Double-Beta Decay of ^{96}Zr and Double-Electron Capture of ^{156}Dy to Excited Final States

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Thesis Defense

March 25, 2015

Outline

- Introduction to second-order weak decays
  - Nature of the neutrino
- Double-β decay of ^{96}Zr
  - Two-coaxial HPGe apparatus
  - Analysis and results
- Resonantly enhanced double-electron capture of ^{156}Dy
  - Two-clover HPGe apparatus
  - Analysis and results
- Concluding remarks

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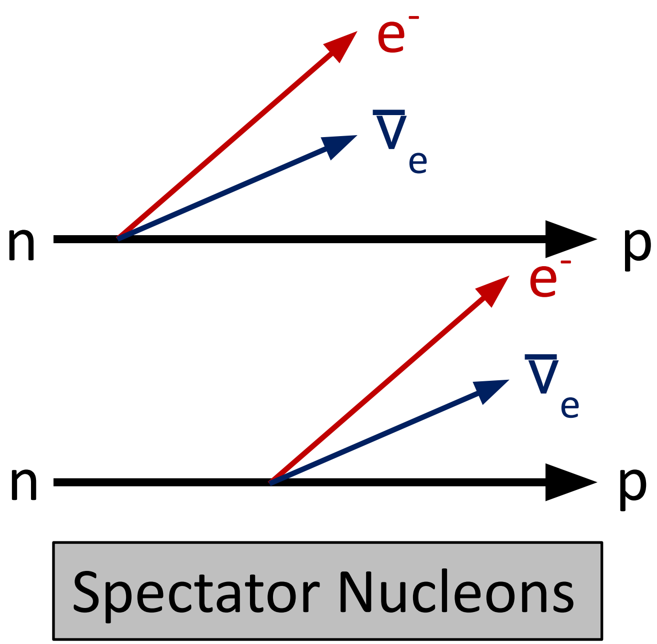
Weak Nuclear Decays

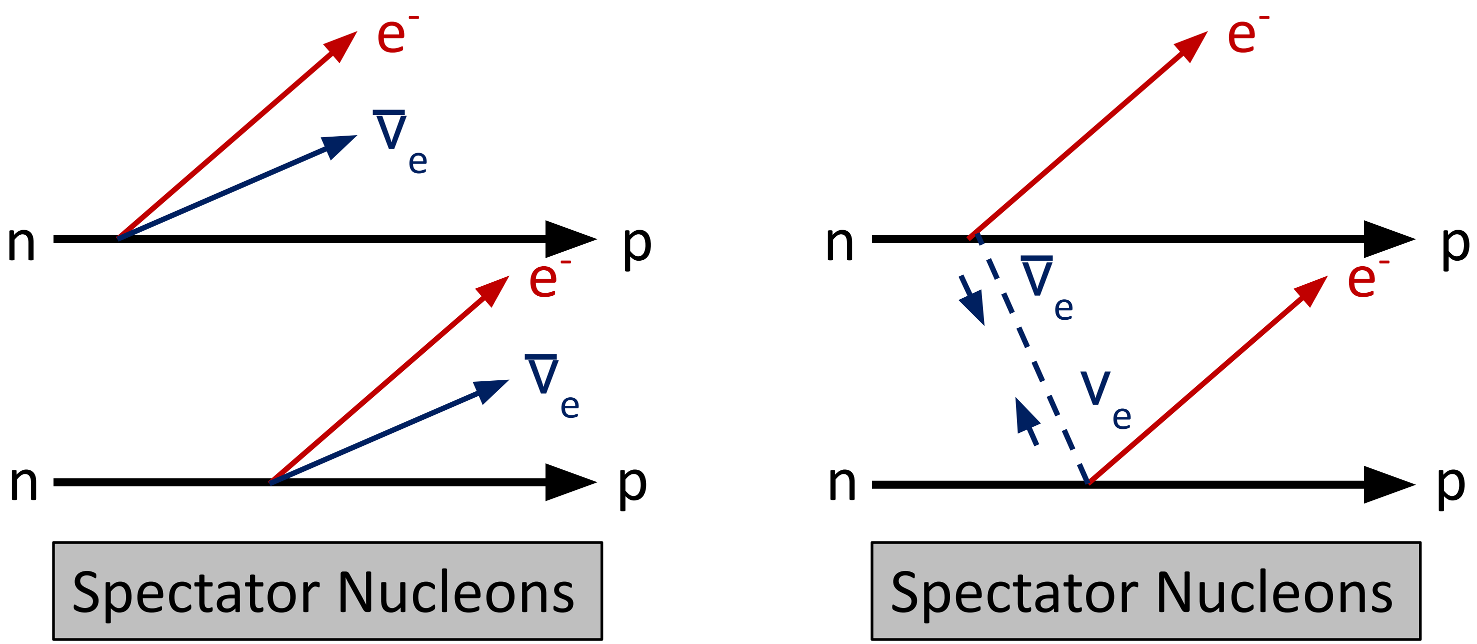
- β decay: $n \longrightarrow p + e^- + \bar{\nu}_e$
- Double-β decay: $2n \longrightarrow 2p + 2e^- + 2\bar{\nu}_e$
- 35 nuclides capable of ββ; Observed in 11



Neutrinoless-ββ Decay

- $n_1 \longrightarrow p_1 + e^-_1 +$ “ν_e”

  “ν_e” $+ n_2 \longrightarrow p_2 + e^-_2$
- Never observed (one questionable claim)



Majorana Neutrinos

$0\nu\beta\beta$ requires:

- Helicity flip
  - Solved by massive neutrinos
- Neutrinos are their own antiparticle
  - Solved by Majorana neutrinos

- Why is this interesting?
- $0\nu\beta\beta$ violates lepton number conservation
- Allows measurement of neutrino mass:
  - $\lambda_{2\nu\beta\beta} = G_{2\nu}\,|M_{2\nu}|^2$
  - $\lambda_{0\nu\beta\beta} = G_{0\nu}\,|M_{0\nu}|^2\,\langle m_\nu \rangle^2$
- Best limits on ^{76}Ge (GERDA)
  - $T_{1/2}(2\nu)=1.84^{+0.14}_{-0.10} \times 10^{21}$ yr
  - $T_{1/2}(0\nu) > 2.1 \times 10^{25}$ yr
  - $m_\nu < 200\text{-}400$ meV

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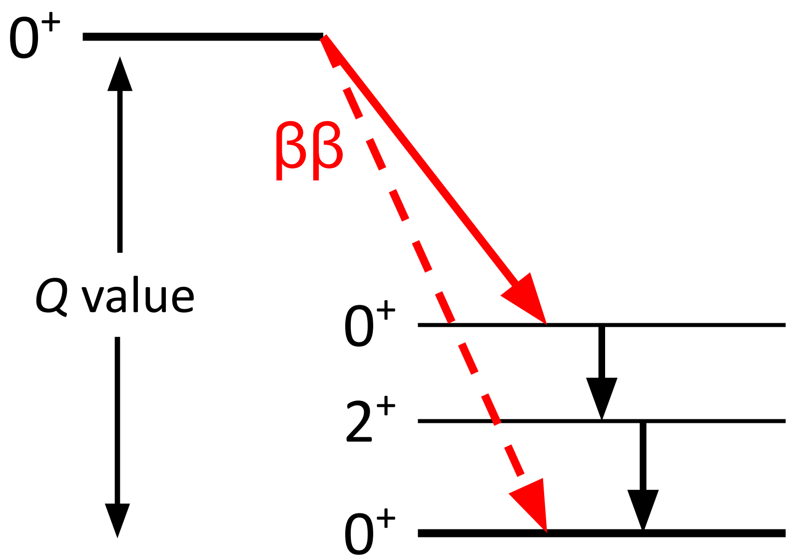
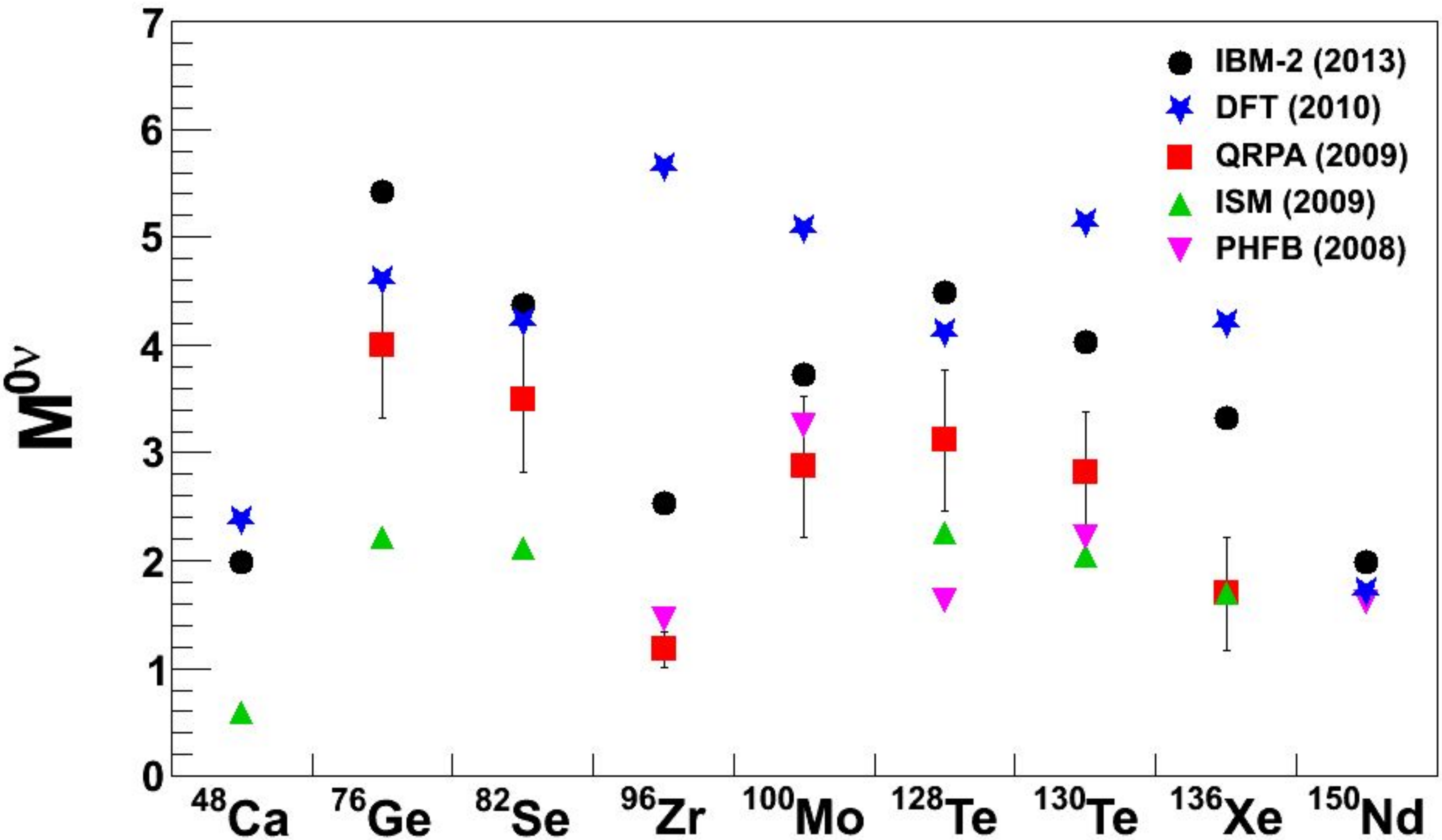
2νββ to Excited Final States

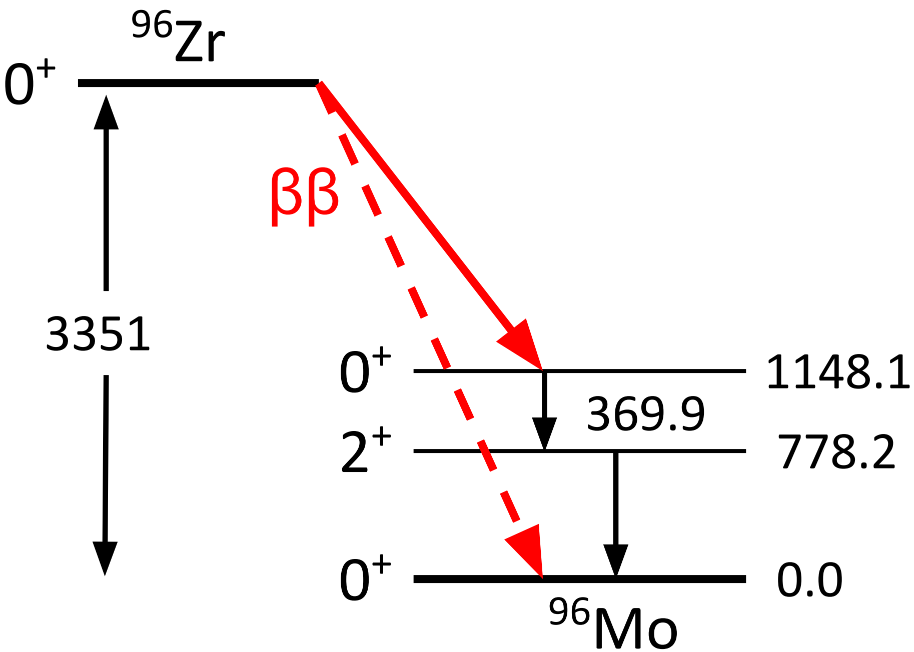


- $\lambda_{2\nu\beta\beta} = G_{2\nu} \left|M_{2\nu}\right|^2$
- $\lambda_{0\nu\beta\beta} = G_{0\nu} \left|M_{0\nu}\right|^2 \langle m_\nu \rangle^2$
- 0νββ matrix elements must be calculated
  - Tuned to reproduce 2νββ matrix elements
  - Decays to excited final states provides an additional constraint

