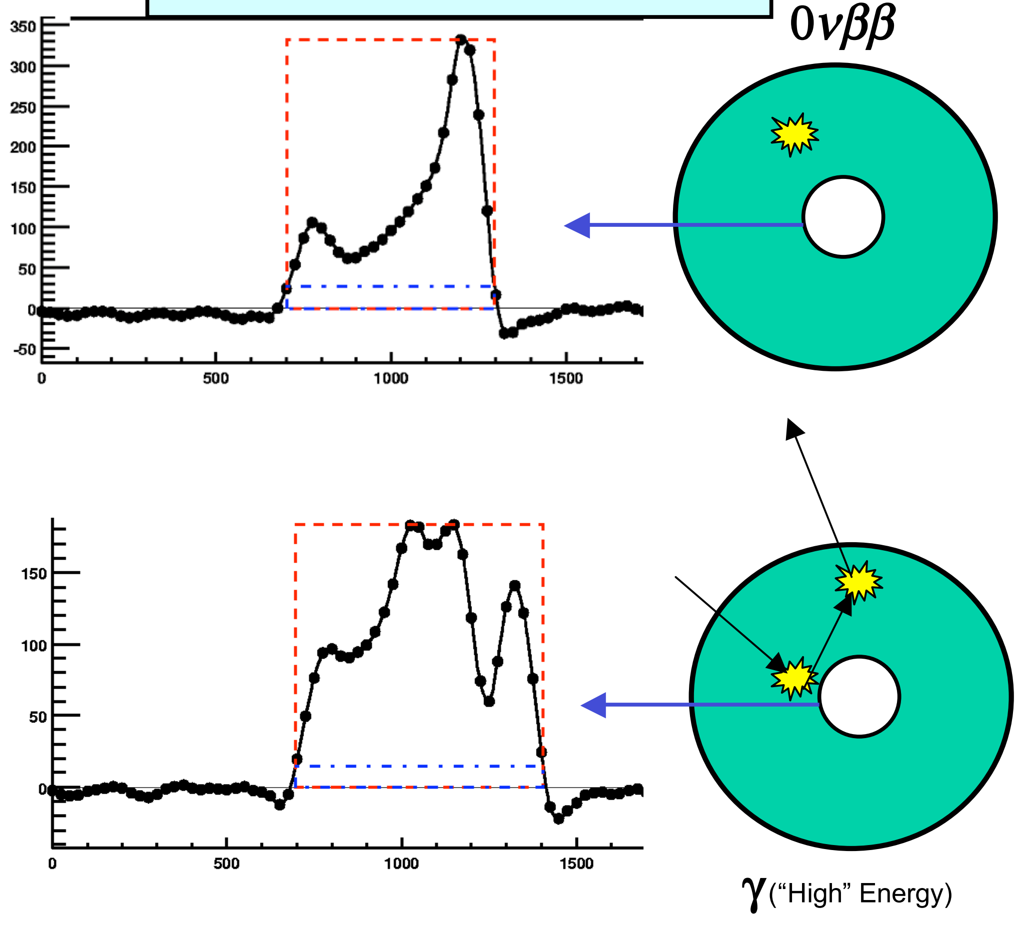
IEEE Transactions on Nuclear Science, vol.36, no. 1, pp.926-30, Feb. 1989. LBNL-25694



