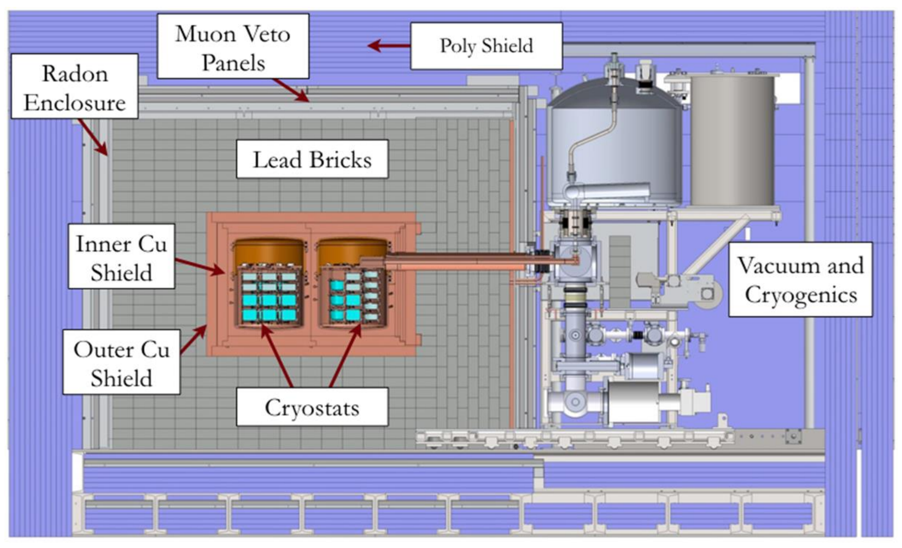
The MAJORANA DEMONSTRATOR's search for ββ-decay of ^{76}Ge to Excited States of ^{76}Se

Ian Guinn on behalf of the MAJORANA Collaboration

Introduction

The MAJORANA DEMONSTRATOR studied ββ-beta decay using an array of high purity germanium detectors. The experiment operated at the Sanford Underground Research Facility in Lead, SD until March 2021.

Final limit for 0νββ (64.5 kg-yr active exposure): $T^{0\nu}_{1/2} > 8.3 \times 10^{25}$ yr[1]



Cross-section of the MAJORANA DEMONSTRATOR's compact shield and detector modules

- 2 modules, with detectors operated in vacuum
- 44 kg of detectors (30 kg enriched to 88% in ^{76}Ge)
- Compact graded shield and active muon veto
- Low background materials
- Excellent energy resolution: 2.5 keV FWHM at 2039 keV
- P-type Point Contact (PPC) detectors allow pulse-shape discrimination of backgrounds