Nuclear Matrix Elements

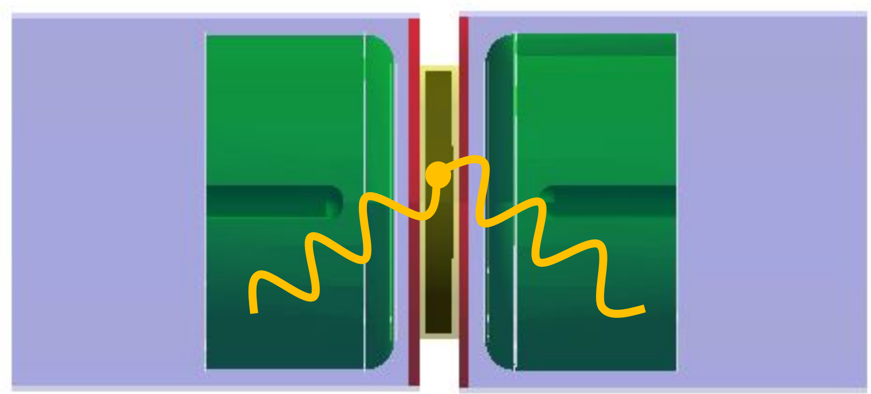


Experimental Technique



An excited state decay with two coincident γs

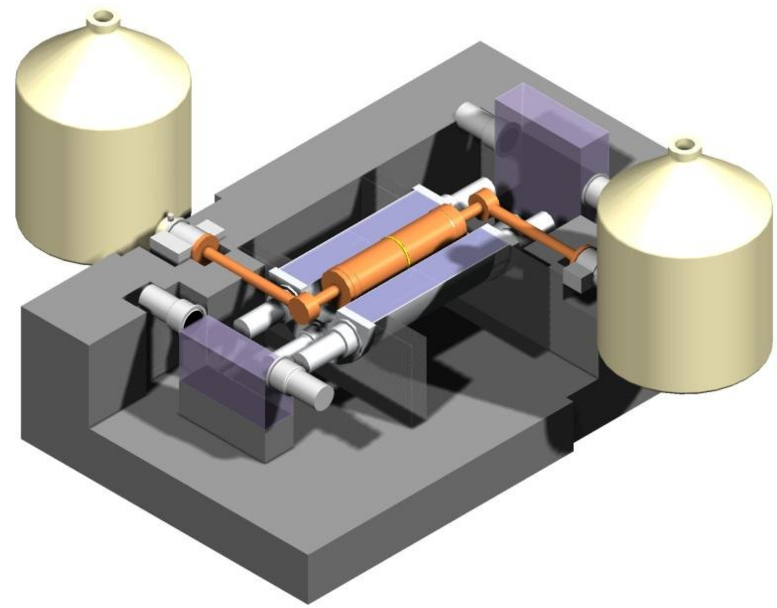
All energies in keV



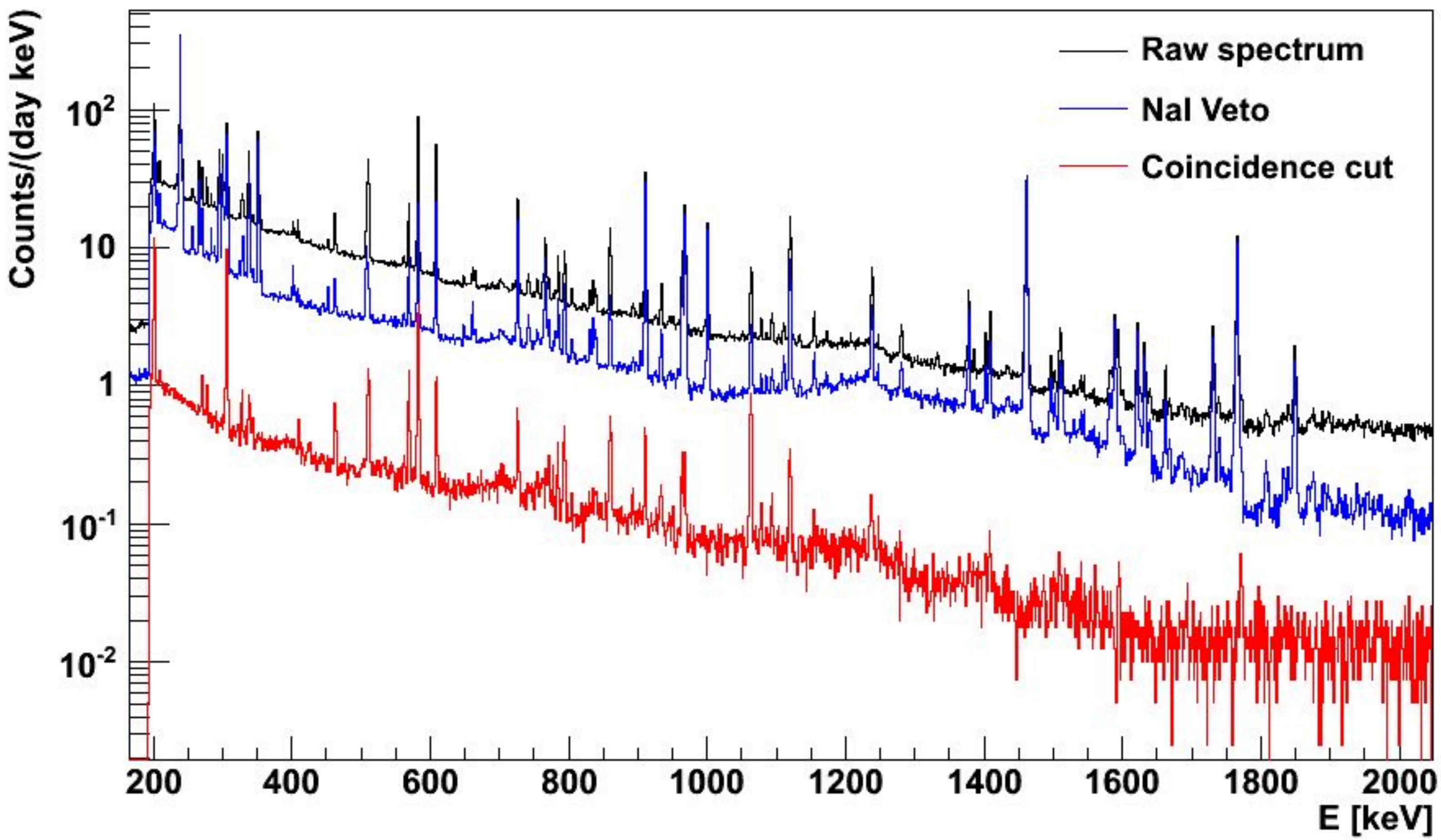
Sample between two coaxial-HPGe detectors

Two-Coaxial HPGe Apparatus

- Two-coaxial HPGe detectors sandwich sample
- Active veto
  - NaI annulus for Compton suppression
  - Plastic end caps
- Passive shielding
  - ¾” OFHC copper
  - 6” lead

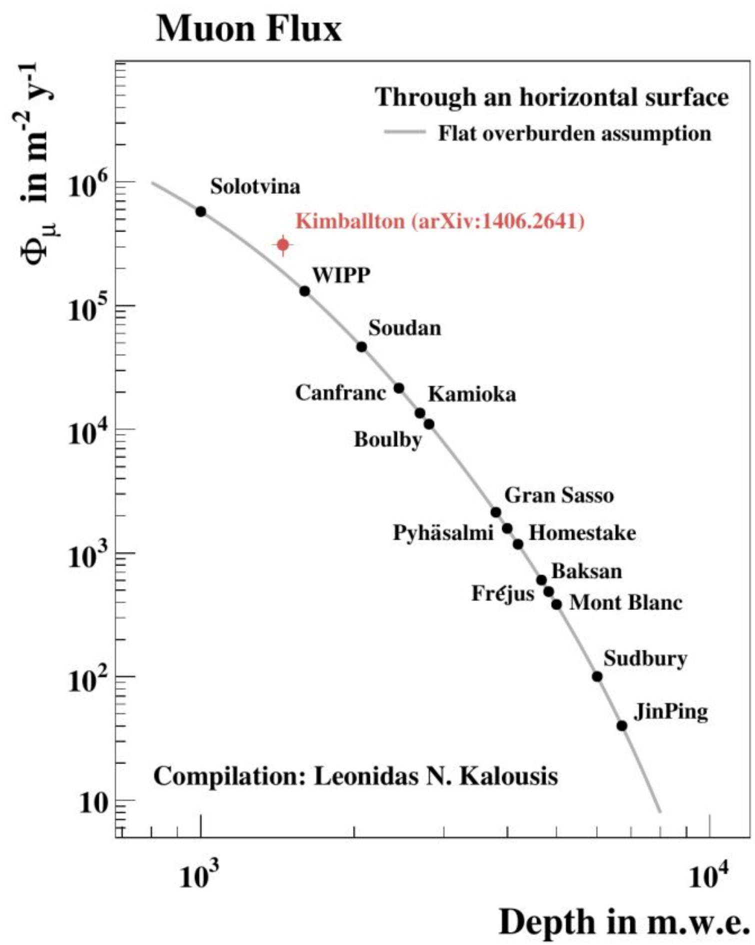


HPGe Spectrum



Kimballton Underground Research Facility (KURF)

- Active limestone mine
- Ripplemead, Va
  - 30 minutes from VT
  - 4 hours from Duke
- 1700 feet limestone overburden
- 1450 m.w.e. shielding from cosmic rays
- Internet access allows experiments to be controlled remotely



KURF

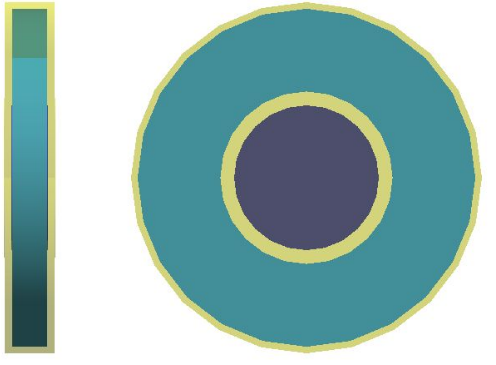
KURF Lab

A. micoLENS (VT)
B. Neutron Spectroscopy (Maryland)
C. Present experiment (Duke)
D. Low background radioassays (UNC)
E. MALBEK (UNC)
F. Low activity Ar (Princeton)
G. Watchboy (LLNL)

^{96}Zr Sample

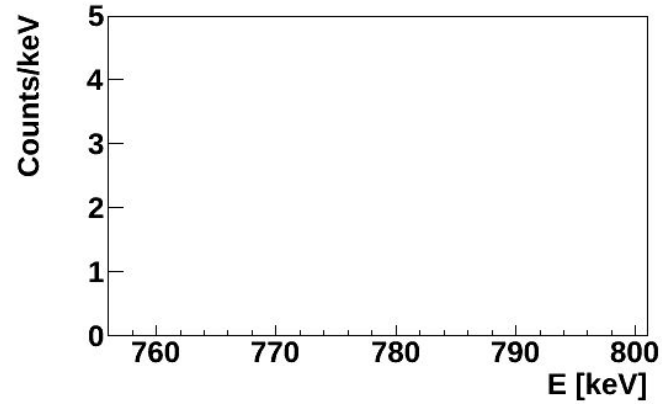
- ^{150}Nd and ^{100}Mo are the only two nuclides where ββ decay to an excited state has been observed
- ^{96}Zr as a ββ-decay candidate
  - High *Q* Value (3347 keV)
  - Ground state decay measured by NEMO collaboration

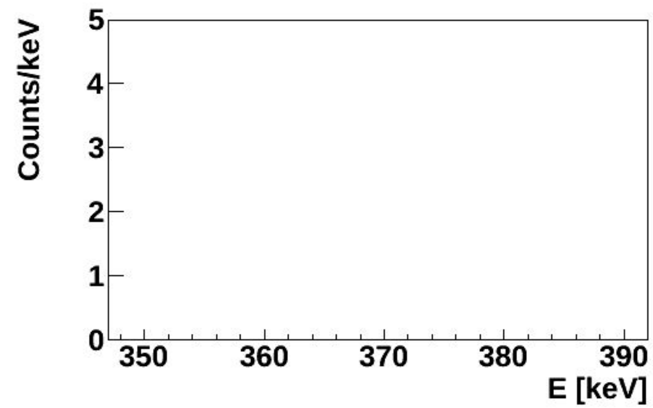
    $T_{1/2}$ = [2.35 ± 0.14 (stat) ± 0.16 (syst)] x 10^{19} yr
  - 2.8% natural abundance
- ZrO_2 sample from ORNL:
  - 7.283 g enriched to 91.39%
  - 26.968 g enriched to 64.18%
  - Total of 17.914 g ^{96}Zr