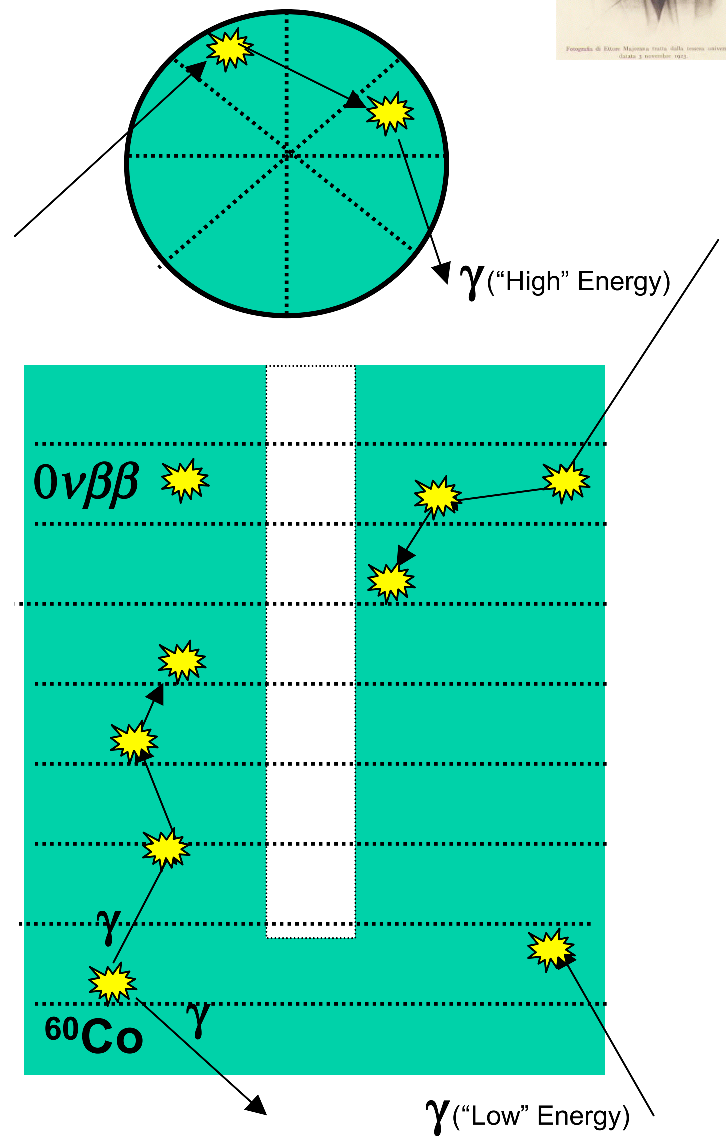




Pulse-shape discrimination

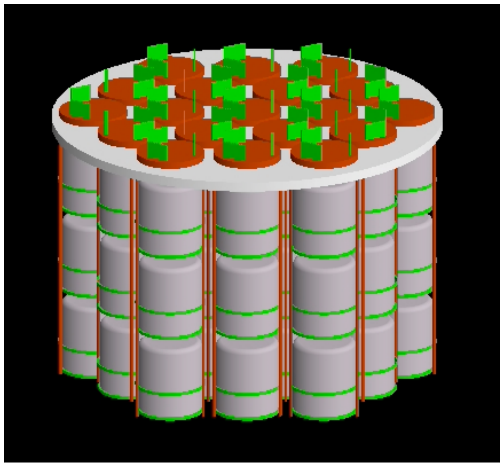


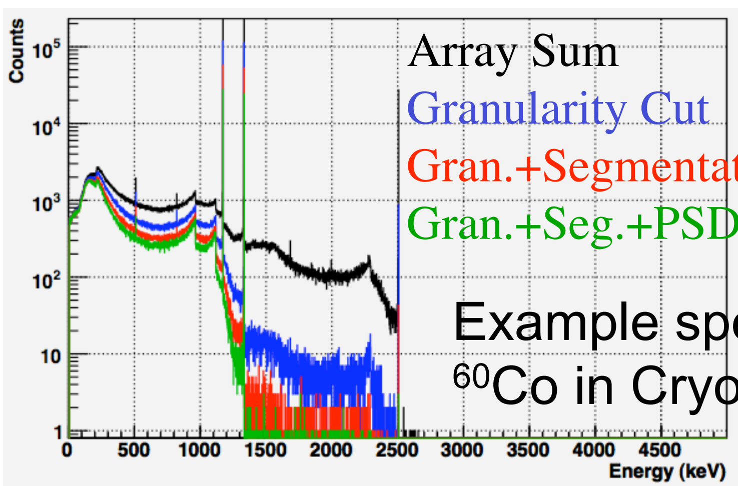
Segmentation



MAJORANA Simulation

Simulated Geometry
Shields & Cryostat Removed





Example spectra:
^{60}Co in Cryostat

Simulation Includes:

- 57 Enriched crystal w/ deadlayers.
- LFEPs
- Support Rods
- Ge Trays
- Contact Rings
- Cryostat
- Surface Alphas
- Shields:
  - Inner, Outer Cu
  - Inner, Outer Pb
  - Neutron shield.
  - Room, rock wall.
- 45,000 CPU hours, 12,000 jobs.

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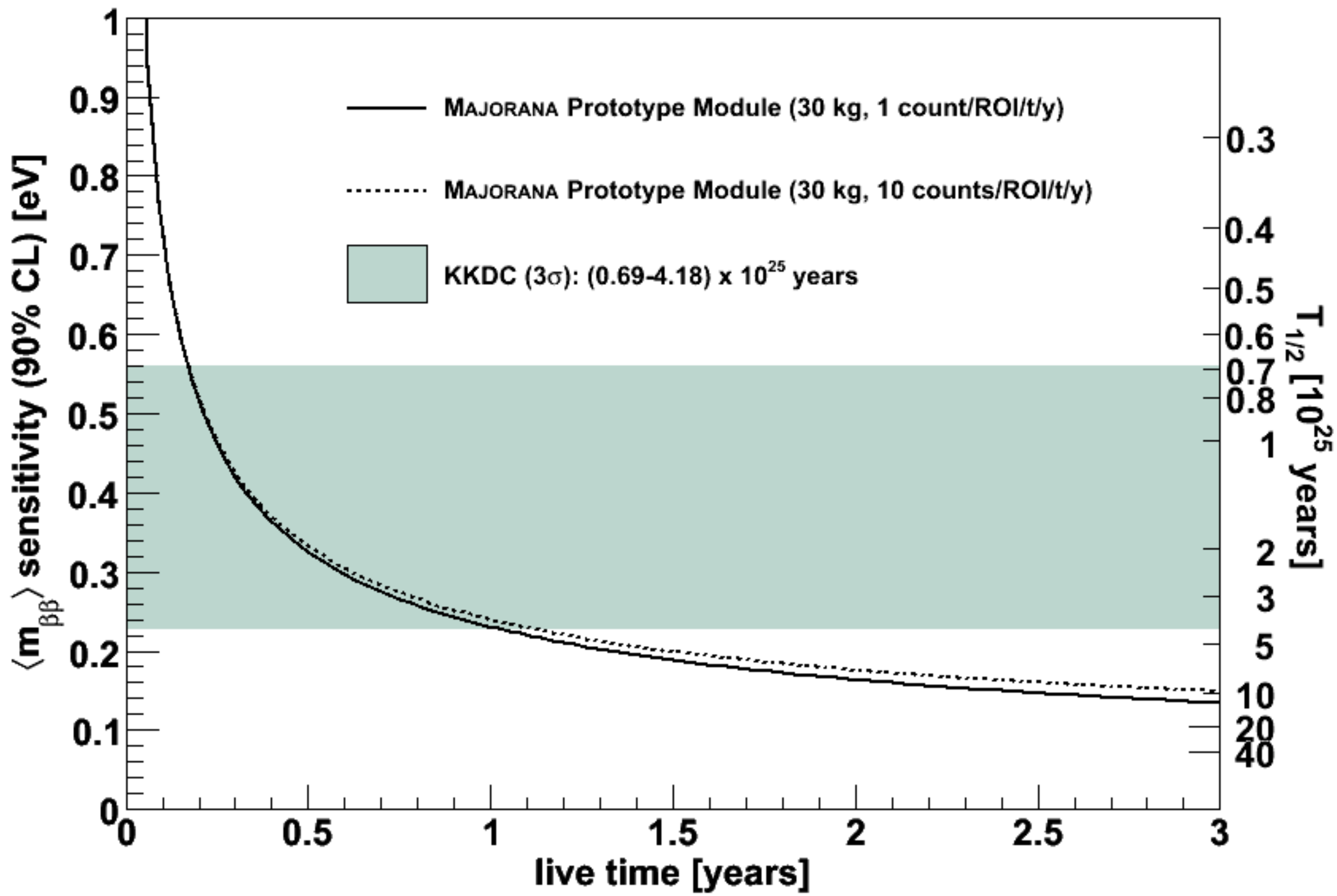
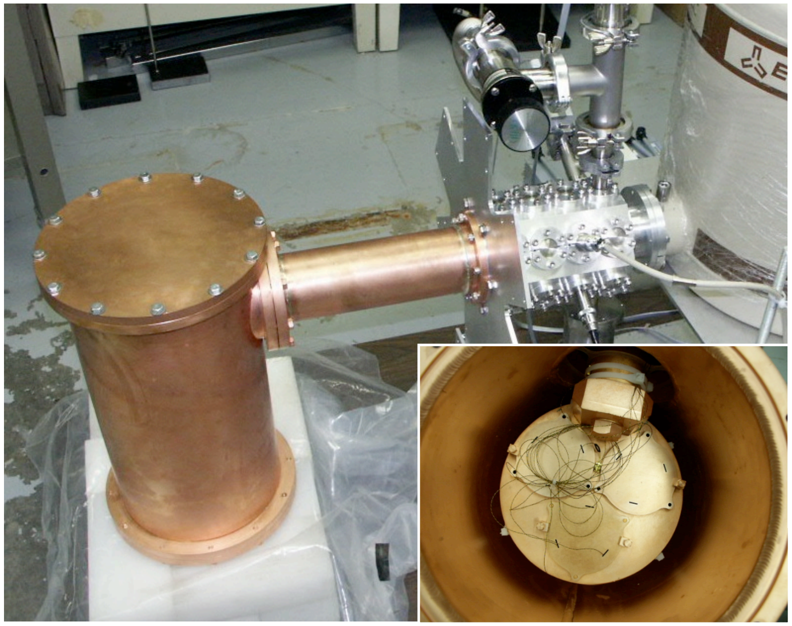
MAJORANA Prototype Module Sensitivity

