Ultra Low Background Front End Electronics for the Majorana Demonstrator

Paul Barton

Applied Nuclear Physics Program, Nuclear Science Division
Lawrence Berkeley National Laboratory

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Conference on Science at SURF
Semiconductor Detector Lab Activities at LBNL

- Low Mass Front End (LMFE) for Majorana
- LAr LMFE for LEGEND $0\nu\beta\beta$
- LDRD for LEGEND ASIC
- CPG CdZnTe Module w/ depth sensing
- Spherical Coded Aperture / Compton Imager
- HPGe double-sided strip detectors for gamma ray imaging
- Collimated 5 mCi $^{88}\text{Y}$ Source
- 8 μm Mylar Window
- 12 Mpx $4\times4\text{cm}^2$ CCD
- LBNL Scientific CCD for MeV Photon Beam Diagnostics
Neutrinoless Double Beta Decay

Is the neutrino it’s own antiparticle?

in $^{76}$Ge
Double-Beta Decay

- **2νββ-decay**: SM allowed and observed.
- **0νββ-decay**: Violates lepton number conservation (a requirement of some neutrino mass models). Not yet observed.
- For \(^{76}\text{Ge}\) (Q = 2039 keV):
  \[ T^{2\nu}_{1/2} \sim 10^{21} \text{ y} \rightarrow \text{Rare process.} \]
  \[ T^{0\nu}_{1/2} > 10^{26} \text{ y} \rightarrow \text{Search needs ultra-low background, large mass, and long counting time. Good energy resolution helps distinguish from 2νββ-decay.} \]
  e.g. \[ T^{0\nu}_{1/2} \sim 10^{28} \text{ y} \] would give signal of \( \sim 0.5 \) counts/ton/yr
RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment.

A ton-scale instrument designed to search for this as-yet unseen nuclear decay will provide the most powerful test of the particle-antiparticle nature of neutrinos ever performed. With recent experimental breakthroughs pioneered by U.S. physicists and the availability of deep underground laboratories, we are poised to make a major discovery.
Next Generation $^{76}\text{Ge: LEGEND}$

**Large Enriched Germanium Experiment for Neutrinoless $\beta\beta$ Decay**

**Mission:** “The collaboration aims to develop a phased, Ge-76 based double-beta decay experimental program with discovery potential at a half-life beyond $10^{28}$ years, using existing resources as appropriate to expedite physics results.”

Select best technologies, based on what has been learned from GERDA and the Majorana Demonstrator, as well as contributions from other groups and experiments.

**First phase:**
- (Up to) 200 kg.
- Modification of existing GERDA infrastructure at LNGS.
- BG goal ($\times 5$ lower) $0.6 \text{ c}/(\text{FWHM} \cdot t \cdot y)$.
- Start by 2021.

**Subsequent stages:**
- 1000 kg (staged).
- Timeline connected to U.S. DOE down select process.
- BG goal ($\times 30$ lower) $0.1 \text{ c}/(\text{FWHM} \cdot t \cdot y)$.
- Location: TBD.
  Required depth (Ge-77m) under investigation.
The MAJORANA Demonstrator

Requires very low background front end electronics!
(< 1 count in ROI per ton, per year!)
Detector Geometries

Coaxial

Small Electrode

C ~ 20 pF

C ~ 1 pF
Germanium Point Contact Detector

- Originally proposed as dark matter detector
- Discrimination of multi-site events
- Low capacitance $\rightarrow$ low noise
- Lower trapping from p-type (than n-type), hence the LBNL P-Type Point Contact (PPC) detector

![Diagram of Germanium Point Contact Detector](image)

### Resistive Feedback

**Pro**
- Simple

**Con**
- Johnson noise
- Excess noise
- Resistor mass/radioactivity
- Energy-rate limitation
- Pole-zero difficulties

Increase $R_f$ a-Ge resistor

### Pulsed Reset

**Pro**
- No feedback resistor

**Con**
- Reset crosstalk (multi-channel system)
- Dead time during reset
- Added input capacitance
- Added complexity
Resistive Feedback JFET Front End