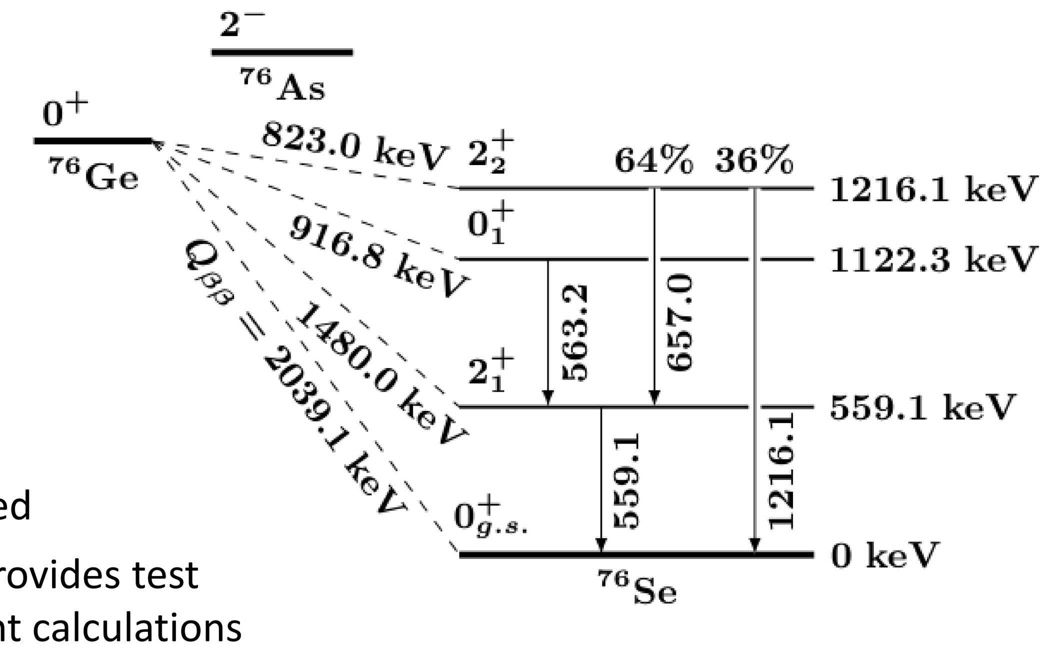
ββ-decay to Excited States

^{76}Ge can ββ-decay into three excited states (E.S.) of ^{76}Se, resulting in:

- Broad energy spectral feature from 2νββ decay
- Prompt emission of one or more γ-rays
- 0νββ peak at Q-value if neutrino is Majorana

Motivation

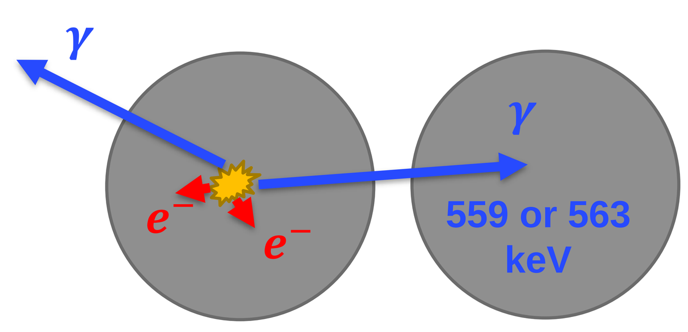
- ββ-decay to E.S. of ^{76}Se has not yet been observed
- Half-life measurement provides test of nuclear matrix element calculations
- Half-lives of some transitions are sensitive to exotic physics



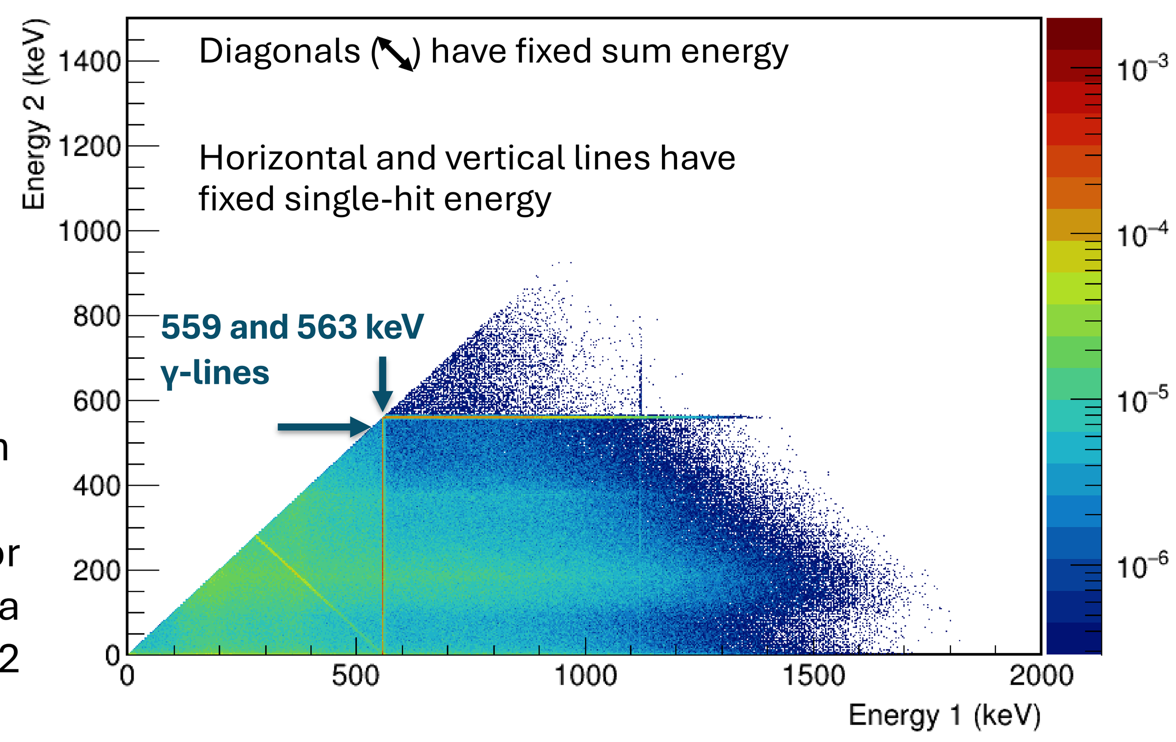
Energy level diagram for ββ-decay of ^{76}Ge