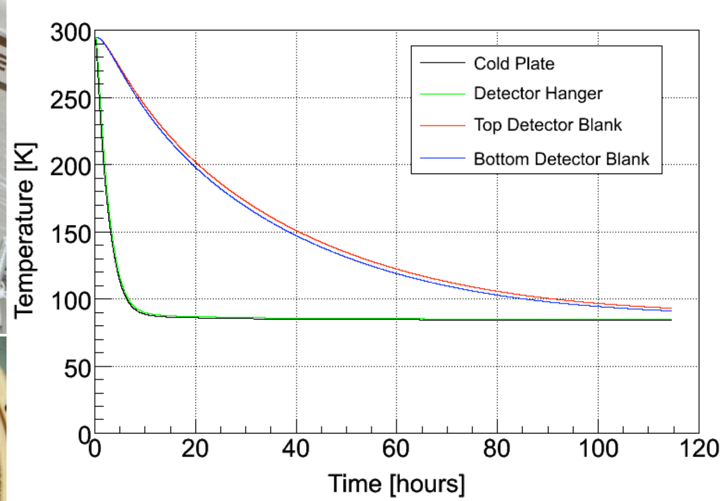


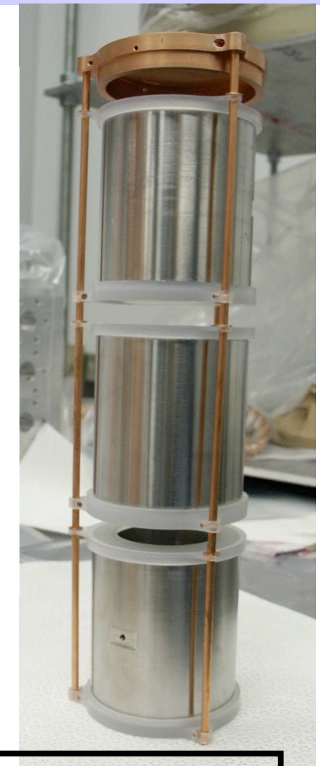
MAJORANA R&D Project Summary

- Pursuing "R&D" funding to build a prototype ^{76}Ge Demonstrator module (~60 kg total mass) as part of a longer-term program to develop a 1-ton 0νββ-decay experiment.)
  - Received support as part of the FY2007 DUSEL R&D funding process (from both DOE and NSF).
  - August 2007 - The collaboration will submit a "R&D" proposal covering the full development of the prototype module. (with most of the R&D funding requested in FY09-11).
  - Hope to begin making major purchases in FY09 with data taking beginning in FY11
- Technology down-select with GERDA and propose 1-tonne project sometime thereafter.