^{96}Zr 2νββ Data

- ^{96}Zr source in place
  - 623.8 days (1.92 yr) of data
  - 4 events in ± 3σ ROI
  - 2 events in ± 2σ ROI
  - Consistent with background
- Backgrounds
  - ^{212}Bi (^{232}Th decay chain)
  - Compton scattering
  - Discriminate with energy resolution





Limit Setting

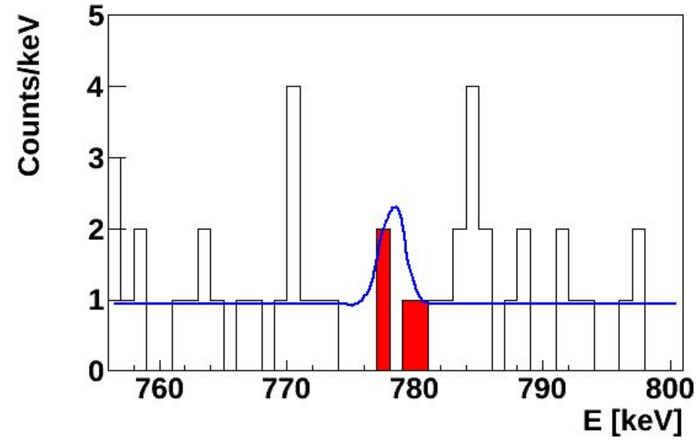
- $T_{1/2} > \frac{\ln(2) N_0 t f_b \epsilon}{N_d}$
  - N_0 Number of nuclei
  - t Exposure time
  - f_b Branching ratio
  - ϵ Efficiency
  - N_d Statistical factor
- Method of Feldman-Cousins used for confidence intervals

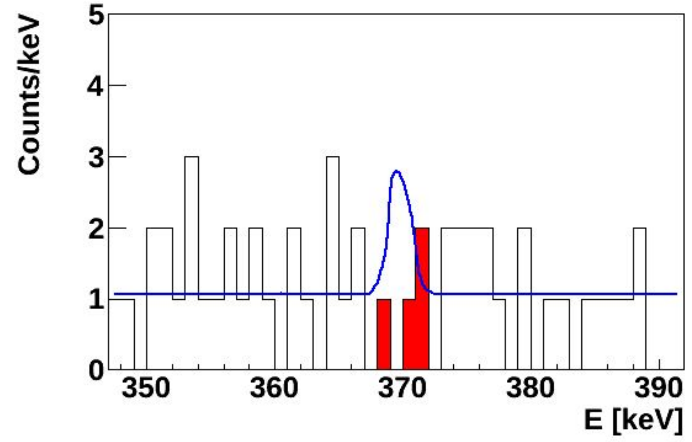
Limit versus sensitivity

- Limit: $N_d(N_{obs}, N_{bkgd})$
- Sensitivity: $N_s(N_{bkgd})$
  - The mean limit N_d reported by an experiment with background N_{bkgd} and no signal

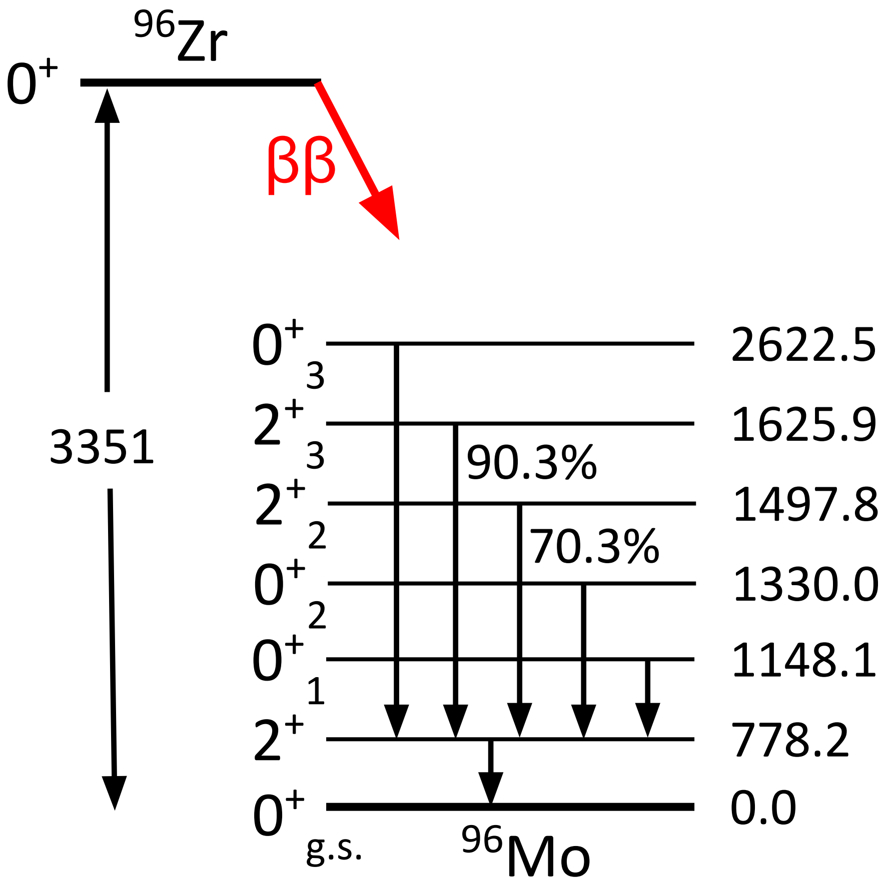
New limits

- Limit at 90% C.L.
  - $T_{1/2} > 3.2 \times 10^{20}$ yr
  - Sensitivity: $T_{1/2} > 2.8 \times 10^{20}$ yr
- Previous limit
  - $T_{1/2} > 6.8 \times 10^{19}$ yr
  - Used single well-type HPGe; no coincidence
  - Limited by high background and uncertainty from statistical fits





To Higher Excited States



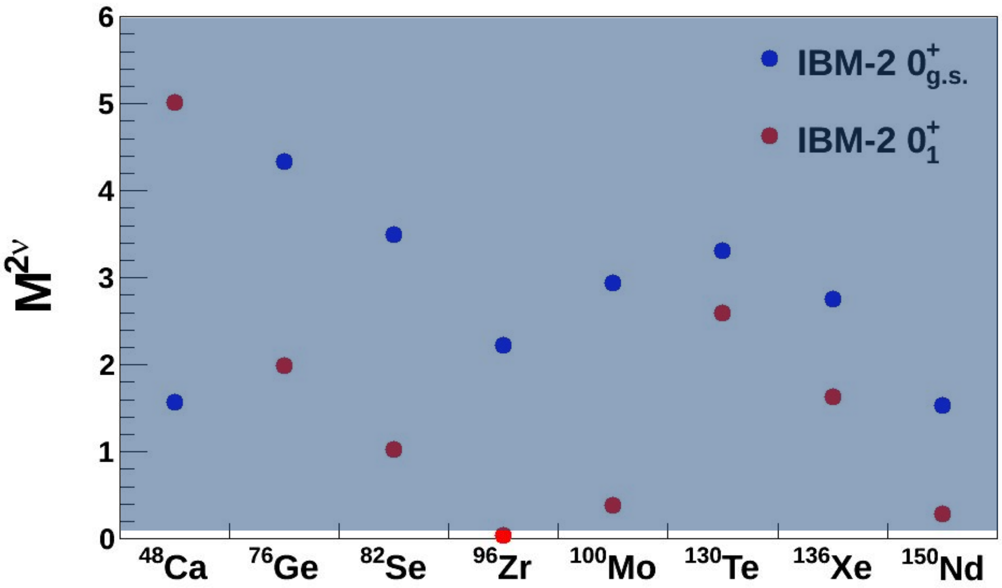
All energies in keV

J^π	E [keV]	$T_{1/2}$ [yr] C.I.	$T_{1/2}$ [yr] Sensitivity
0^+_1	1148.1	> 3.2×10^{20}	> 2.8×10^{20}
0^+_2	1330.0	> 1.4×10^{20}	-
2^+_2	1497.8	> 1.0×10^{20}	-
2^+_3	1625.9	> 1.2×10^{20}	-
0^+_3	2622.5	> 1.1×10^{20}	> 1.0×10^{20}

Limits on NME

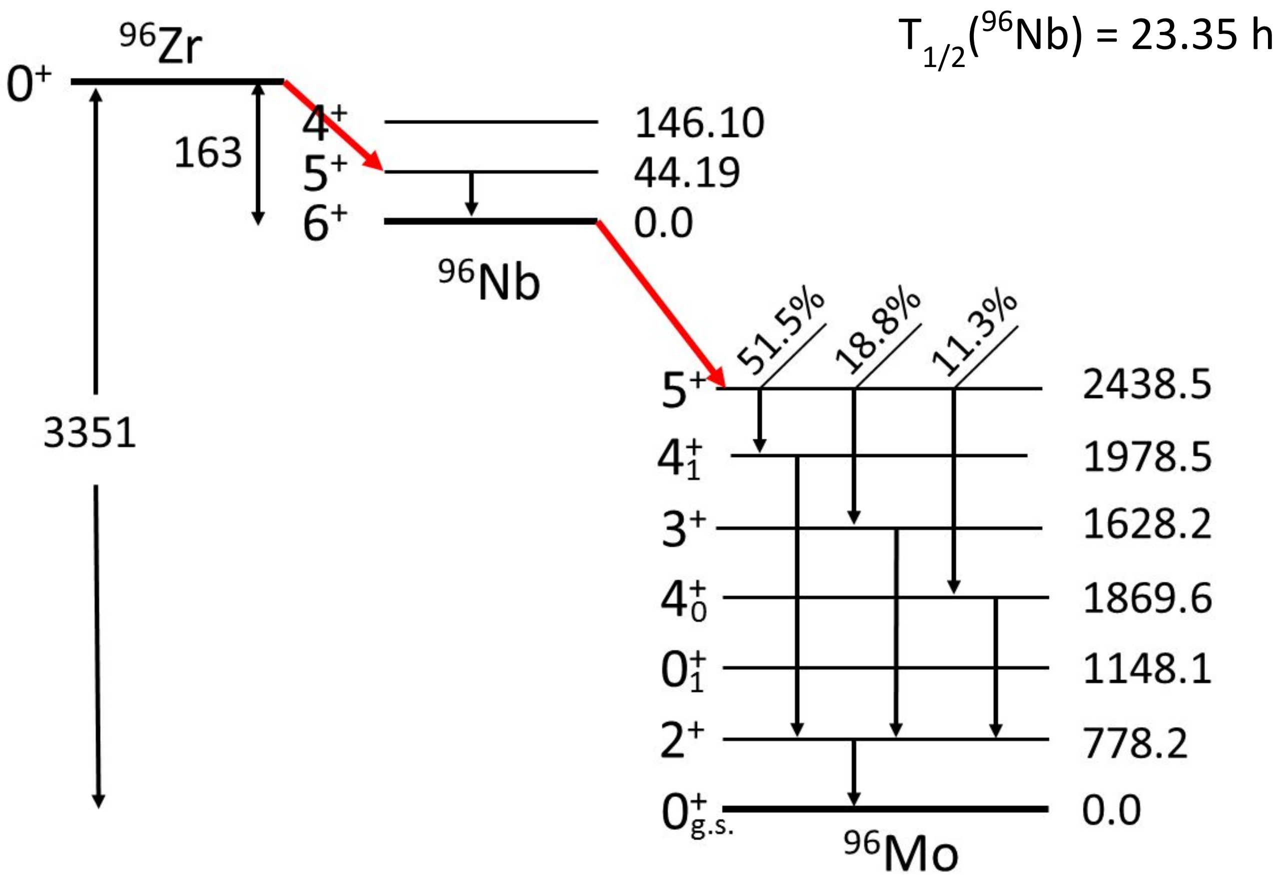
- $\lambda_{2\nu\beta\beta} = G_{2\nu\beta\beta}|M_{2\nu\beta\beta}|^2$

- Experiment:
  $\left|M_{2\nu\beta\beta}\ (0_1^+)\right| < 0.11$
- IBM-2 theory[1]:
  $\left|M_{2\nu\beta\beta}\ (0_1^+)\right| = 0.04$



[1] J. Barea, J. Kotila, and F. Iachello, Phys. Rev. **C** 87, 014315 (2013)

