Duke-TUNL Activities at KURF: Excited State Decays

KURF User's Meeting
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Duke University and TUNL

Duke
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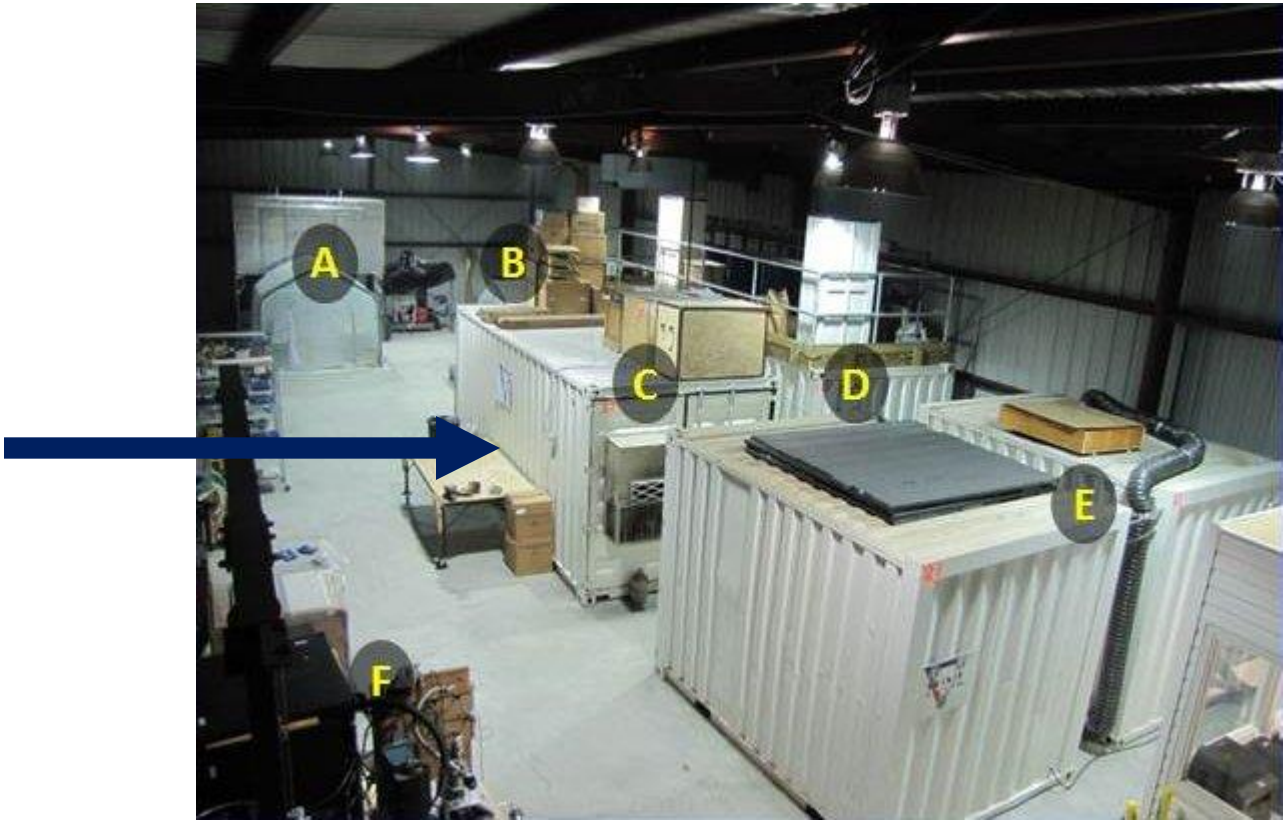
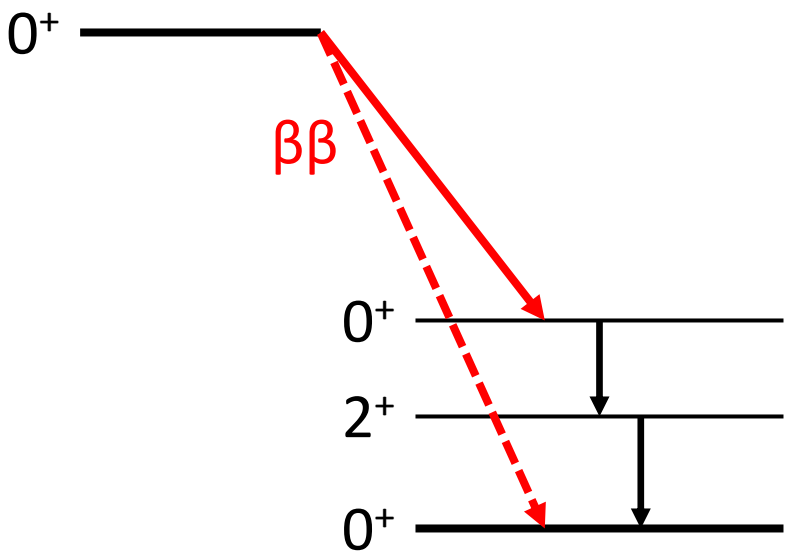
TUNL