Test Cryostat for String Design







Detector String

1. Cryostat holds 3 strings - Each string holds 3 detectors
2. 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

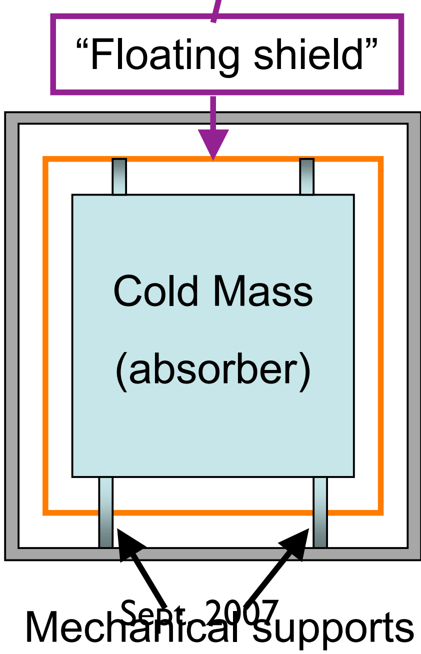
Thermal Test

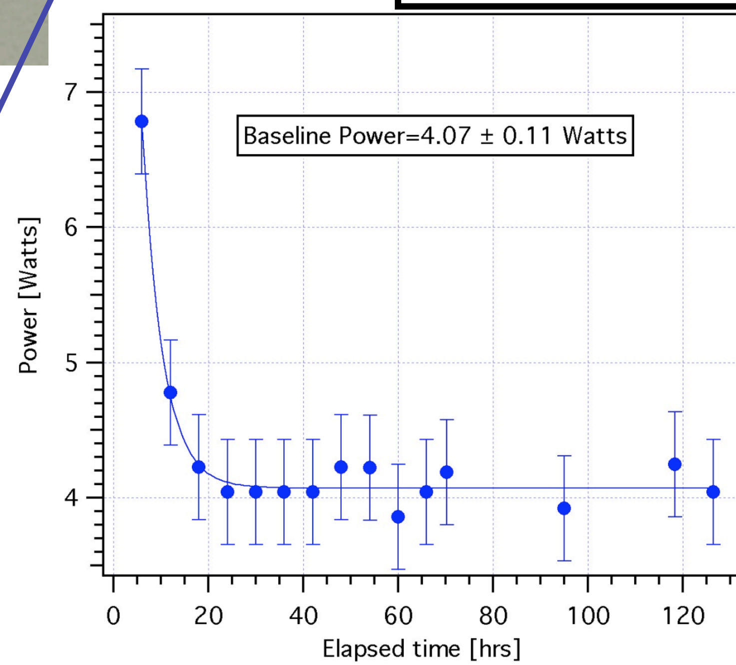
1. Stainless steel “detector blanks” (above) similar thermal mass and emissivity of Ge crystals
2. Thermocouples mounted on crystal and copper parts show temperature response when cooled (above)
3. Successful cooling of detectors by radiation

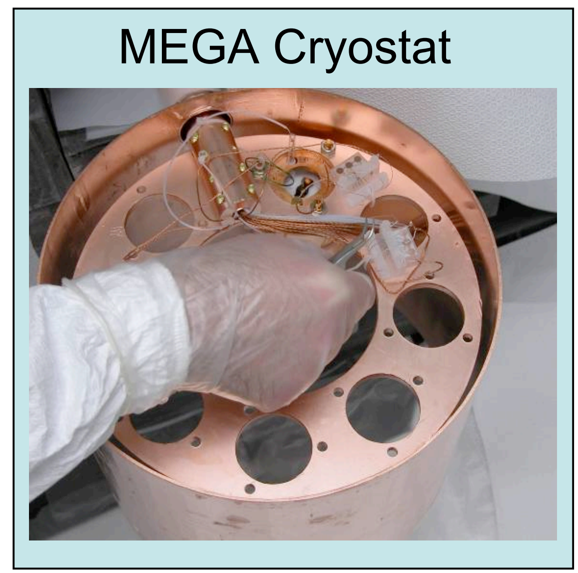
Large cryostat cooling tests

Demonstration of cooling of a large cryostat and quantitative evaluation of passivated copper emissivity

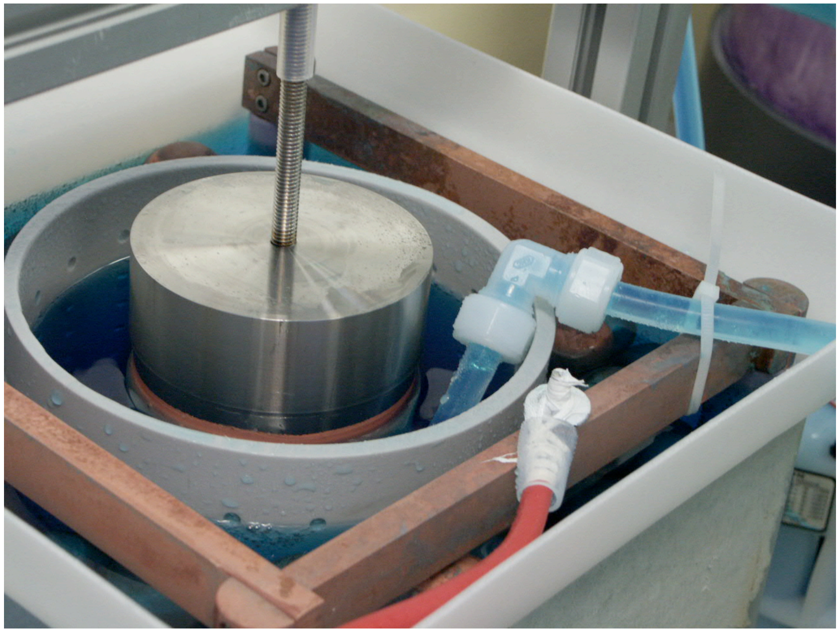
1. **Initial cooling of MEGA cryostat indicated excellent performance of a Majorana-scale cryostat**
2. **MEGA heat load estimated at 9 Watts; implied ε_{Cu}~3%**
3. **Quantitative measurements made with large-scale test cryostat shown schematically below**
4. **Test cryostat heat load of only 4 Watts;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