Detection Signature

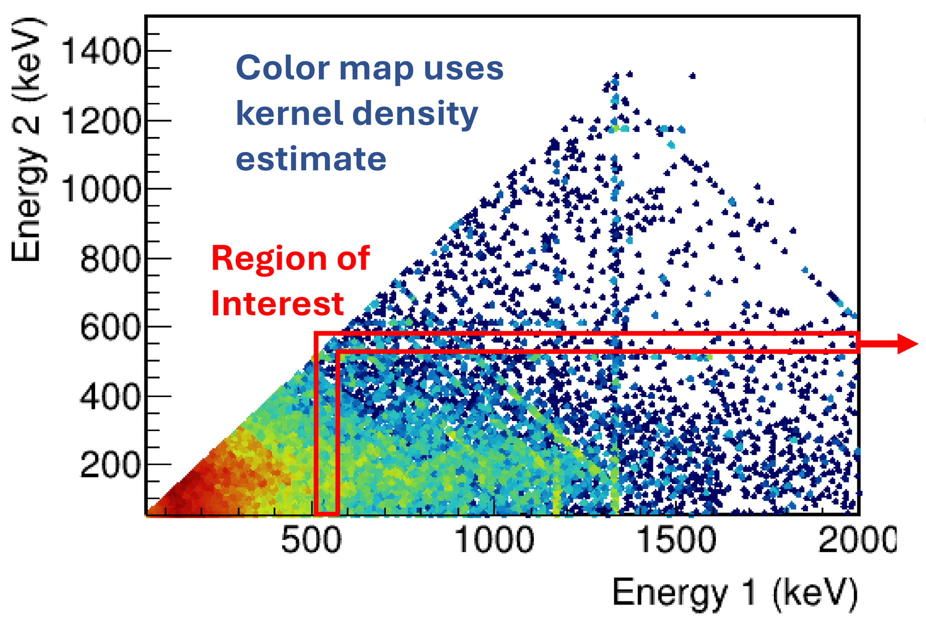
ββ-decay to excited state events are **inherently multi-site**. Search for an **energy-peak** in **high multiplicity events** when a deexcitation γ-ray is fully absorbed in a second detector



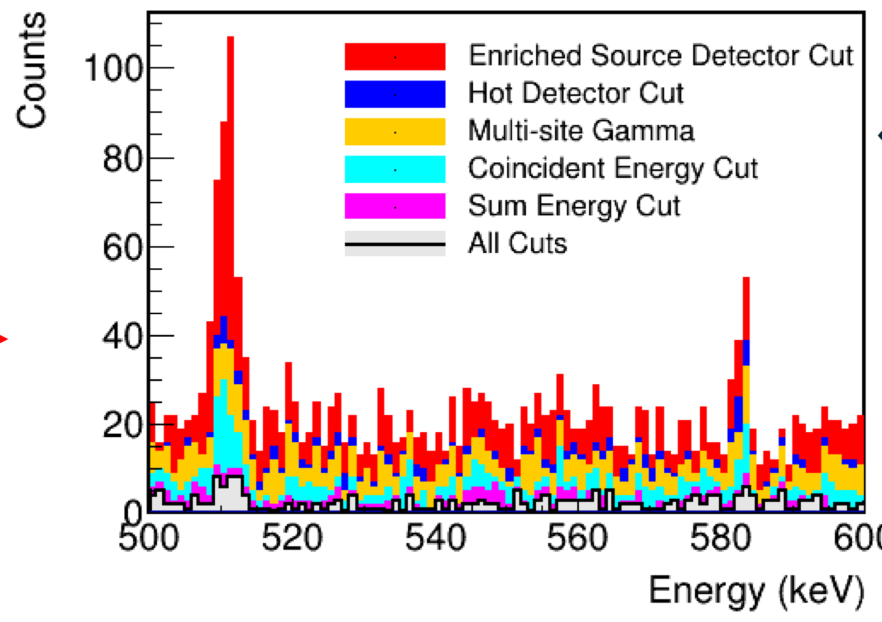
Above: detection signature for this search