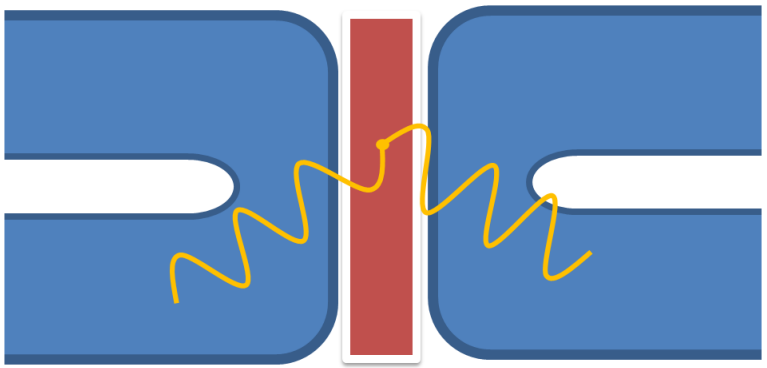
The Duke-TUNL Conex



Experimental Technique



An excited state decay with two coincident γs



Sample in between two coaxial HPGe Detectors

Outline

- 2νββ to excited final states
  - Existing apparatus
  - Previous measurements of ^{100}Mo and ^{150}Nd
  - Current experiment on ^{96}Zr

- Resonant ECEC to an excited state
  - Experiment on ^{156}Dy
  - Newer apparatus

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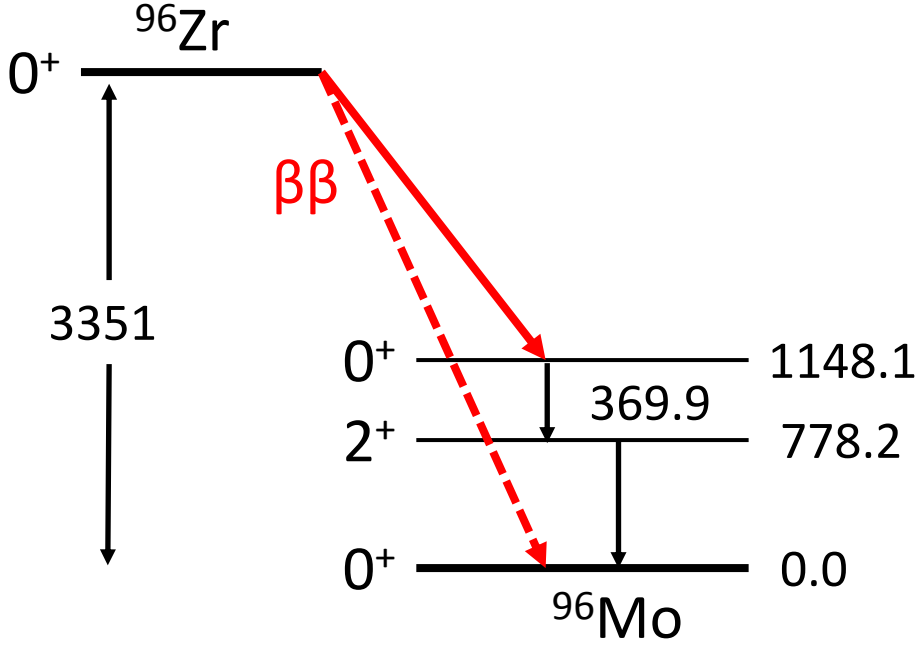
2νββ to Excited Final States

$$\lambda_{2\nu\beta\beta} = G_{2\nu}(Q_{\beta\beta}, Z)\left|M_{GT}^{2\nu} - M_{F}^{2\nu}\right|^2$$

$$\lambda_{0\nu\beta\beta} = G_{0\nu}(Q_{\beta\beta}, Z)\left|M_{GT}^{0\nu} - M_{F}^{0\nu}\right|^2 \langle m_\nu \rangle^2$$