Underground electroforming at WIPP



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 xxx M acid solution onto SS mandrel**

Test Part

Copper "Beaker" fabricated

660 gm

160 mm high, 110 mm diameter

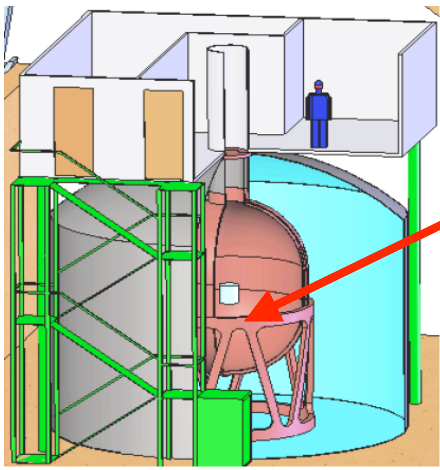
Wall thickness ~1 mm

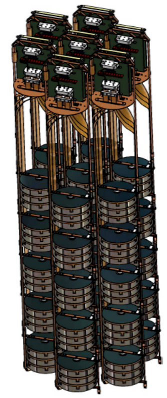
~10 days of UG electroforming in two stretches

Solution is 1.5 kg copper sulfate dissolved in 16 L DI water

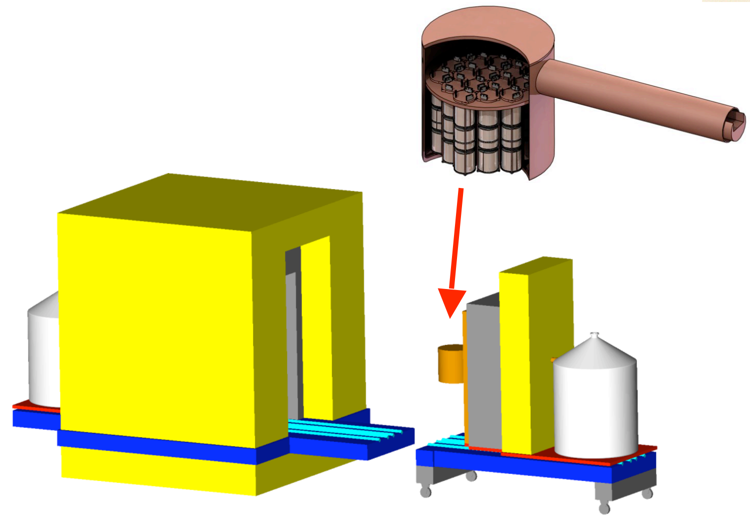
Part removed from mandrel by successive dunks in boiling water and liquid nitrogen

GERDA





MAJORANA



- '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

- Modules of ^{enr}Ge housed in high-purity electroformed copper cryostat
- Shield: electroformed copper / lead
- Initial phase: R&D prototype module

Total 60 kg (30 enriched)

Joint Cooperative Agreement:

- Open exchange of knowledge & technologies (e.g. MaGe, R&D)
- Intention to merge for 1 ton exp. Select best techniques developed and tested in GERDA and MAJORANA

NUCLEAR MATRIX ELEMENTS 2007 AND IMPACT ON CUORE PROSPECTS

Define the signal to background fluctuation ratio:

$$S / BGF \equiv \lambda N t \varepsilon / \sqrt{bMt\delta E}$$

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

$$\lambda \equiv 1/\tau = \ln 2 / T_{1/2}^{0} = (\ln 2) G^{0\nu} \left| M_\nu \right|^2 (\langle m_\nu \rangle / m)^2$$

$$\lambda = (\ln 2) F_N (\langle m_\nu \rangle / m)^2$$

$$S / BGF = \left[\frac{F_N}{\sqrt{b}} \right] \frac{\ln 2 (\langle m_\nu \rangle / m_e)^2}{\sqrt{Mt\delta E}} \times N t \varepsilon$$