Right: Simulated energy spectrum for 2νββ-decay to 0^+_1 E.S. events with a detector multiplicity of 2



All multiplicity 2 events from all datasets used in this analysis (98.2 kg-y of isotopic exposure)



Energy spectrum in region of interest near 559- and 563-keV γ-rays emitted in ββ-decay to 0^+_1 E.S. of ^{76}Se. Cuts (right) keep 74% of signal events and only 10% of background events!

Background reduction cuts

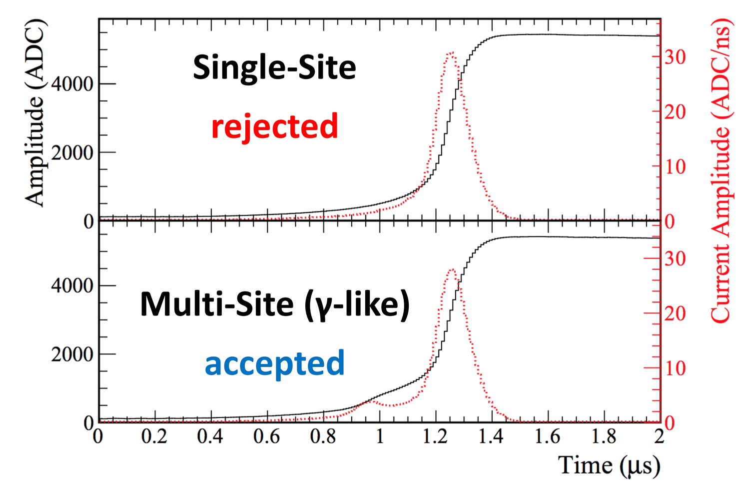
Utilize additional observables from multi-detector events to efficiently reject background events.

These cuts were developed using the background model for the MAJORANA DEMONSTRATOR (see *A. Reine*'s poster)

Enriched source detectors: reject event candidates with ββ-site in natural isotopic abundance detector

Hot detectors: reject events including hits in two detectors with high rate due to nearby point-like ^{232}Th source

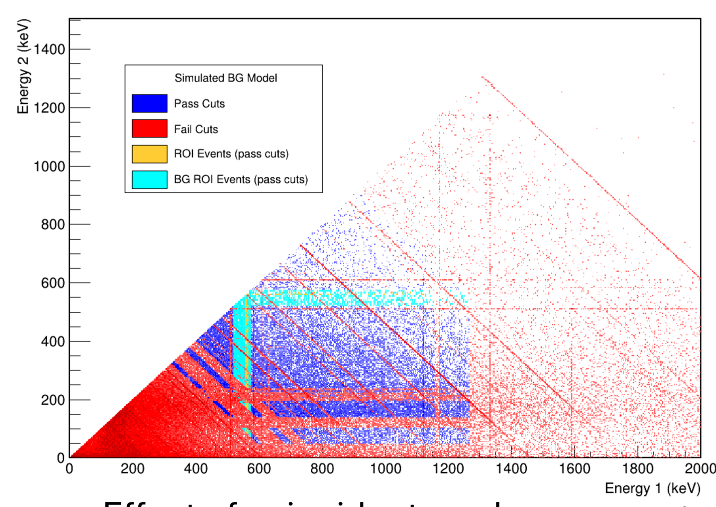
Multi-site Gamma: events in full absorption γ-peak are more likely to be multi-site; use *AvsE*[2] PSD technique to reject single-site hits