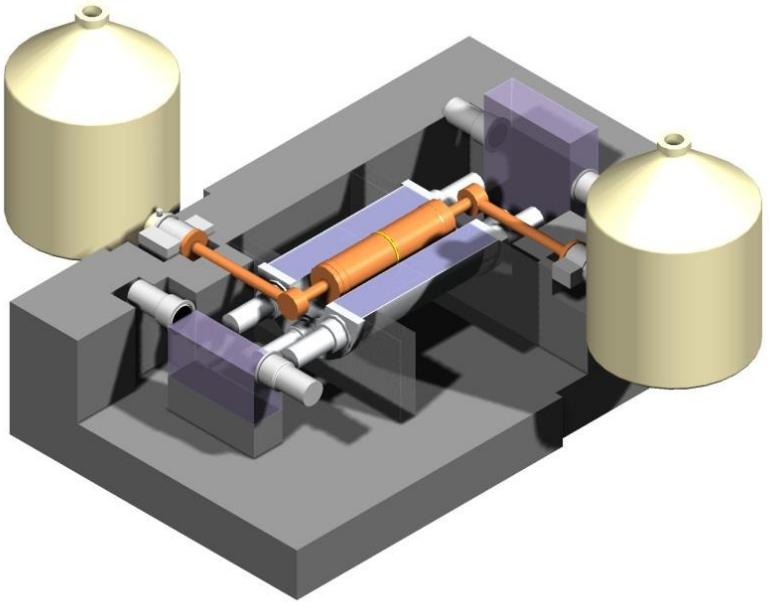


All energies in keV

- 0νββ matrix elements must be calculated
  - Tuned to reproduce 2νββ matrix elements
  - Decay to excited final state provides additional constraint

Existing Experimental Apparatus

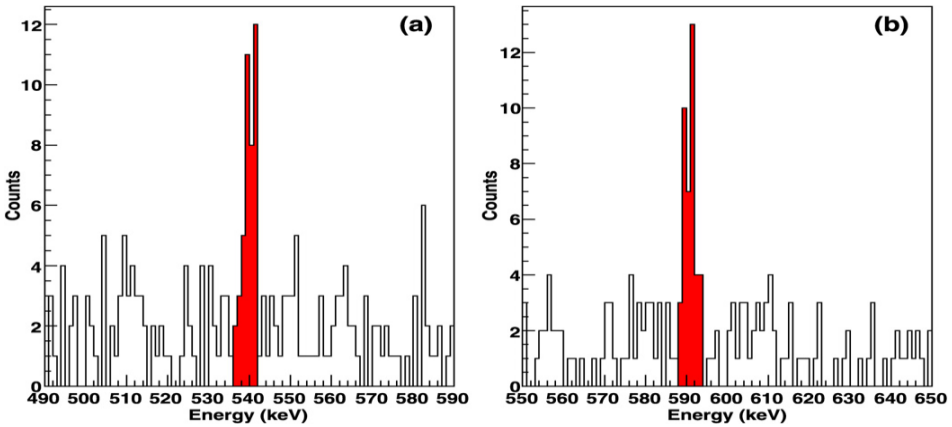
- Two HPGe detectors sandwich sample
  - Coincidence technique lowers background
- Active veto
  - NaI annulus for Compton suppression
  - Plastic end caps
- Passive shielding
  - ¾” OFHC Copper
  - 6” Lead