Junction Field Effect Transistor (JFET) – a Voltage Controlled Resistor (tens of ohms)

Front End Electronics

Moxtek JFET
Electronic Noise & Equivalent Noise Charge (ENC)

Voltage (Series) Noise
ENC \sim V_{n,FET} (C_{FET} + C_{Det} + C_{F} + C_{stray} + \ldots)
V_{n,FET} \sim C_{FET}^{-1/2}
\rightarrow \text{Min. noise: } C_{FET} \sim (C_{Det} + C_{F} + C_{stray})

Current (Parallel) Noise
ENC \sim (2qI_{L} + 4kT/R_p)^{1/2}
I_{L} \text{ – full shot-noise leakage current}

1/f Noise
Lossy dielectric, trapping-detrapping, ...
LMFE Test with Mini-PPC

Low Mass Front End

Test Cryostat

Optimization of JFET operating temperature with thermally isolating glass PCB
No Detector (preamp only)
preamp & detector

LMFE Minimum Noise

ENC² (e_{rms}²)

7/22/09
LMFE - mini PPC
MOXTEK MX-11
Vd = 2.6 V, Id = 8 mA

85 eV FWHM

50 eV FWHM

FWHM time (µs)
Mini-PPC Spectral Performance

Am-241

060109B
LMFE - miniPPC (HP41002-1b)
Vb = 150 V
shaping time = 24 us

60 keV

378 eV FWHM

95 eV FWHM

pulser

Counts

Channel No.
BEGe Noise with Moxtek (MX11) JFET

150 eV-FWHM limited primarily by capacitance of crystal

...but OK for some large physics experiments →
LBNL Low Mass Front End (for MAJORANA)
LBNL Low Mass Front End

- Sputtered Ti / Au Traces 200A / 4000A
- 200 µm thick Fused Silica

Front End

~80 K
~200 K

- JFET experiences Joule heating from drain current
- Board thermally separated from LN temperatures
LBNL Low Mass Front End

Cryostat

Epoxied MOXTEK MX-11RC
Al(1% Si)
1 mil Wire Bonds

Gate

Drain Source

Front End

TRA-DUCT 2902 Silver Epoxy
Room temp cure, low outgassing
0.001 ohm-cm
CTE = 0.6e-6 cm/cm/K
3.0 W/m/K

MOXTEK JFET
MX-11RC (reduced capacitance)
designed for x-ray detectors
C_{gs} = 0.7 pF
g_m = 8
\epsilon_n^2 = 1.5 nV/\sqrt{Hz}
LBNL Low Mass Front End

Low Mass Front End

Pulser
Feedback

Front End

3D Electrostatic Simulation
Set voltages, Look for charge

Cryostat

Capacitance = \( V^{-1} \int \text{Surface charge density} \)

C\(_f\) = 176 fF
C\(_p\) = 45 fF

Pulser
Feedback
LBNL Low Mass Front End

Sputtered Germanium, LBNL-B77
4000A
24 hr pumpdown, 2 mTorr, 120 W, 90 A/min

R_f

a-Ge at low temperatures = low noise

\[ R(G\text{-ohm}) \]

3/3/09
LMFE a-Ge resistors

a-Ge (17.5% H2)
a-Ge (Ar)

77 K
160 K 140 K

\[ T^{(-1/4)} \]
LBNL Low Mass Front End

Front End

Preamplifier

Cryostat

Simple cascode design a la F. Goulding (1967)
### Low Mass (~Radio-Pure) Materials