Single-β decay of ^{96}Zr



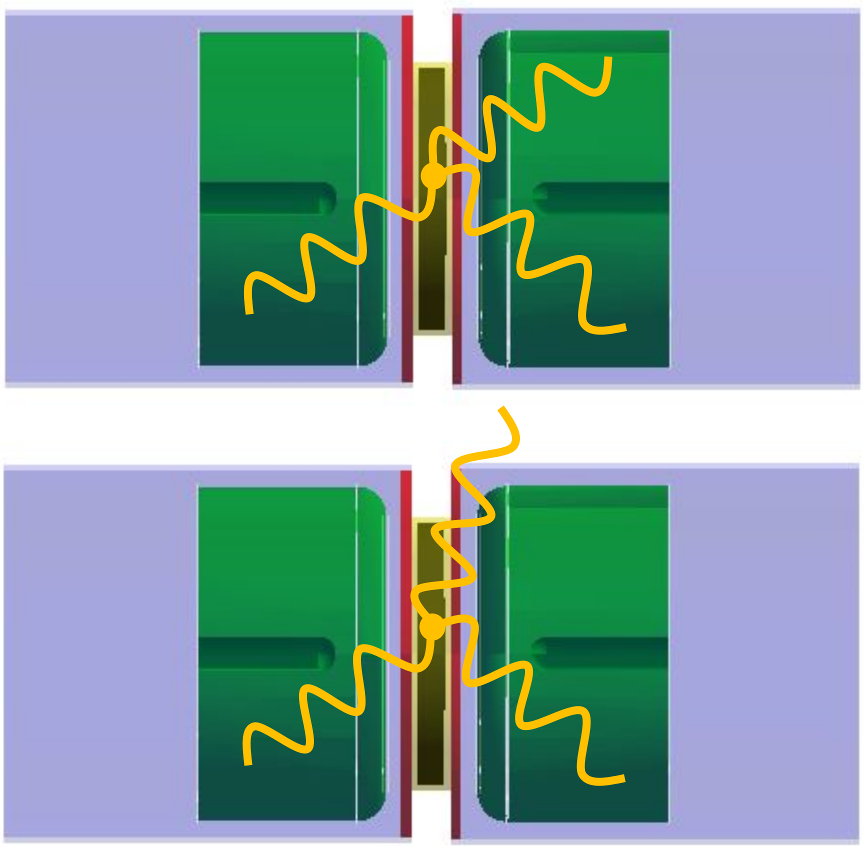
All energies in keV

Experimental Motivation

- Help understand the nuclear structure of ^{96}Zr
- Possible background for experiments searching for $0\nu\beta\beta$ in ^{96}Zr
- Previous experiments used a single HPGe detector
  - β decay forms an irreducible background for excited state decays
- Using the coincidence technique in present work can unambiguously distinguish β decay and ββ decay

Limits on Single-β decay of ^{96}Zr

Three coincident γs



- Present Experiment
  - Sum three most intense decay modes
    - Branching ratio 81.6%
  - 13 events in ROI , expect 11.1 events background
  - $T_{1/2} > 2.4 \times 10^{19}$ yr
- Previous measurement
  - $T_{1/2} > 3.8 \times 10^{19}$ yr
- Theory[2] (QRPA)
  - $T_{1/2} = 2.4 \times 10^{20}$ yr

[2] H. Heiskanen, M.T. Mustonen, and J. Suhonen, J. Phys. Rev. **G** 34, 837 (2007)

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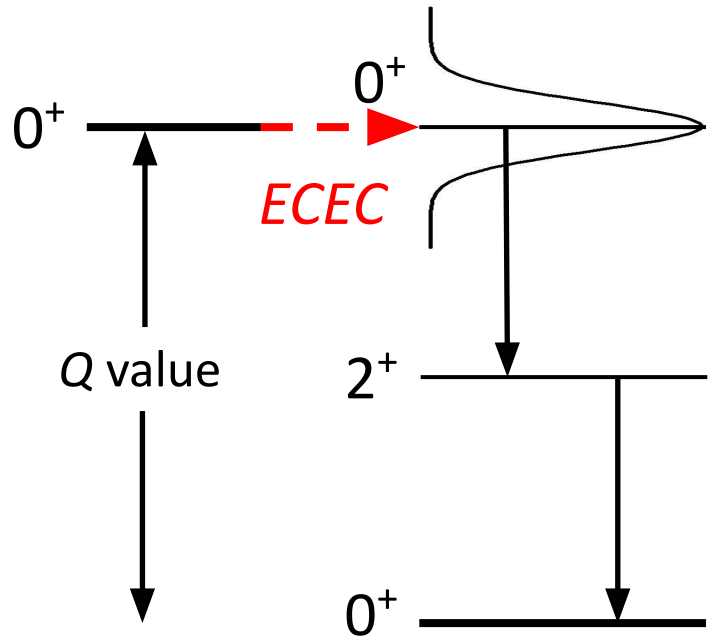
Resonant ECEC to Excited Final States

- Nucleus captures atomic electron
  - $p + e^- \rightarrow n + \nu_e$
- Second-order nuclear decay
  - $^{156}Dy + 2e^- \rightarrow {}^{156}Gd + 2\nu_e$
- For Majorana neutrinos
  - $^{156}Dy + 2e^- \rightarrow {}^{156}Gd^*$
  - Possible experimental alternative to $0\nu\beta\beta$
- No outgoing particles
  - No method to dissipate excess energy
  - Requires "monumental coincidence" that an excited nuclear state in the daughter nucleus is degenerate with the *Q* value

Resonant ECEC to Excited Final States

- Two neutrino mode strongly disfavored by phase space
- Observation would be evidence for Majorana neutrinos
- Rate enhancement if the *Q* value is degenerate with an energy level



ECEC in ^{156}Dy

E_γ [keV]	I^π	Electron Orbitals	(B_{XY}) [keV]	Δ [keV]	Γ_{XY} [eV]	EF	$\lvert\Psi_x\rvert^2\lvert\Psi_y\rvert^2$
1946.375	1^-	KL_1	58.822(8)	0.75(10)	26	4.1×10^6	1.23×10^{10}
1952.385	0^-	KM_1	52.192(8)	1.37(10)	35	1.7×10^6	2.68×10^{10}
1988.5	0^+	L_1L_1	16.914(8)	0.54(24)	8	2.5×10^6	1.65×10^{10}
2003.749	2^+	M_1N_3	2.160(24)	0.04(10)	15	7.7×10^8	1.52×10^1

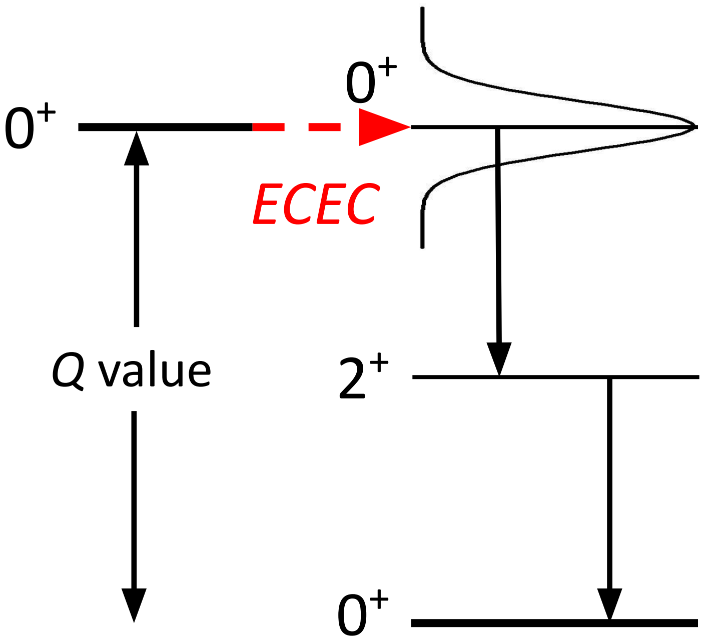
$$\text{EF} = \frac{\Gamma_{XY}}{\Delta^2+\frac{1}{4}\Gamma_{XY}^2}$$

$$\lambda^{0\nu ee} = G_{0\nu ee}|M^{0\nu ee}|\,\langle M_\nu\rangle^2\,(EF)$$

[3] S. Eliseev *et al.*, Phys. Rev. **C** 84, 012501(R) (2011)

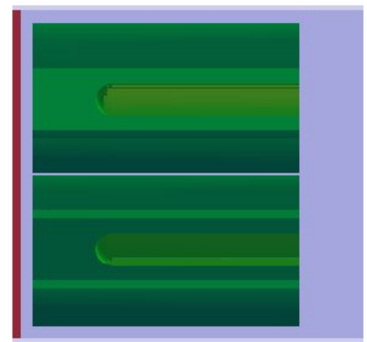
Resonant ECEC in ^{156}Dy

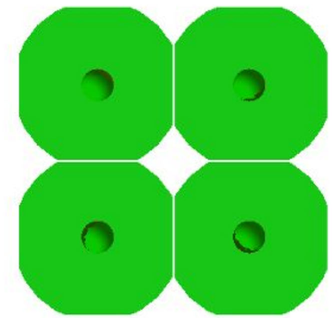
- ^{156}Dy is currently one of the most promising candidates
  - Extremely low natural abundance: 0.056%
- Enriched sample from ORNL
  - 1.15 grams
  - Enriched to 21%
  - Total = 213 mg
- Detectable only by γ-ray transitions in daughter

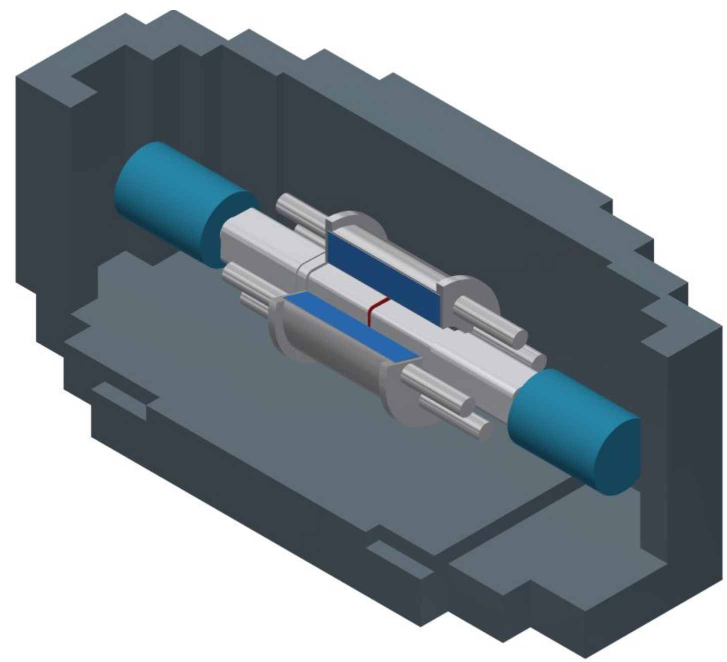


New Two-Clover HPGe Apparatus

- Use two clover HPGe detectors
  - Segmented
  - Larger volume
- NaI annulus
- 6-8” Lead shielding
- Timeline
  - Built in 2010
  - Characterization and efficiency measurements 2010-2012
  - Moved to KURF Fall 2012
  - ^{156}Dy sample 2013-2014

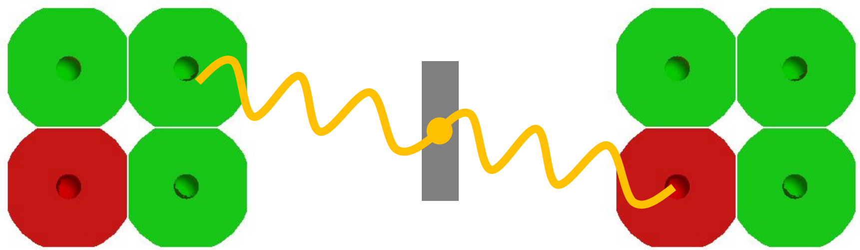




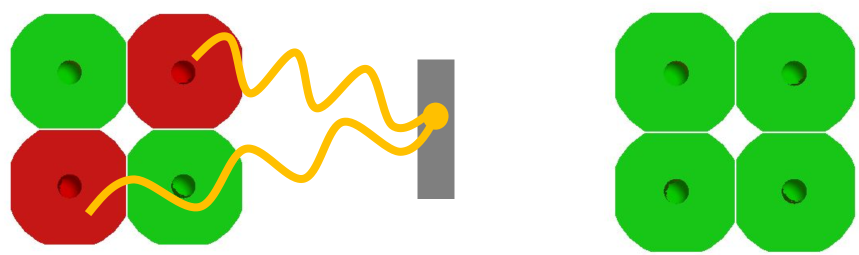


Coincidence and Addback

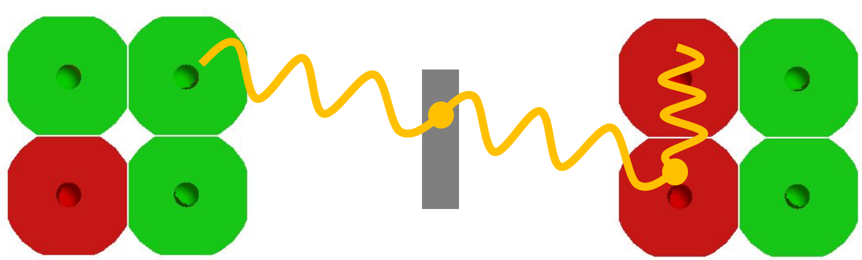
- External coincidences



- Internal coincidences



- Addback coincidences



Previous Searches

Belli *et al.*[4]