Previous Data: ^{100}Mo

- 1.033 kg ^{100}Mo
  - 1.05 kg enriched to 98.4%
- 905 days of data acquisition (at TUNL - ground level)
- 35.5 ± 6.4 events (539.51 + 590.79 keV)

$$T_{1/2} = 5.5^{+1.2}_{-0.8}(stat) \pm 0.3(syst) \times 10^{20} years$$



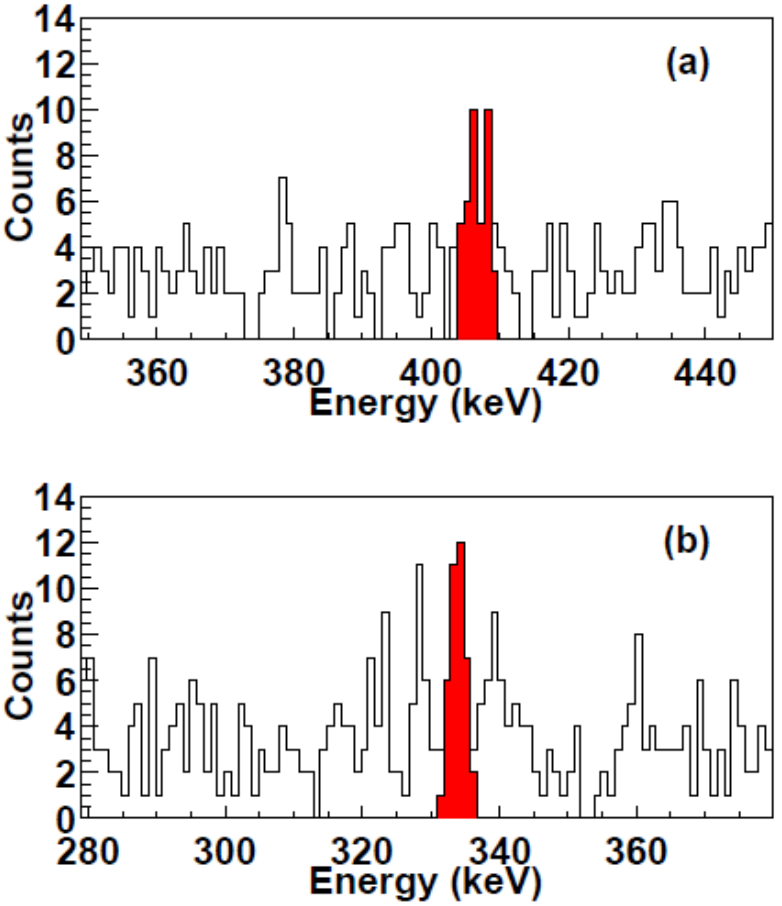
[1] M.F.Kidd et al., Nuc. Phys. A, 821 251

Previous Data: ^{150}Nd

- 40.13 g ^{150}Nd
- 642 days of data acquisition at KURF
- 333.97 + 406.52 keV
- 21.5 ± 7.5 events

$$T_{1/2} = (1.08^{+0.58}_{-0.28}(stat) \pm 0.07(syst.)) \times 10^{20} \text{ years}$$