#### Preliminary Assay results courtesy J. Loach

- **715 nBq / LMFE → 0.3 cnt/ROI-ton-yr**

#### Budget
- Budget < 4.1 cnt/ROI-ton-yr
- Goal = 3 cnt/ROI-ton-yr

#### Materials and Components

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Purity (g / g)</th>
<th>Counts / ROI / t / y</th>
<th>Ref.</th>
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<tr>
<td></td>
<td></td>
<td>$^{232}$Th</td>
<td>$^{238}$U</td>
<td></td>
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<tr>
<td>Substrate</td>
<td>Fused silica</td>
<td>$101 \times 10^{-12}$</td>
<td>$284 \times 10^{-12}$</td>
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<td>Resistor</td>
<td>a-Ge</td>
<td>$5 \times 10^{-9}$</td>
<td>$5 \times 10^{-9}$</td>
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<tr>
<td>Traces</td>
<td>Au</td>
<td>$47(1) \times 10^{-9}$</td>
<td>$2.0(0.3) \times 10^{-9}$</td>
<td>0.0421</td>
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<td>Traces</td>
<td>Ti</td>
<td>$&lt; 400 \times 10^{-12}$</td>
<td>$&lt; 100 \times 10^{-12}$</td>
<td>$\sim 0$</td>
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<td>FET</td>
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<td>$&lt; 2 \times 10^{-9}$</td>
<td>$&lt; 141 \times 10^{-12}$</td>
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<tr>
<td>Bonding wire</td>
<td>Al</td>
<td>$91(2) \times 10^{-9}$</td>
<td>$9.0(0.4) \times 10^{-12}$</td>
<td>$0.0004$</td>
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<tr>
<td>Epoxy</td>
<td>Silver epoxy</td>
<td>$&lt; 70 \times 10^{-9}$</td>
<td>$&lt; 10 \times 10^{-9}$</td>
<td>$&lt; 0.0685$</td>
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<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>&lt; 0.1476</strong></td>
<td><strong>&lt; 0.0720</strong></td>
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</table>

- Ultrasonically Drilled Holes (Bullen, Inc.) for MAJORANA
Majorana LMFE Design Layout

1. Revision
2. Lot
3. Wafer
4. Board

Layout 10 boards per 2 inch wafer

$\text{Ti} / \text{Au} = 11.76 \text{ mm}^2 (x \ 200A / 4000A)$

$\text{Ge} = 0.71 \text{ mm}^2 (x \ 4000A)$

$1/20^{th}$ mil ($1.27 \mu$m) Laser Transparency
Majorana LMFE Fabrication
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Majorana LMFE Fabrication
Class-100 clean room (with ESD flooring) @ LBNL

- T & humidity control
- Dry boxes to store production parts under LN boil-off atmosphere
- Ionizer + HEPA filter bench
Loading Electroformed Copper Clips
Production: QA

mechanical QA

- pressure corresponding to 650g applied on board

electrical QA

- full signal path + preamp test
- check baseline
- pulser check of 1st and 2nd stages
Majorana LMFE Assembly at SURF
Power + digitizer

Back-end electronics

Front-end electronics

WARM

Low-noise LV power supply

Controller card

Mother board

Preamp.

COLD

Front-end board
The MAJORANA Demonstrator (prelude to ton-scale)

Located at the 4850’ level of Sanford Underground Research Facility in South Dakota

Low background passive Pb and Cu shield with active muon veto

Ultraclean electroformed copper cryostat

- 30 kg of 87% enriched $^{76}\text{Ge}$
- 10 kg of natural Ge
Noise performance

FWHM_{Avg} \leq 250 \text{ eV}

Threshold_{Avg} \leq 700 \text{ eV}

![Graph showing FWHM and Threshold for different detector IDs.](image)
Spectroscopic performance

Energy Resolution (FWHM)

2.4 keV FWHM at Q=2039 keV
Silica substrate (radio-pure, electrical, thermal, mechanical)

1-100 GΩ Amorphous-Ge $R_f$ (radio-pure, low excess noise)

200 eV-FWHM noise with large PPC detectors (Majorana)

150 eV-FWHM noise with BEGe detector

85 eV-FWHM noise with mini-PPC detector (55 eV w/o detector)

Can we lower the noise?
Thank You...