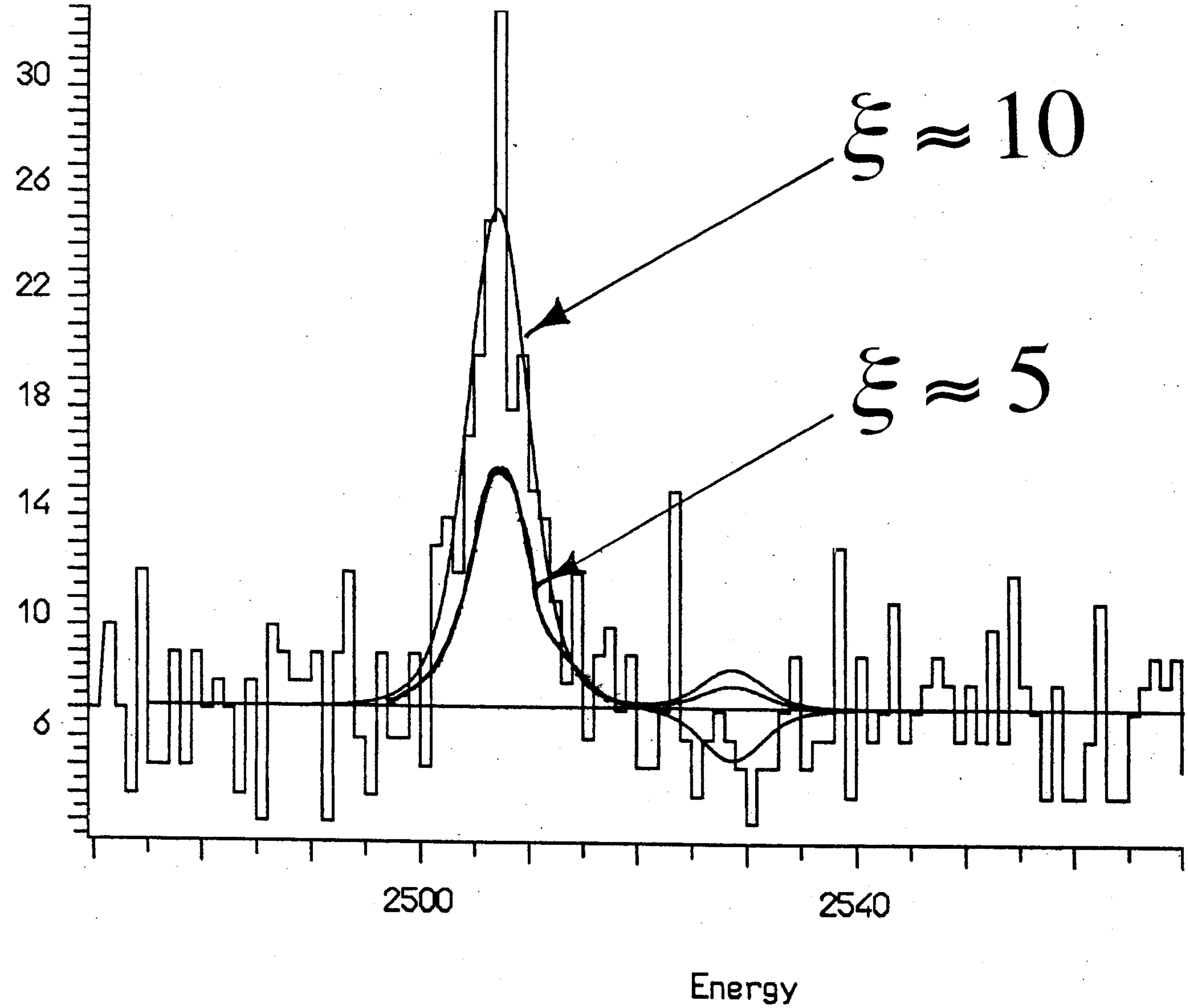

30
26
22
18
14
10
6
2500
2540
Energy
$\xi \approx 10$
$\xi \approx 5$

Table A. $\xi \equiv s / fbg$ for various nuclear models, including the Rodin et al., Erratum. These values are for 1 ton of (86%) ^{76}Ge and $\langle m_{\beta\beta} \rangle$=0.05eV and t=10 y.

b	ξ^{ROD}	ξ^{SM}	ξ^{CIV}	ξ^{Rod}_{corr}
0.10	0.34	0.32	0.52	0.91
0.05	0.48	0.45	0.74	1.28
0.01	1.08	1.01	1.65	2.87
0.005	1.53	1.43	2.33	4.06
0.001	3.41	3.19	5.22	9.08
0.0005	4.83	4.52	7.38	12.84

Other parameters: $\varepsilon = 0.90$, $\delta E = 3keV$; $T^{0\nu}_{1/2} = 8.6 \times 10^{26} y$.

Table D: $\xi \equiv s / fbg$ for various nuclear models, including the Rodin et al., and the Erratum, for 30kg of ^{76}Ge for t=5 y, and $\langle m_{\beta\beta} \rangle = 0.20 eV$ (KKDK lowest value).

b	ξ_{2006}^{Rodin}	ξ^{SM}	ξ^{CIV}	ξ_{corr}^{Rod}
0.10	0.67	0.62	1.02	1.77
0.05	0.94	0.88	1.44	2.51
0.01	2.11	1.98	3.22	5.61
0.005	2.99	2.80	5.46	7.94
0.001	6.67	6.24	10.19	17.74
0.0005	9.44	8.84	14.42	25.10

The other parameters are: $a = 0.86, \varepsilon = 0.90$ and $\delta(E) = 3keV$; $T_{1/2}^{0\nu} = 5.35 \times 10^{25} y$.

FAESSLER et al., PHYS. REV. C 68 (2003) 044302, FIXED THE PARTICLE-PARTICLE INTERACTION STRENGTH PARAMETER, g_{pp}, BY ADJUSTING IT TO PRODUCE THE MEASURED $2\nu\beta\beta-$DECAY HALF LIFE. THEY FOUND THAT $M^{0\nu}_{F,GT}$ WERE LESS SENSITIVE TO:

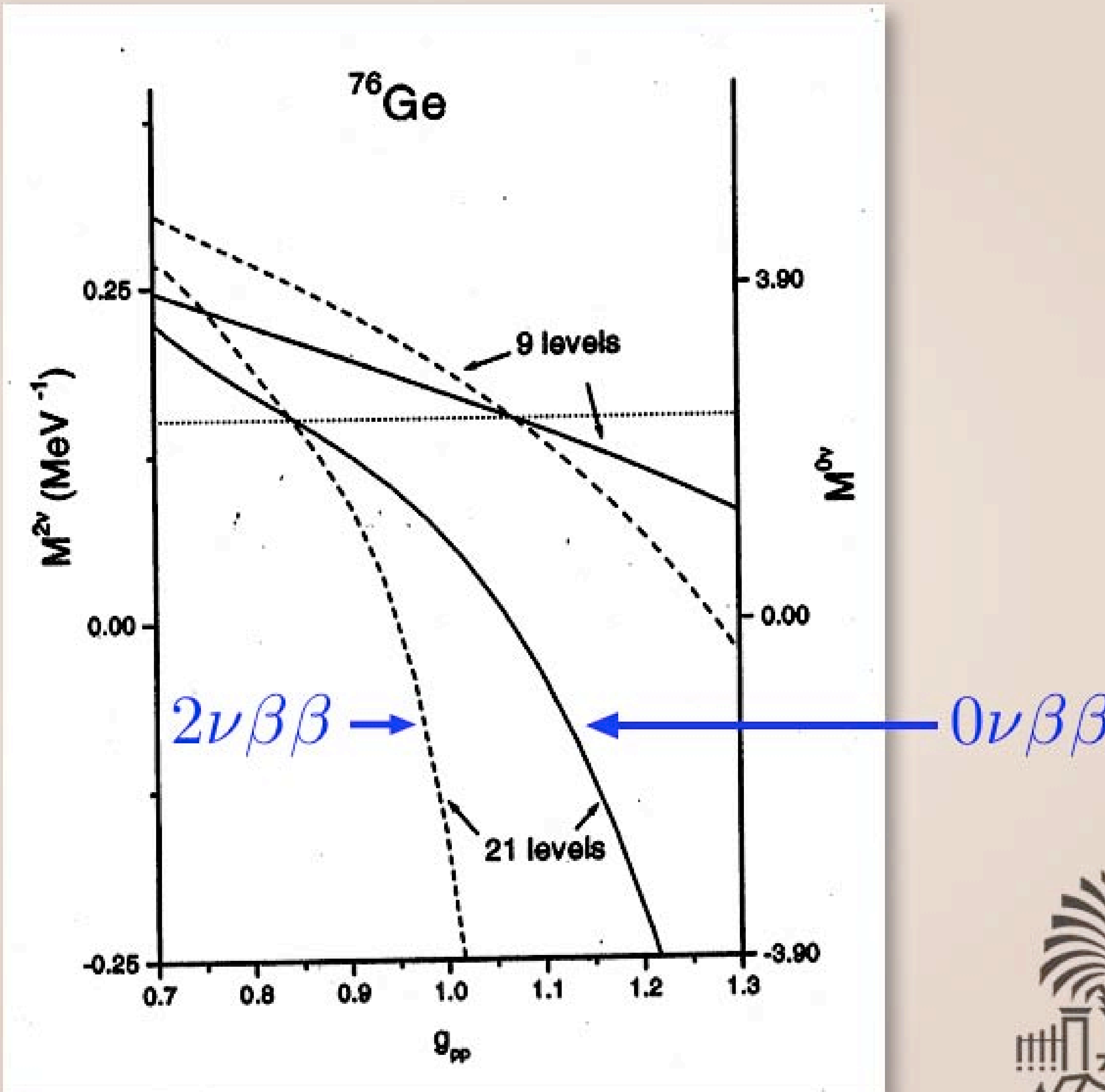
1. THE SIZE OF THE SINGLE-PARTICLE BASIS,
2. THE NUCLEON-NUCLEON POTENTIAL, AND
3. THE QUENCHING OF AXIAL VECTOR STRENGTH.

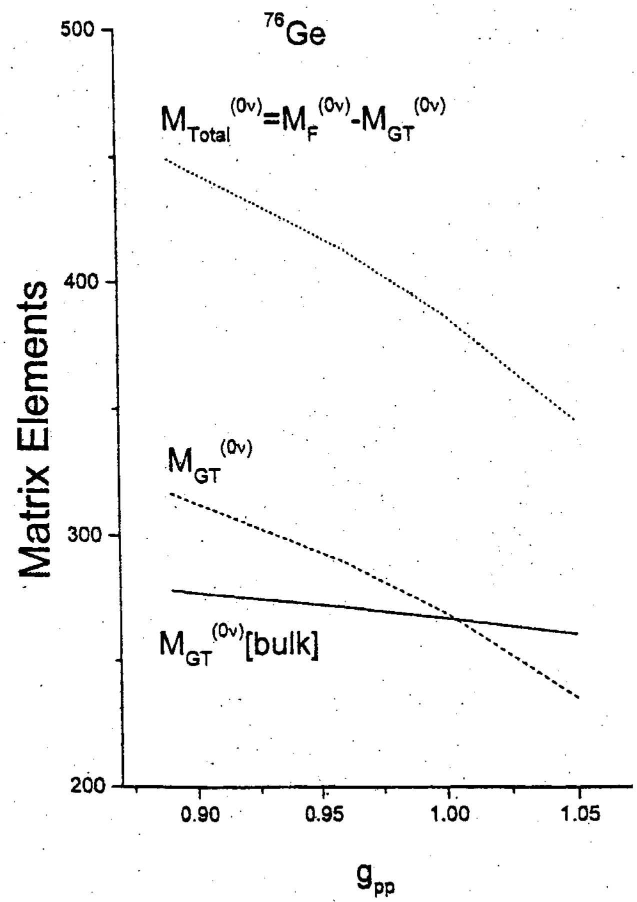
CIVITARESE AND SUHONEN DISAGREED WITH THIS PROCEDURE OF FIXING $g_{PP.}$ THEIR MATRIX ELEMENTS WERE SIGNIFICANTLY LARGER FOR ^{130}Te:

$$F_N \equiv G^{0\nu}\left|M^{0\nu}_{\beta\beta}\right|^2; \quad F_N = \left(\frac{m_e}{\langle m_{\beta\beta}\rangle}\right)^2 \frac{1}{T^{0\nu}_{1/2}}$$

$$F_N^{SM}(2007) = 2.57\times10^{-13}y^{-1}$$
$$F_N^{CIV}(2006) = 5.13\times10^{-13}y^{-1}$$
$$F_N^{Jyv}(2007) = 7.46\times10^{-13}y^{-1}$$
$$F_N^{Rod}(2003) = 1.20\pm0.27\times10^{-13}y^{-1}$$

See: Rodin et al., Nucl. Phys. A **706** (2006) 107-131. It explains a great deal.