- NME: $0.0231^{+0.0037}_{-0.0045}$
- Thesis of Mary Kidd



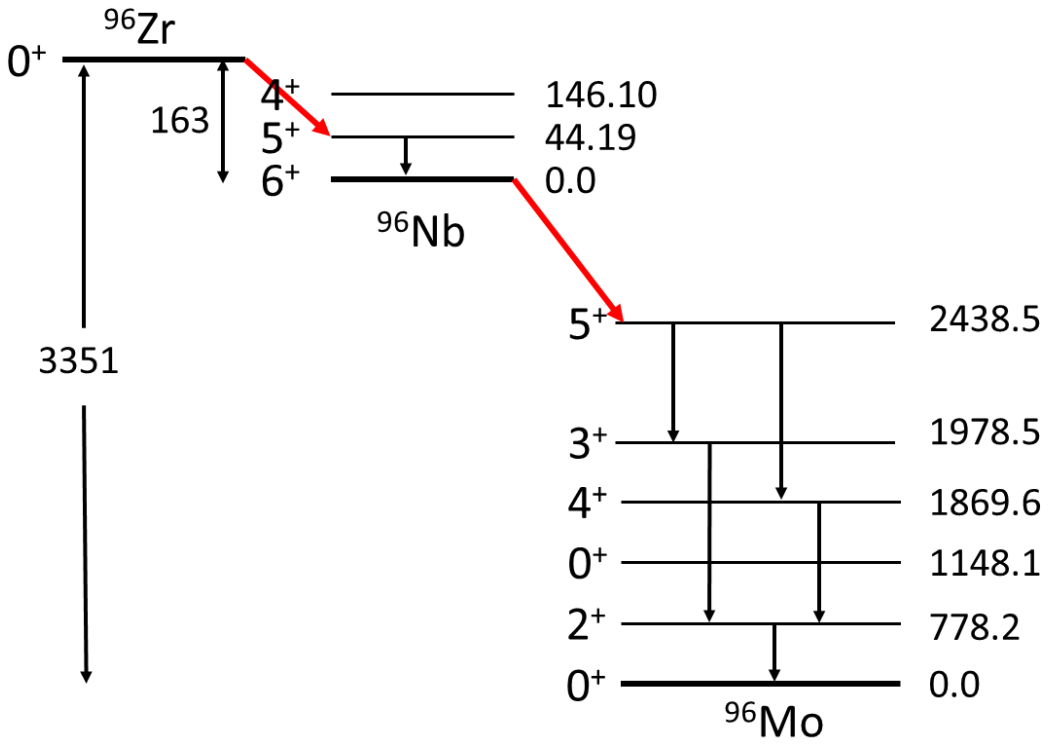
Extending to ^{96}Zr

- ^{150}Nd and ^{100}Mo are the only two nuclei where ββ-decay to an excited state has been observed.
- ^{96}Zr as a ββ-decay candidate
  - High Q-Value (3347 keV)
  - 2.8% natural abundance
  - Ground state decay measured by NEMO collaboration

    $T_{1/2} = [2.35 \pm 0.14(stat) \pm 0.16(syst)] \times 10^{19}$ y
- 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

Single-β decay of ^{96}Zr

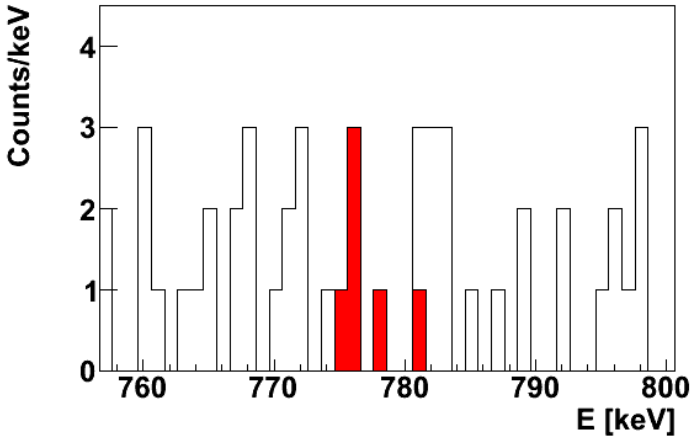
- Single-β decay energetically allowed
  - Suppressed by angular momentum (4th forbidden)
  - Theoretical estimate $T_{1/2} = 2.4 \times 10^{20}$
- ^{96}Nb $T_{1/2}$ = 23.3 h
- Irreducible background for experiment looking at single γ rays.