- 322 g natural Dy_2O_3
- 157 mg ^{156}Dy
- 104.7 days
- Single HPGe at LNGS

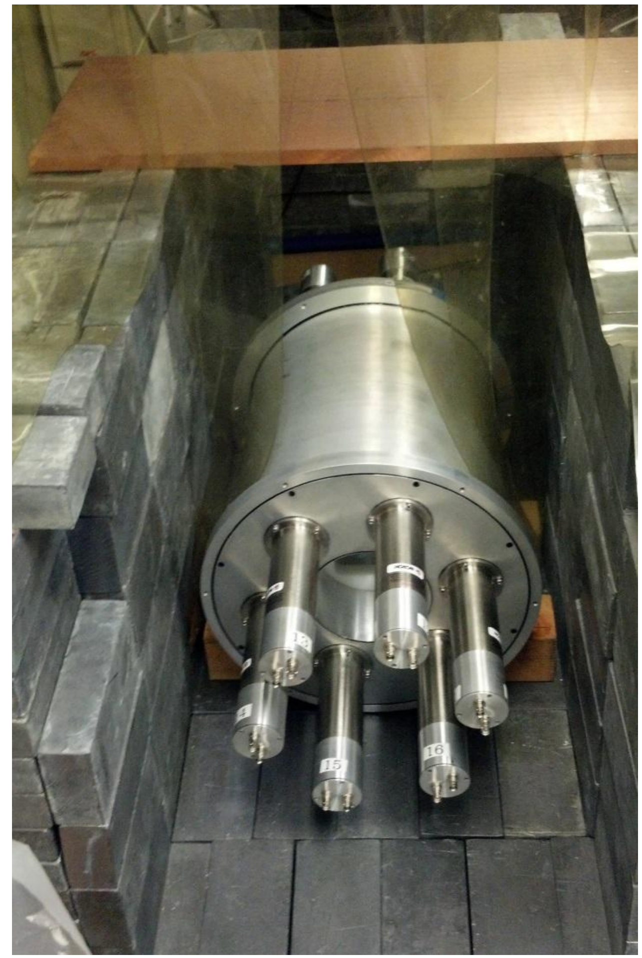
This work

- Enriched sample
  - Reduce γ-ray attenuation by sample
- Cover a larger solid angle
- Ability to look at coincidence γ-rays from cascades
  - Reduce background

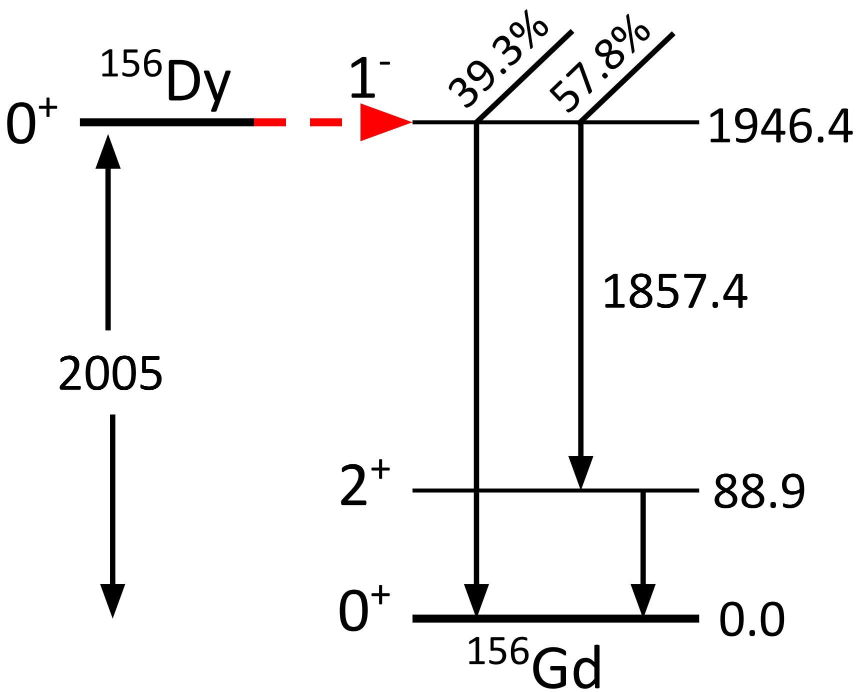
[4] P. Belli *et al.*, J. Phys. Conf. Ser. **375**, 042024 (2012)

^{156}Dy Data Acquisition

- Run #1
  - 151.95 mg
  - 99.13 days
- Run #2
  - 213.57 mg
  - 132.82 days
- Presented results are the sum of both runs
  - 0.119 g·yr of exposure



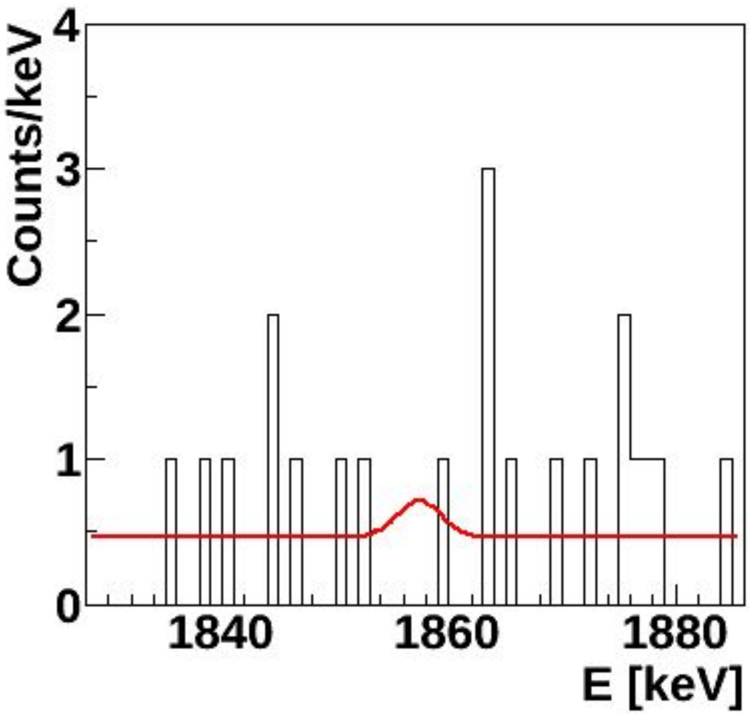
Capture to the 1946 keV State



All energies in keV

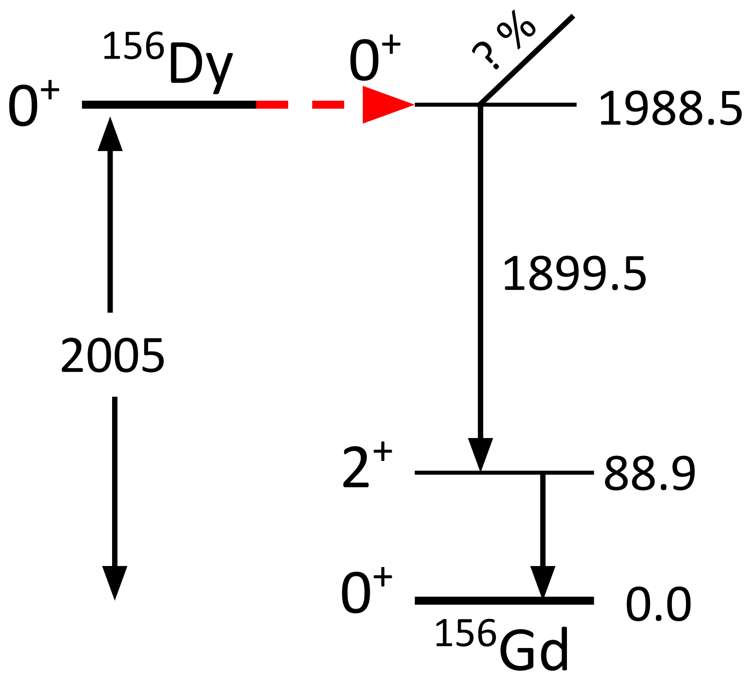
- Branching ratio 57.8%
- Gate on 88.9 keV γ ray in one clover segment
- Allow singles and addback on 1857 keV

Capture to the 1946 keV State



- Branching ratio 57.8%
- Gate on 88.9 keV γ ray in one clover segment
- Allow singles and addback on 1857 keV
- 1 event in ROI, expected 4.12 events background
  - $N_d = 1.275$
  - $N_s = 4.86$

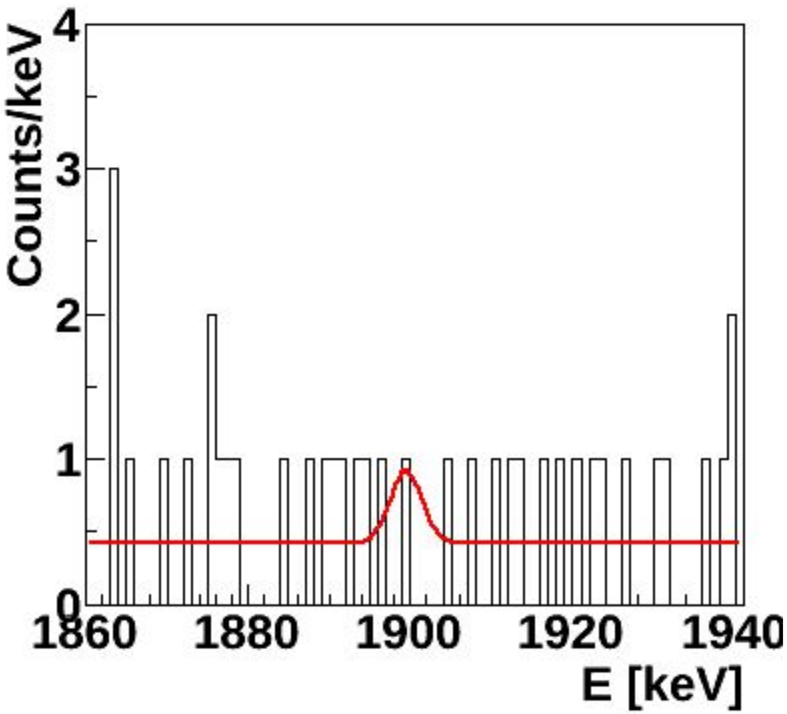
Capture to the 1988 keV State



All energies in keV

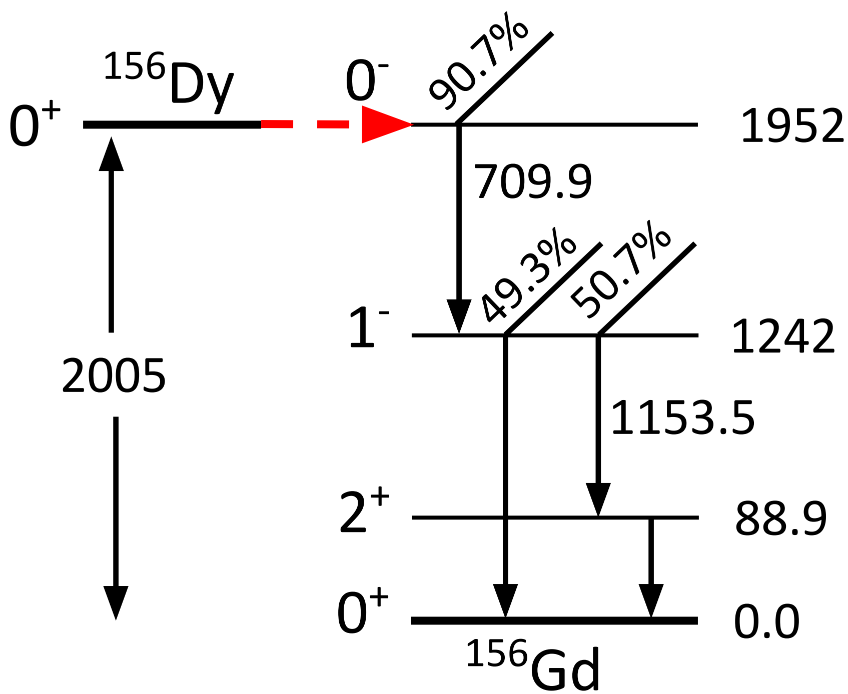
- No nuclear data available on state
- Assume a strong transition to the 2$^+$ state
  - Branching ratio = 100%
- Gate on 88.9 keV γ ray in one clover segment

Capture to the 1988 keV State



- No nuclear data available on state
- Assume a strong transition to the 2^+ state
  - Branching ratio = 100%
- Gate on 88.9 keV γ ray in one clover segment
- 2 events in ROI, expected 3.76 events background