This work was funded by: DOE {NP, NNSA {DNN R&D, NSSC}}

I gratefully acknowledge the support of my colleagues: Kai Vetter, Paul Luke, Mark Amman, Alan Poon, et al.
Equivalent Noise Charge

\[ ENC^2 = Q_n^2 = \left( \frac{e^2}{8} \right) \left[ \frac{4kT}{g_m} + e_{na}^2 \right] \frac{C_d^2}{\tau} + 4A_f C_d^2 + \left( 2q_e I_d + \frac{4kT}{R_f} + i_{na}^2 \right) \tau \]

- \( T \): JFET temperature
- \( g_m \): JFET transconductance (~gain)
- \( e_{na}^2 \): preamp / amp voltage noise
- \( C_d^2, C_d^2 \): detector (and other) capacitance
- \( \tau, \tau \): shaping time constant
- \( A_f \): fabrication-dependent factor
- \( I_d \): detector leakage current
- \( T \): feedback resistor temperature
- \( R_f \): feedback resistance
- \( i_{na}^2 \): preamp / amp current noise

**Front-End Related**

- \( e^2/8 \) from shaping filter (affects V/I differently)

**Related**

- Voltage (series)
- 1/f
- Current (parallel)

140 eV-FWHM at \( \tau = 8.2 \mu s \)

\[ T = 100:140 \]
\[ C_d = 1.2 \text{ pF} \]
\[ I_d = 3.0 \text{ pA} \]
\[ R_F = 16 \text{ G}\Omega \]
The Shaping Amplifier and Ideal Filters

Semi-Gaussian Shaper: \( \frac{\tau s}{1 + \tau s^n} \)
e.g. Canberra 2026 Spectroscopy Amplifier

Judicious choice of shaping filter can (de)emphasize Series vs. Parallel noise

Less series noise
JFET Heating Affects Feedback Resistance

Convert decay time into $R_f$ by:

$$\tau = R_f \times C_f,$$

where $C_f$ is known and constant

176 fF $\rightarrow$ 8-17 GΩ (~20 K range)

(time after preamp turn-on)
JFET Heating Fights Feedback Resistor

2009 – Mini PPC

Series Coeff.

1 mA

7 mA

1/F Coeff.

Parallel Coeff.
MOSFET Alternative to JFET

Investigating cold (<77 K) CMOS options:

XGLab CUBE ASIC
Entire Preamp-on-a-chip
Originally for SDD
Functional at 4 K

Pulsed-Reset
0.75 x 0.75 mm²
3.4 el.rms alone

would be 24 eV-FWHM in Ge, for a safe threshold of 70 eV!

4.4 electrons-rms for Silicon Drift Detector
Cold CMOS Schematic

HV pulser for C-V

Trade feedback resistor for Reset transistor

Preamp-on-a-chip

CMOS improves below LN\textsubscript{2}

ENC\textsuperscript{2} = \frac{4kT}{g_m} C\textsubscript{in}^2 + \frac{e^2}{\tau_p} + \frac{1}{f} A_f C\textsubscript{in}^2 + F_i (2q_e I\textsubscript{in} + i^2_n) \tau_p

Voltage 1/f Current
Microphonics from LN$_2$ Boiling

And mechanical cryocoolers have significantly more vibrations
Ultra-Low Vibration GM-Cycle Cryostat

Test HPGe and electronics at 10 – 100 K with GM Cryocooler
National Nuclear Security Consortium (NSSC) Supported

Additional vibration isolation used in optical systems for nm-scale vibration
CUBE ASIC Printed Circuit Board

PCB: Rogers 4000 – Low Dielectric Loss (low leakage current)

Power supply filters (RC surface mount) for $V_{io}$ and $V_{sss}$

Minimal test pulse capacitor

Test Pulse Capacitor

$C_p = 10.3 \text{ fF simulated}$

$= 9.3 \text{ fF measured}$
From Pin to Wirebond

Advantages
1. Reduce capacitance
2. Streamline assembly
3. Improve reliability
4. Reduce microphonics
5. Minimize mass