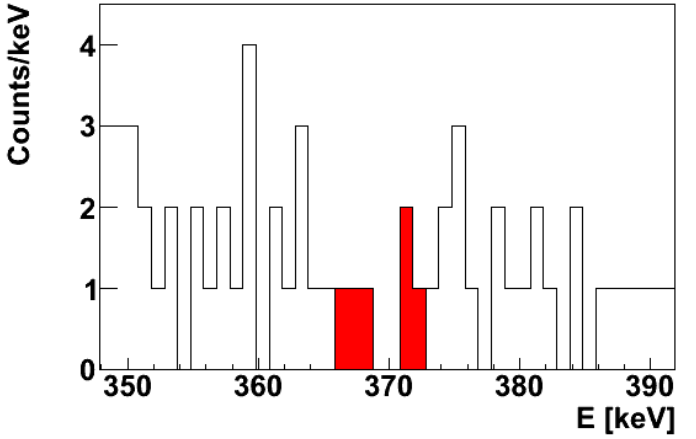


All energies in keV

^{96}Zr Backgrounds

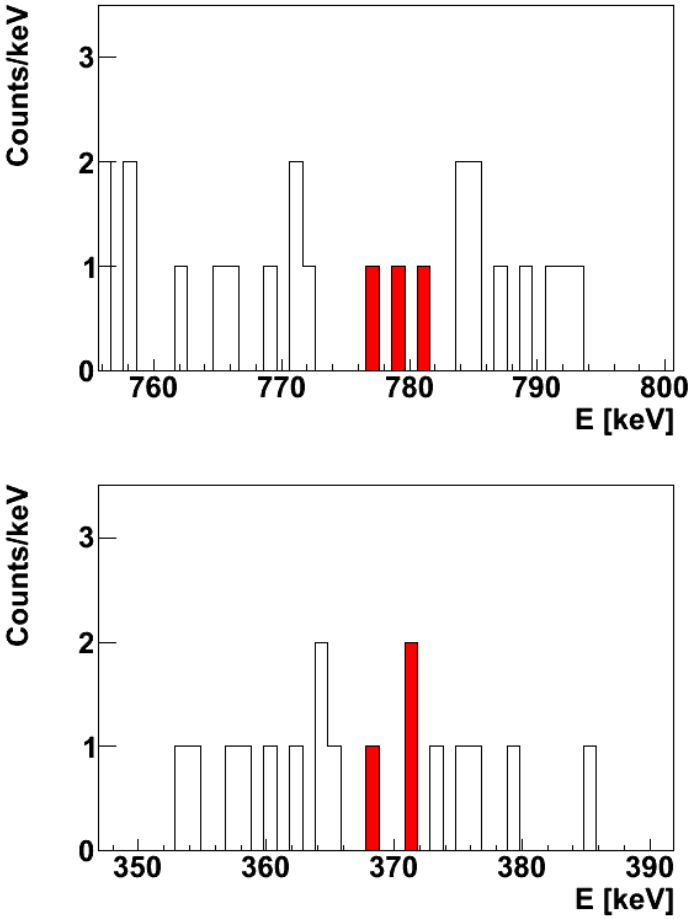
- Previously collected data
  - 643 days ^{150}Nd
  - 181 days no sample
  - Total 824 days (2.25 y)
- Investigate ^{96}Zr's 369-778 keV coincidence
  - 6 events in ROI
  - All occurred with ^{150}Nd sample in place





^{96}Zr 2νββ Data

- ^{96}Zr source in place
  - 382.2 days (1.05 y) of data
  - 3 events in ROI (consistent with background)
- Backgrounds
  - ^{232}Th impurities in sample
  - Compton scattering
  - Discriminate with energy resolution



New limits

- No counts above background
  - $T_{1/2} > 1.6 \times 10^{20}$ y
- Previous limit
  - $T_{1/2} > 6.8 \times 10^{19}$ y
  - Used single well-type HPGe
  - Limited by high background and statistical fits

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Resonant ECEC to Excited Final States

- $^{A}_{Z}X_{N} + 2e^{-} \rightarrow ^{A}_{Z-2}X''_{N+2} + 2\nu_{e}$
- $^{A}_{Z}X_{N} + 2e^{-} \rightarrow ^{A}_{Z-2}X''_{N+2}$
- Possible experimental alternative to 0νββ
- Rate enhancement if the Q-value is degenerate with an energy level
  - Two neutrino mode strongly disfavored by phase space
  - Observation would be evidence for Majorana neutrinos
- Detectable only by γ-ray transitions in daughter