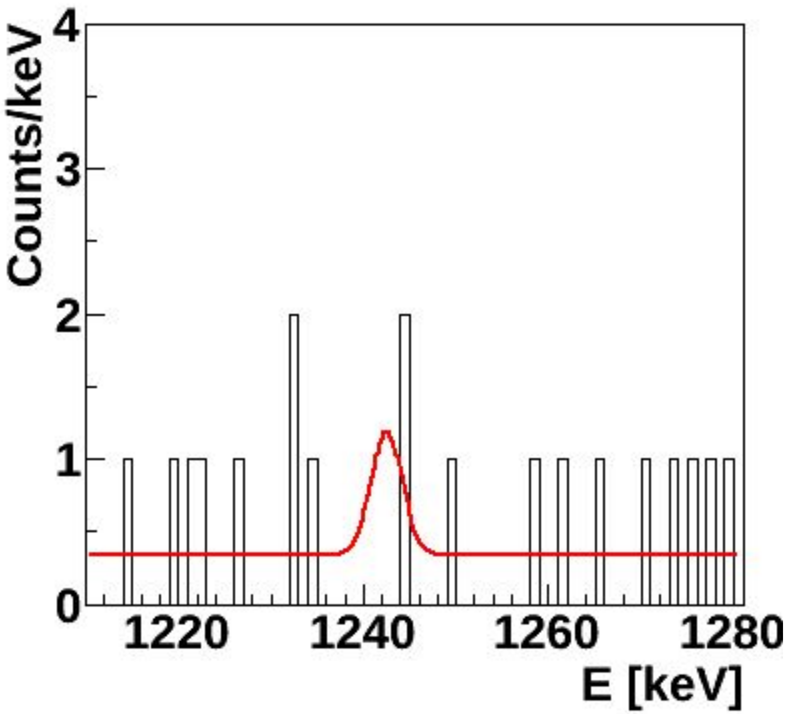
Capture to the 1952 keV State



All energies in keV

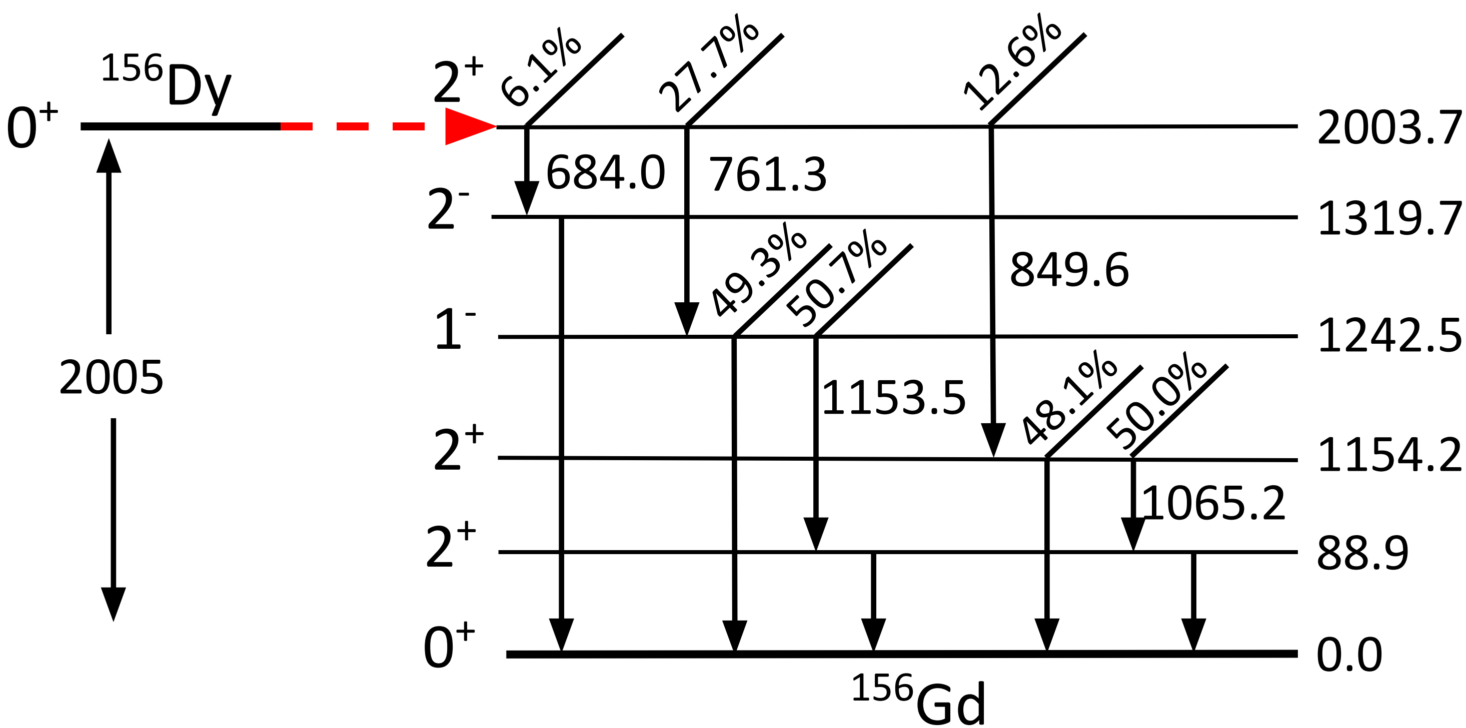
- Two γ-ray decay mode
  - Branching ratio 44%
- Allow addback on both γs
- Three γ-ray decay mode may be reconstructed in addback
  - Additional 26.3% increase to sensitivity

Capture to the 1952 keV State



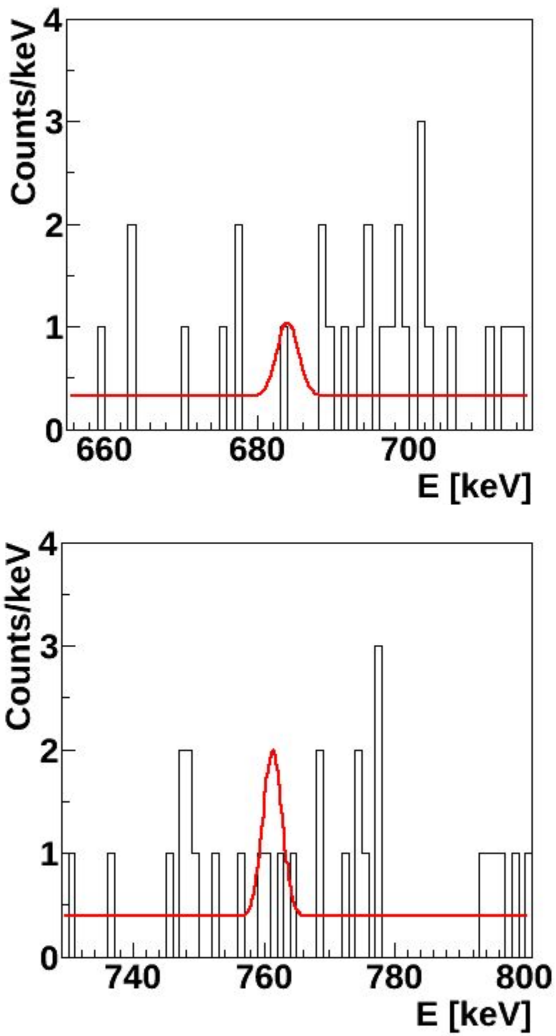
- Two γ-ray decay mode
  - Branching ratio 44%
- Allow addback on both γs
- Three γ-ray decay mode may be reconstructed in addback
  - Additional 26.3% increase to sensitivity
- Given 709.9 keV event
- 2 events in ROI, expected 2.38 events background

Capture to the 2003.7 keV State



All energies in keV

Capture to the 2003.7 keV State



- Two γ-ray decays
  - Branching ratio 25.8%
- Including contribution from ternary γ-ray decays
  - Increase sensitivity by 18%
- Top: in coincidence with 1319.7
- Bottom: in coincidence with 1242.5
- Sum all three decay modes
  - 6 events in ROI, expected 5.64 events background

Summary of Results

J^π	E [keV]	$T_{1/2}$ [yr] This work C.I.	$T_{1/2}$ [yr] This work Sensitivity	$T_{1/2}$ [yr] Previous limit[4]
1^-	1946.4	$> 1.0 \times 10^{18}$	$> 2.8 \times 10^{17}$	$> 9.6 \times 10^{15}$
0^-	1952.4	$> 2.2 \times 10^{17}$	$> 1.9 \times 10^{17}$	$> 2.6 \times 10^{16}$
0^+	1988.5	$> 9.5 \times 10^{17}$	$> 5.0 \times 10^{17}$	$> 1.9 \times 10^{16}$
2^+	2003.7	$> 6.7 \times 10^{16}$	-	$> 3.0 \times 10^{14}$

[4] P. Belli *et al.*, J. Phys. Conf. Ser. **375**, 042024 (2012)

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The Future

- Many $0\nu\beta\beta$ experiments are currently underway with more about to begin
  - Underway: EXO-200, GERDA, KamLAND-Zen
  - Near future: CUORE, Majorana, SNO+
- Collaborations are progressing towards 1-ton scale experiment
- Goals:
  - Illuminate the Dirac or Majorana nature of the neutrino
  - Set limits on the neutrino mass

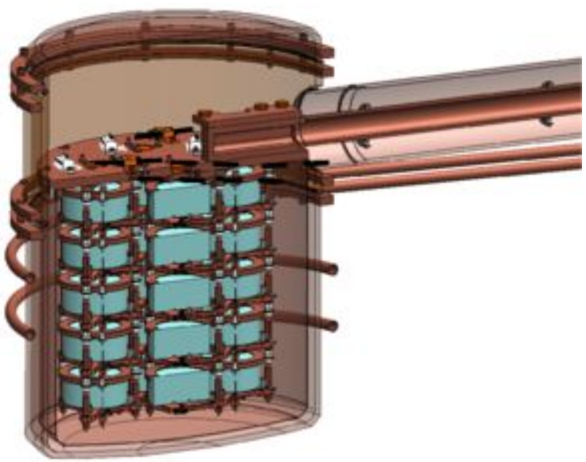
Summary

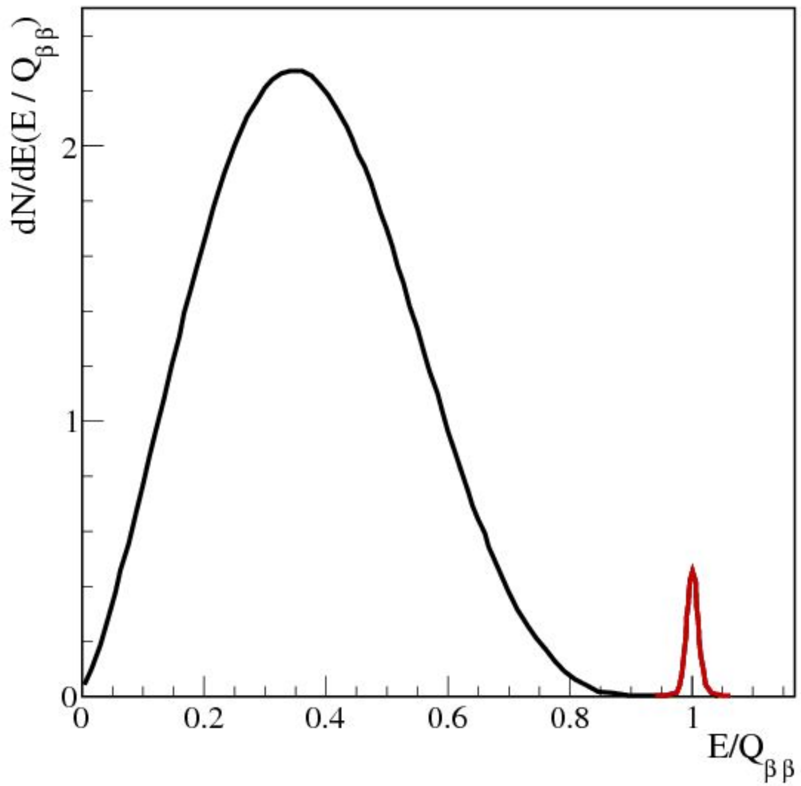
- $\beta\beta$ of ^{96}Zr to excited states
  - Improve theoretical understanding of NMEs
    - Reduce uncertainty
  - Excited state decay modes could help verify discovery
    - Decreased background by coincidence technique
  - $T_{1/2}(\beta\beta) > [1.0\text{-}3.2] \times 10^{20}$ yr
  - $T_{1/2}(\beta) > 2.4 \times 10^{19}$ yr
- $0\nu ECEC$ to excited states
  - Experimental alternative to $0\nu\beta\beta$
  - Resonant enhancement could greatly increase experimental sensitivity
  - $T_{1/2} > [0.67\text{-}10] \times 10^{17}$ yr

Thank you

How to Observe 0νββ

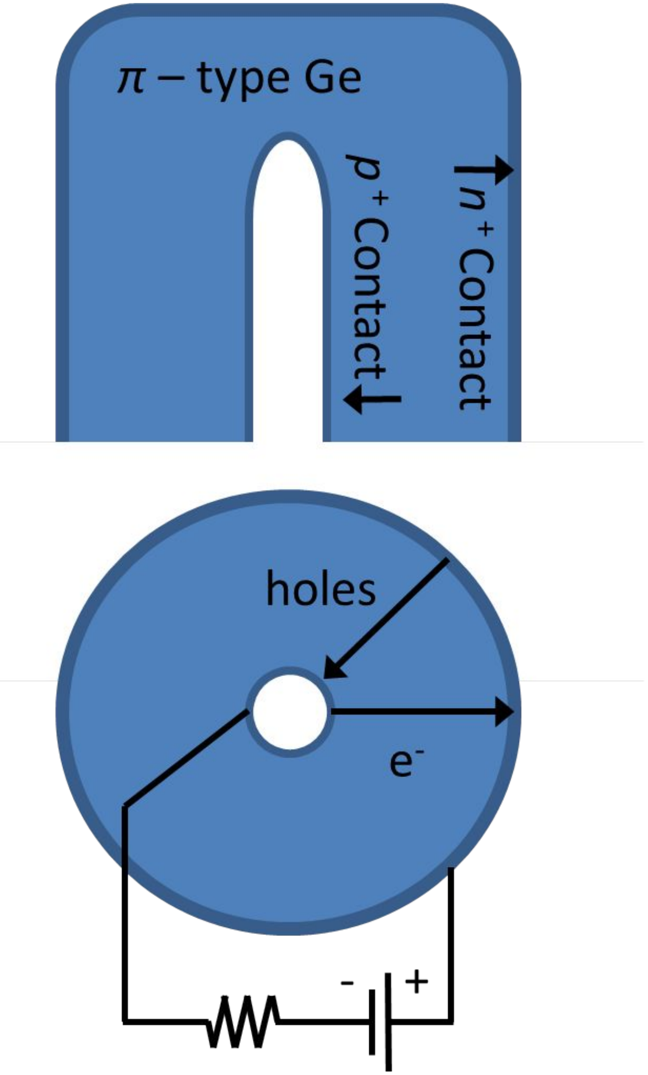
- How to observe
  - Neutrinos escape
  - Electrons deposit energy in detector
- Majorana Experiment
  - ^{76}Ge