^{76}Ge
$M^{2\nu}$ (MeV^{-1})
$M^{0\nu}$
0.25
0.00
-0.25
3.90
0.00
-3.90
9 levels
21 levels
$2\nu\beta\beta$
$0\nu\beta\beta$
0.7
0.8
0.9
1.0
1.1
1.2
1.3
g_{pp}



BULK=ALL MULTIPOLES EXCEPT $J^{\pi}=1^{+}$. THE OTHERS INCLUDE $J^{\pi}=1^{+}$ ALSO.

FAESSLER ORIGINALLY CLAIMED THAT CIVITARESE AND SUHONEN WERE NOT INCLUDING CORRECTIONS FOR SHORT RANGE CORRELATIONS AT ALL. THEY ARGUED THAT THEY WERE. WE HAD A MEXICAN STAND OFF FOR 4 YEARS.

WHEN ON 23 JUNE 2007, FAESSLER SENT AN ERRATUM TO THE $\beta\beta-$COMMMUNITY, (arXiv:0706.4304v1), CORRECTING THE "CODING ERROR" IN THEIR SHORT RANGE CORRELATIONS, THE RESULTS RELEVANT TO CUORE, MAJORANA AND EXO WERE VERY DIFFERENT. THE RATIOS ARE:

$$F_N^{New}(^{130}Te)/F_N^{orig}(^{130}Te) = 4.03$$

$$F_N^{New}(^{76}Ge)/F_N^{Orig}(^{76}Ge) = 2.66$$

$$F_N^{New}(^{136}Xe)/F_N^{Orig}(^{136}Xe) = 4.04$$

IN 2006 CIVITARESE, SUHONEN and KORTELAINEN USED THE METHOD OF FIXING g_{pp} IN THE QRPA WITH THE $2\nu\beta\beta-$ DECAY HALF LIVES, TO REPEAT THE WORK OF RODIN, FAESSLER, SIMKOVIC, AND VOGEL.

THEY AGREED WITH THEIR EARLIER WORK, AND WITH THE SAME DISCREPENCY THEY HAD WITH RODIN et al., EARLIER.

CONCLUSION: THE DIFFERENT METHODS OF FIXING g_{pp} WAS NOT THE CAUSE OF THE DISCREPENCY!

THERE WERE MANY DISCUSSIONS ABOUT THE TECHNIQUES FOR APPLYING SHORT-RANGE CORRELATION CORRECTIONS.

AT THIS POINT, THE TUEBINGEN GROUP DISCOVERED A "CODING ERROR" IN THE SHORT RANGE CORRELATION SECTION OF THEIR CODE, AND SENT IT AS AN ERRATUM TO THEIR 2003 ARTICLE: Nucl. Phys. A **766**, 107 (2003). See: nucl-th/0706.4304. v1. AGREEMENT WAS VERY MUCH IMPROVED.

BUT,THIS IS NOT THE END OF THE STORY!

WHAT EFFECT WOULD THESE SHORT-RANGE CORRELATION CORRECTIONS HAVE ON MAJORANA?

The Gamow-Teller, Fermi and Total $0\nu\beta\beta-$ QRPA Matrix Elements OF ^{76}Ge: "Bare" With Jastrow and UCOM-Bonn-A Parameterization With UCOM. Table (3) of Kortelainen et al.

ME	Bare	Jastrow	UCOM Bonn-A
$M_{GT}^{0\nu}$	-6.755	-4.688	-6.265
$M_{f}^{0\nu}$	2.474	1.788	2.310
Total	-8.328	-5.811	-7-734

M. Kortalainen, O. Civitarese, J. Suhonen, and J. Toivanen nucl-th/0701052 v1 18 Jan. 2007.

CONCLUSIONS

1. THE TWO MAIN QRPA THEORY GROUPS ARE IN FAR BETTER AGREEMENT THAN THEY WERE JUST 6 MONTHS AGO.

2. THE MAIN DISAGREEMENT WAS DUE TO A COMPUTATIONAL ERROR.

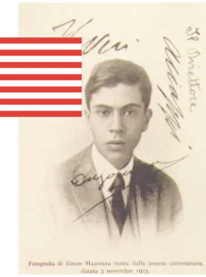
3. THE ISOTOPES ^{76}Ge, ^{130}Te, and ^{136}Xe ARE, ACCORDING TO BOTH RECENT QRPA CALCULATIONS, ALL GOOD CANDIDATES FOR $0\nu\beta\beta -$DECAY EXPERIMENTS.

4. THERE IS STILL THE IMPORTANT ISSUE OF THE METHOD OF APPLYING THE CORRECTIONS FOR SHORT-RANGE CORRELATIONS. IT HAS A MUCH SMALLER IMPACT THAN THE COMPUTATIONAL ERROR HAD.

5. SHELL-MODEL CALCULATIONS (2007) FRENCH-SPANISH GROUP ARE FAR LESS OPTIMISTIC, HOWEVER. (ALFREDO POVES, TALK AT THE 4TH ANNUAL ILIAS MEETING, FEB. 25-28, CHAMBERY FRANCE 2007).

6. THIS GAME OVER ONLY WHEN QRPA AND LARGE-SPACE SHELL MODEL AGREE.

The MAJORANA Collaboration



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