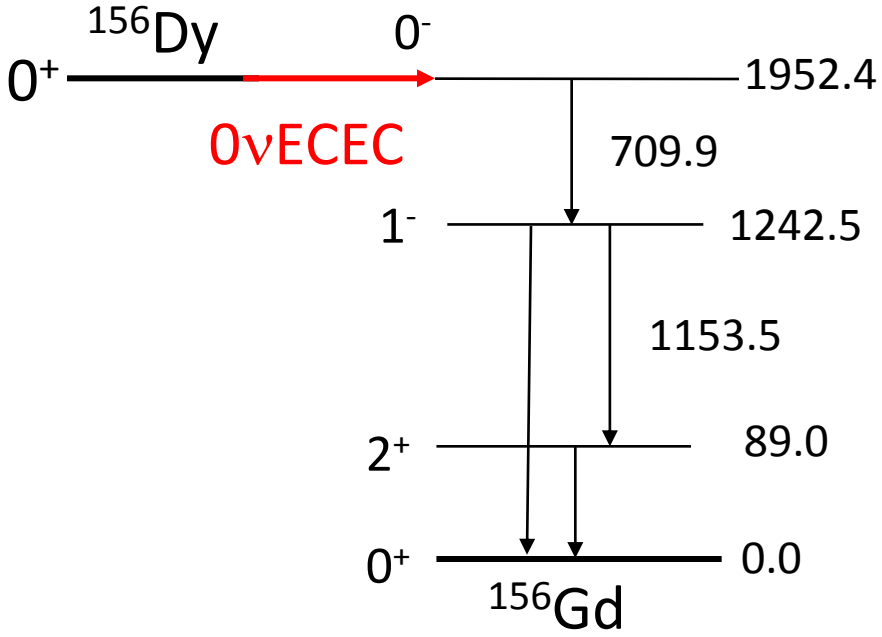
ECEC in ^{156}Dy

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

S. Eliseev et al., Phys. Rev. C 84, 012501(R) (2011)

Resonant ECEC in ^{156}Dy

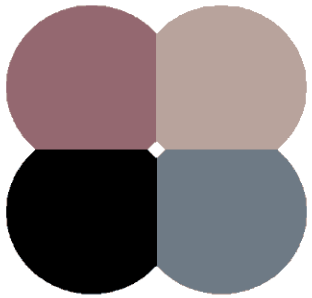
- ^{156}Dy is currently promising candidate
  - Extremely low natural abundance: 0.056%
- Enriched sample from ORNL
  - 1.15 grams enriched to 21%
  - Total = 241 mg



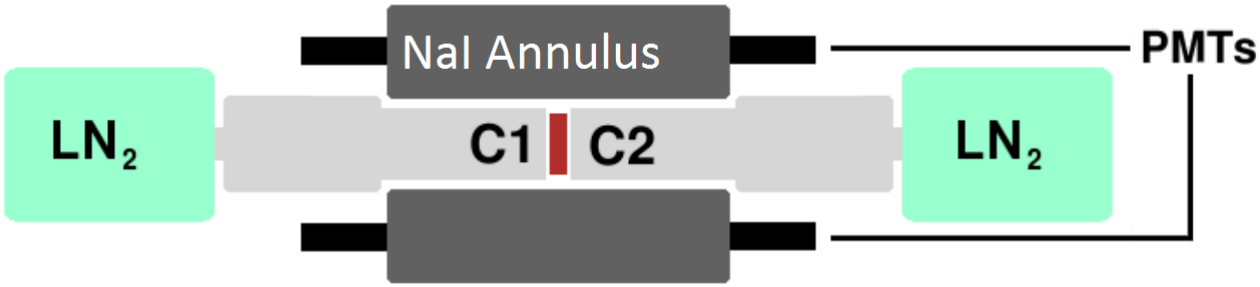
All energies in keV

New Apparatus installed at KURF

- Use two clover detectors operated in coincidence



- Larger volume
  - 4 x (50 x 80 mm)
  - Old apparatus: 88 x 50 mm
- Internal and external coincidences
- Higher efficiency



Two Clover Data

- Belli et. al., arXiv:1201.4581 22 Jan (2012)
  - 332 g natural Dy_2O_3
  - 156 mg ^{156}Dy
  - 104.7 days
  - Single HPGe at LNGS
  - $T_{1/2} > O(10^{14} – 10^{16})$ y
- Currently have 62 days of ^{156}Dy data
- Cover a larger solid angle
- Ability to look at coincidence γ-rays from cascades

Future Plans

- Keep counting!
- ^{96}Zr
  - Continue search for $2\nu\beta\beta$ of ^{96}Zr to first excited 0^+ state of ^{96}Mo
  - Investigate single-β decay
- ^{156}Dy
  - Set limits on resonant ECEC