Charge and current signals from single- and multi-site events in PPC detectors

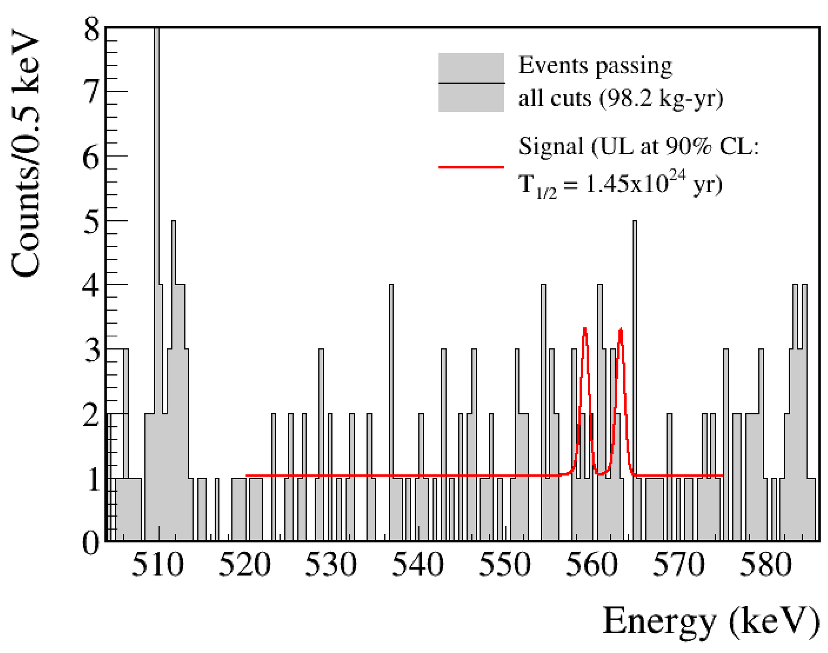
Coincident energy: reject events in coincidence with hits with energy of known backgrounds

Sum energy: reject events with sum energy across detectors equal to known backgrounds



Effect of coincident- and sum-energy cuts on simulated background model

Final Results



Energy spectrum after cuts for 2νββ to 0^+_1 E.S. of ^{76}Se with signal modelled at 90% CL upper half-life limit

New world-leading limits set for all six ββ-decay transitions of ^{76}Ge to excited states of ^{76}Se with 98.2 kg-yr of isotopic exposure!

Decay Mode	Efficiency	$T_{1/2}$ Limit	$T_{1/2}$ Sensitivity
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 0^+_1$	$2.15 \pm 0.24\%$	1.5×10^{24} y	2.2×10^{24} y
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_1$	$1.15 \pm 0.26\%$	3.0×10^{24} y	2.1×10^{24} y
$0^+_{g.s.} \xrightarrow{2\nu\beta\beta} 2^+_2$	$1.76 \pm 0.29\%$	0.88×10^{24} y	1.5×10^{24} y
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 0^+_1$	$2.83 \pm 0.32\%$	7.6×10^{24} y	5.9×10^{24} y
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_1$	$1.58 \pm 0.35\%$	6.1×10^{24} y	6.1×10^{24} y
$0^+_{g.s.} \xrightarrow{0\nu\beta\beta} 2^+_2$	$2.16 \pm 0.32\%$	6.6×10^{24} y	4.3×10^{24} y

For 2νββ to 0^+_1 E.S. of ^{76}Se, the branching ratio limit is:
$BR(0^+_1) < 1.4 \times 10^{-3}$ (sensitivity: 0.9×10^{-3})
approaching theoretical predictions of 0.7×10^{-3}(SM)[3], 1.2×10^{-3}(ET)[4] and 0.2×10^{-3}(IBM-2)[5]; all QRPA predictions to date have been ruled out.

The MAJORANA DEMONSTRATOR achieved world-leading sensitivity thanks to:

- Excellent energy resolution
- Operation in vacuum
- Low background environment

Bibliography

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