Reprocessing Steps
1. Wet etch to remove damage
2. Sputter Al on Li
3. Sputter a-Si on top
4. Evaporate 0.75 mm Al for point contact
5. Wirebond
Detector Characteristics

Detector Capacitance = 0.26 pF
Leakage Current = 20 fF (at 30 K)
Spectral Performance

- **241Am**
  - Be Window

Front View

**Graphs:**
- CUBE + PPC (HP41002-1b)
  - Shaping time = 8 μs
  - HV = 400 V
  - T = 43 K
  - Channels:
    - 59.5 keV
    - 39 eV
    - 353 eV
    - 405 eV
  - FWHM: T = 90 K

- **Temperature vs. Peak Width**
  - 59.5 keV
  - Pulser

- **Pulser Peak Width**
  - eV-FWHM
First: **Mechanically Cooled, Wirebonded PPC HPGe, with CMOS Front End**

- **Atmospheric Pressure He Gas**
  - Provides **ultra-low vibration** thermal link using standard GM cycle (10 – 80 K)
  - Eliminates all vibrations

- **Ultra-Low Capacitance**
  - Smaller point contact (0.26 pF) enabled by wire bonding
  - Ultra-Low Electronic Noise

- **Preamp-on-a-Chip**
  - CMOS ASIC for SDD
  - 4 electrons-rms noise
  - Better than JFET at low temperatures

**Low temperature and ultra-low capacitance** of CMOS and Ge.
**Result:** lowest noise HPGe detector: 39 eV-FWHM at 43 K.
A Common Theme

ASIC Front End Elements

1. the ASIC!
2. die attach (e.g. epoxy)
3. substrate
4. traces
5. bond wires
6. bypass capacitor(s) + passives
7. passives’ attachment
8. connector

Remember:
• Electrical
• Mechanical
• Thermal
• (Radiopurity)
Next Steps for L-1000

LBNL internal LDRD funding for a more suitable preamplifier ASIC

1. Optimized for operation in liquid argon
2. Optimized for large mass 1.5 kg HPGe detectors (1-3 pF?)
3. Single power supply (reducing the cabling needs)
4. Integrated feedback resistor (reduce external a-Ge)
5. Built-in power supply capacitor and filter (eliminate external cap)
6. Differential output for >10 m cable to DAQ

Coupled with silicon MEMS capacitors for off-chip PS decoupling
Silicon (radiopure) PCB, with wirebonds to detector
Thank You...

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A tale of two experiments

Majorana Demonstrator (SURF)

Detectors (29.7 kg enr\(^{76}\)Ge) in 2 vacuum cryostats. Surrounded by passive shield. Ultra-clean materials used. Detector arrays have demonstrated the lowest backgrounds and best energy resolution of all 0νββ decay technologies.

GERDA (LNGS)

- Detectors (37.6 kg enr\(^{76}\)Ge) in liquid argon (LAr).
- LAr an active shield: Backgrounds tagged with scintillation light.
- Reduction of backgrounds is crucial to achieve good discovery potential.
- Majorana and GERDA technologies combined with new R&D to accomplish this.
Current Front End Steps for L-200

Methodology:

- Use best radiopurity elements from Majorana
- Use LAr shielding from GERDA

Tasks:

- Test LMFE in LAr
- Modify a-Ge resistor on LMFE
- Choose JFET (MX11, SF291)
- Modify Preamp (GERDA | Majorana)

High Mass Front End surrogate w/ modified GERDA
LEGEND-200

- Initial 200 kg phase permits early science with a world-leading experiment.
- Exposure 1 ton · yr, sensitivity > 10^{27} yr
- Keeps young people involved and maintains skilled workers.
- Reduces risk for a future ton-scale phase. Reuse of GERDA infrastructure and Majorana/GERDA detectors (60 kg) permits possible data taking in 2021-2022.
- Room in GERDA cryostat for 200 kg of enriched detectors.

Required reduction in background for LEGEND-200 has already been demonstrated as feasible in the Majorana Demonstrator, GERDA, and dedicated test stands.