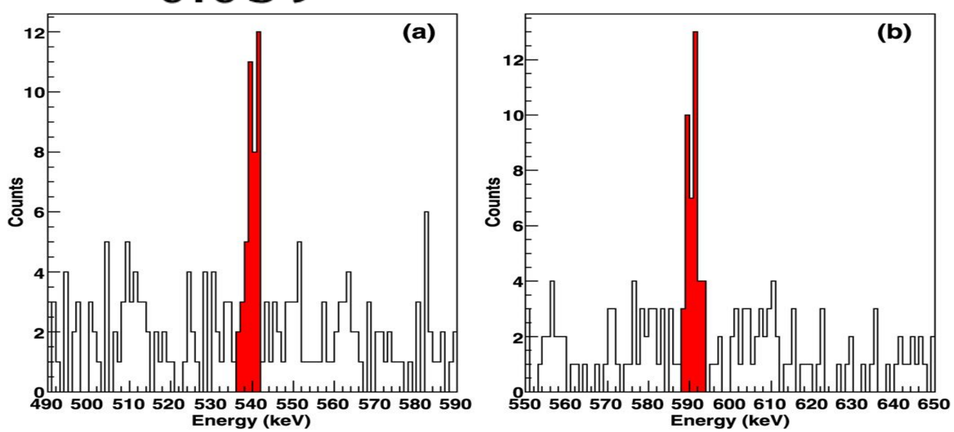
HPGe Detectors

- Photoelectric effect
  - Low energies (<140 keV)
  - Full energy deposition
- Compton scattering
  - Median energies
  - Partial energy deposition
- Pair production
  - High energy
    - Requires 1.022 MeV
  - Dominates > 8 MeV



Previous Data: ^{100}Mo

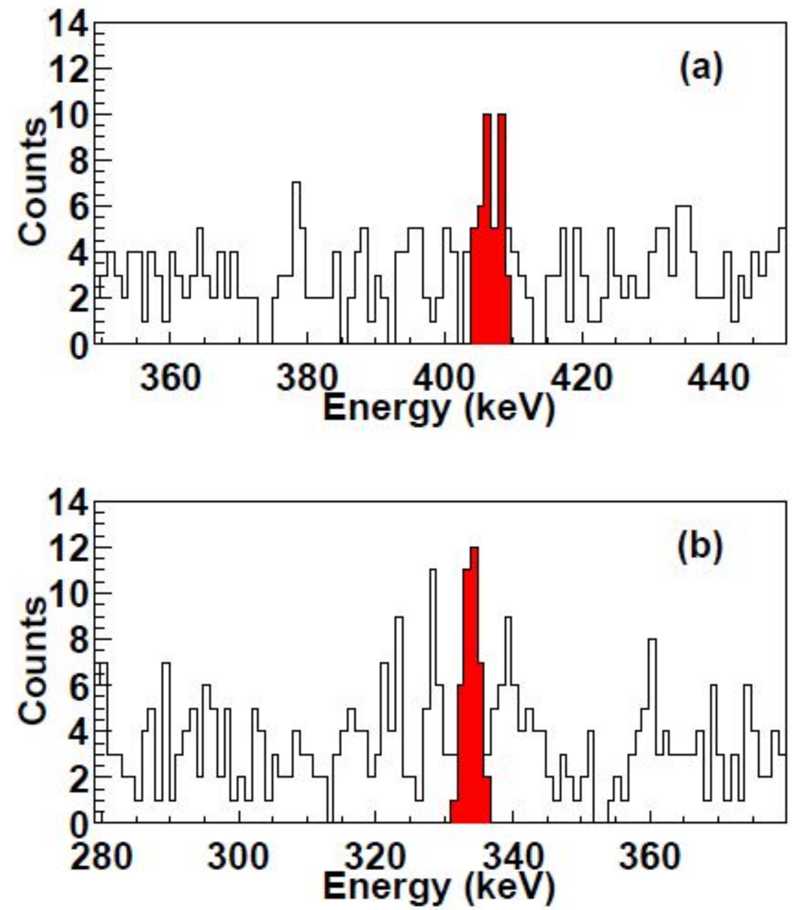
- 1.033 kg ^{100}Mo (1.05 kg metal enriched to 98.4%)
- 905 days of data acquisition (at TUNL - ground level)
- 35.5 ± 6.4 events (539.51 + 590.79 keV)
- $T_{1/2} = [5.5^{+1.2}_{-0.8}$ (stat) $\pm$ 0.3 (syst)] x 10^{20} yr
- NME: $0.144^{+0.029}_{-0.039}$



[5] M.F.Kidd, J.H. Esterline, and W. Tornow, Nuc. Phys. **A** 821, 251 (2009)

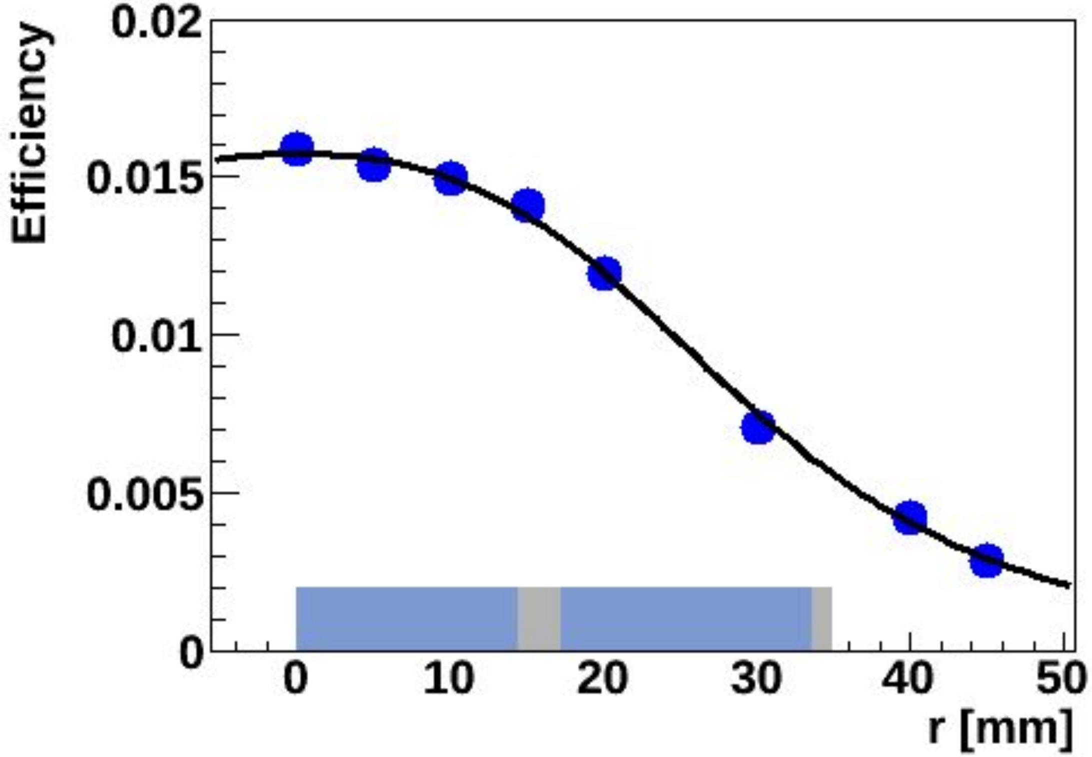
Previous Data: ^{150}Nd

- 40.13 g ^{150}Nd
- 642 days (1.75 y) of data at KURF
- 333.97 + 406.52 keV
- Net 21.6 events
- $T_{1/2} = [1.07^{+0.45}_{-0.25}$ (stat) $\pm$ 0.07 (syst)] x 10^{20} yr
- NME: $0.0465^{+0.0098}_{-0.0054}$



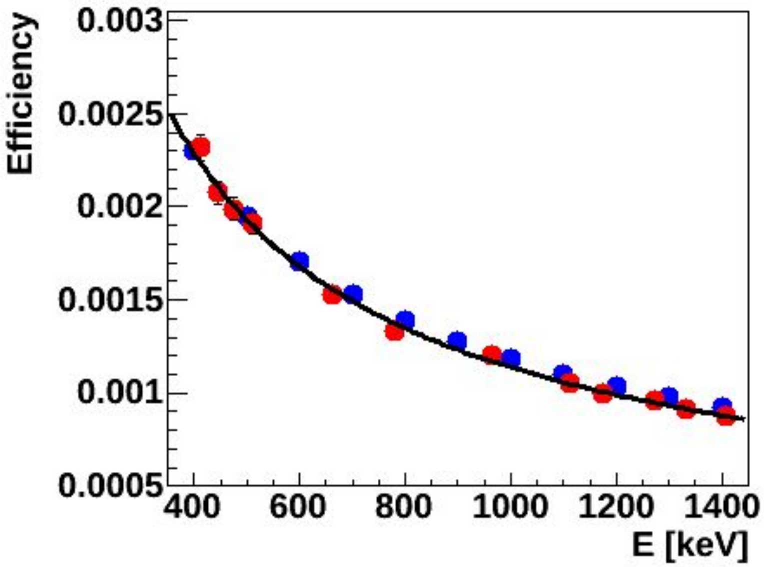
[6] M.F. Kidd, J.H. Esterline, S.W. Finch, and W. Tornow, Phys. Rev. **C** 90, 055501 (2014)

Two-Coaxial Apparatus Efficiency

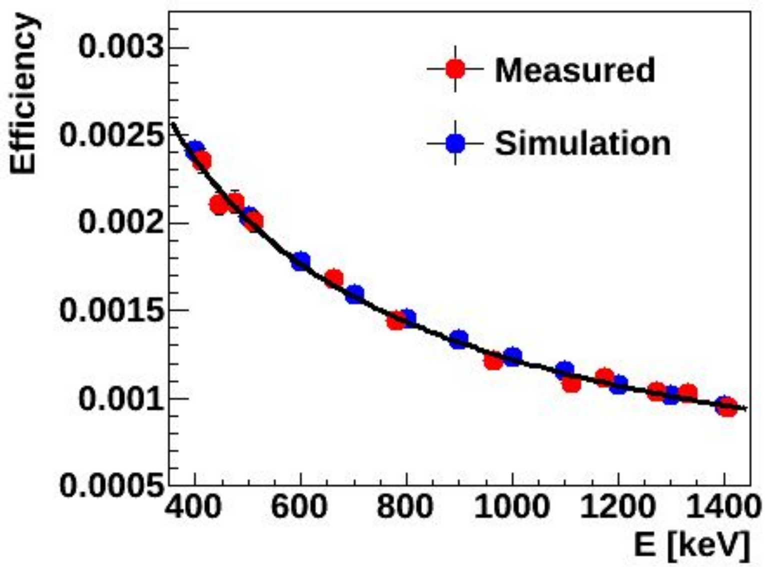


Coaxial HPGe efficiency

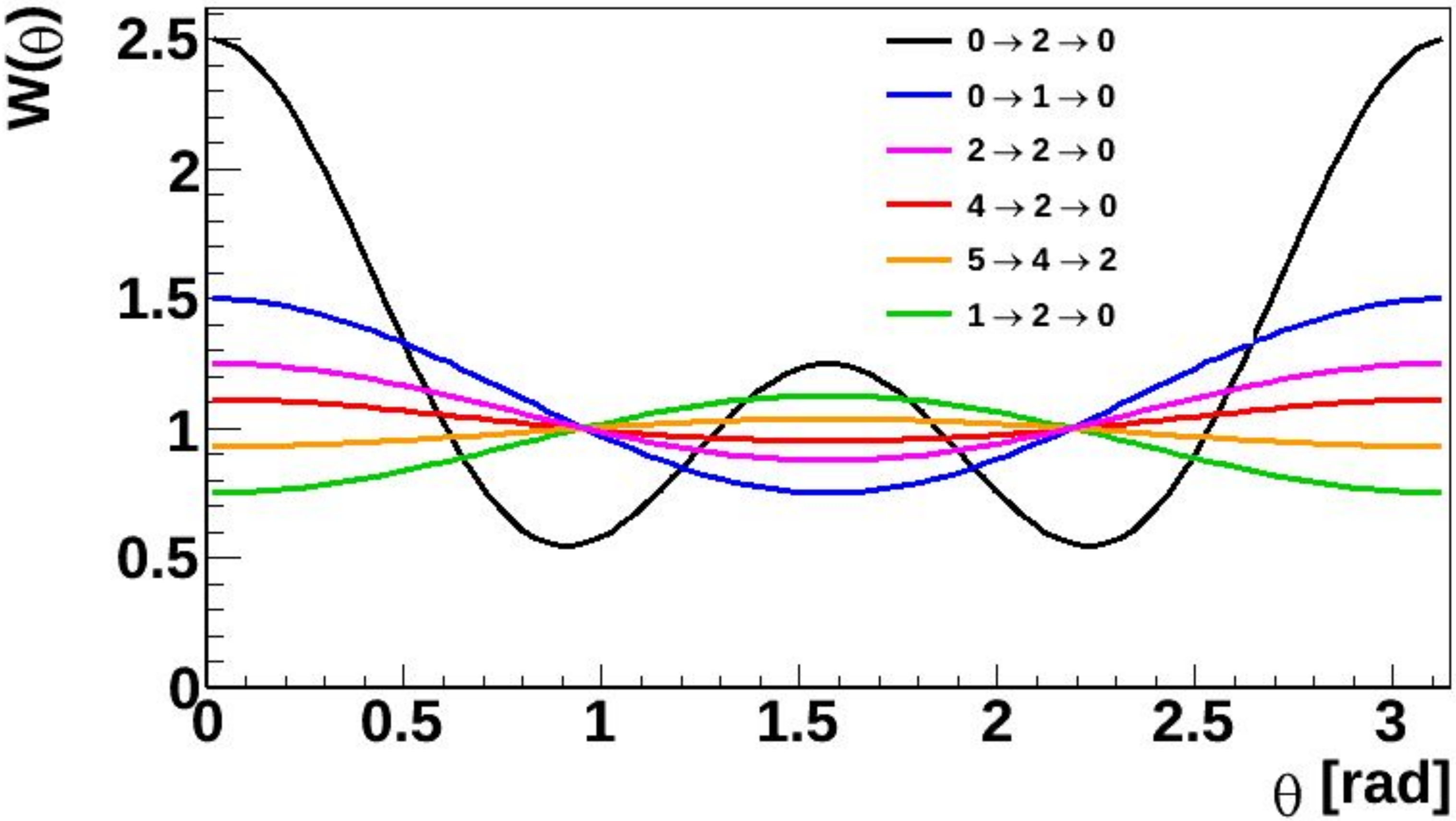
HPGe 1



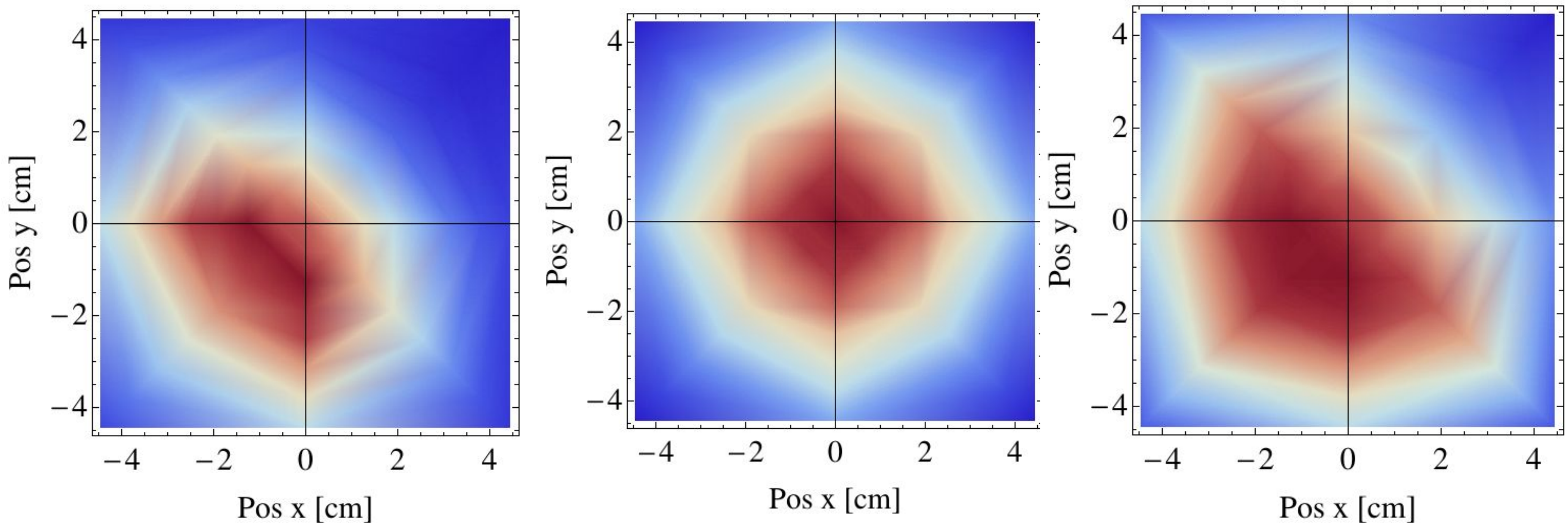
HPGe 2



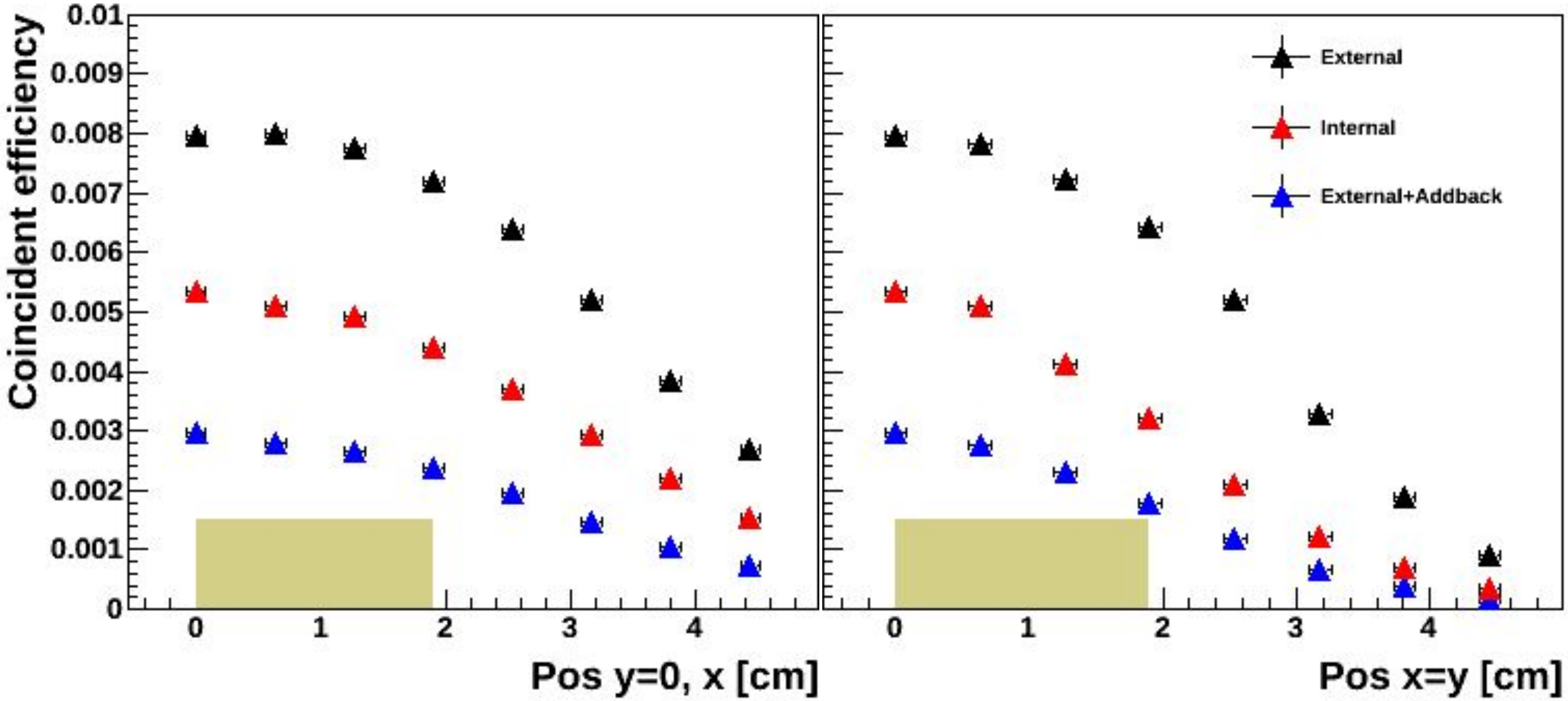
Angular Distribution



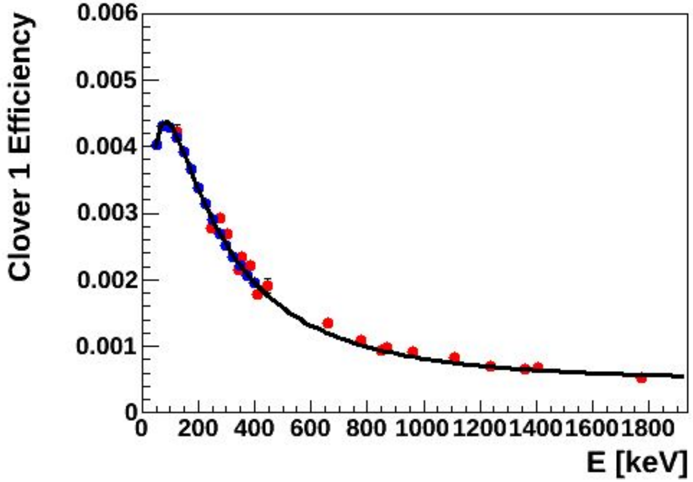
Two-Clover Apparatus Efficiency

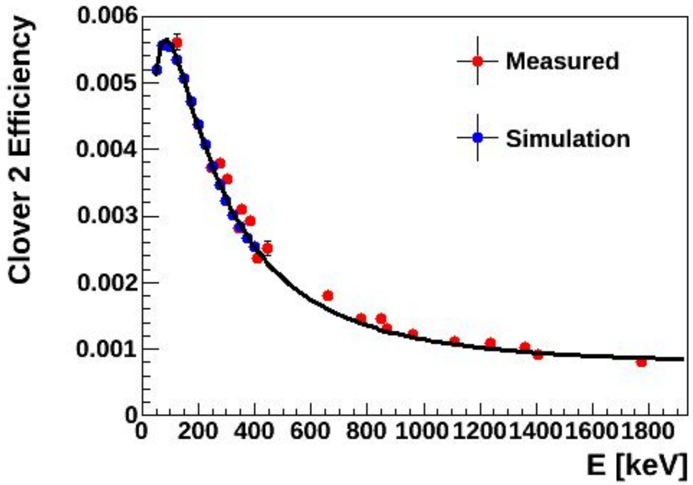


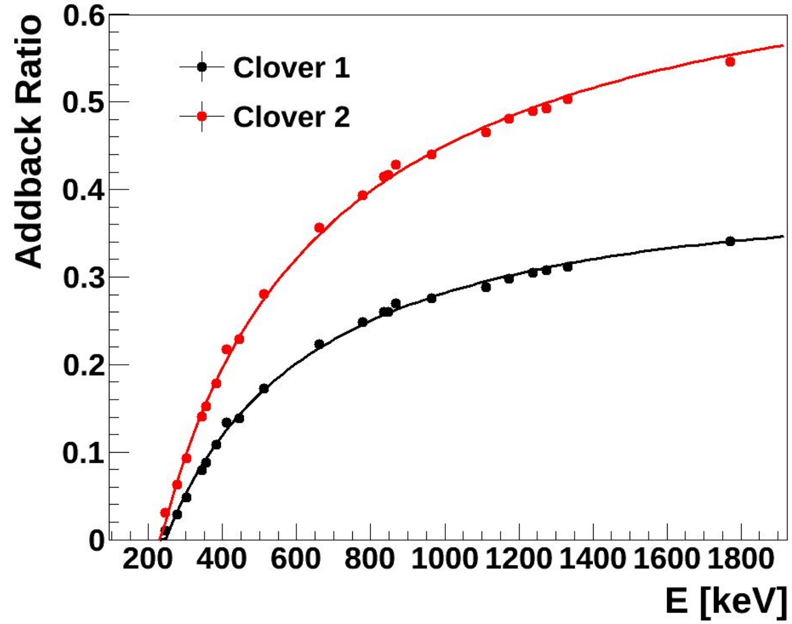
Two-Clover Apparatus Efficiency



Clover Efficiency







Method of Feldman-Cousins

- Background = 3.0, μ = 0.5
- $P(n|\mu) = \frac{(\mu+b)^n}{n!}\exp[-(\mu+b)]$
- $R = P(n|\mu)/P(n|\mu_{best})$
- Add values of *n* in order of *R* until $\sum_n P(n|\mu) > C.L.$
- Here, n = [0,6] at 90% C.L.

n	P(n|μ)	μ_{best}	$P(n\|\mu_{best})$	R	rank
0	0.030	0	0.050	0.607	6
1	0.106	0	0.149	0.708	5
2	0.185	0	0.224	0.826	3
3	0.216	0	0.195	0.936	2
4	0.189	1	0.175	0.996	1
5	0.132	2	0.161	0.753	4
6	0.077	3	0.149	0.480	7

Limits on NME