Progress in Investigating the Characteristics of Neutron-Irradiated Germanium

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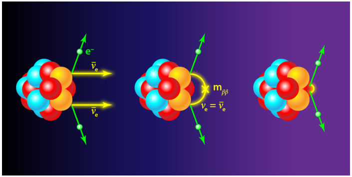
Introduction

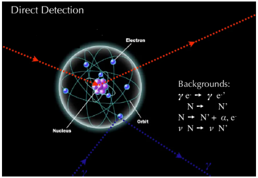
- Applications of bolometers using NTD-Ge thermistors
  - Neutrinoless double beta ($0\nu\beta\beta$) decay measurement (CUORE, CUPID (Italy), CROSS (Spain), TIN.TIN (India), etc.)
  - dark matter (WIMP) search (CUORE, EDELWEISS)
  - solar neutrino measurement
  - x-ray spectroscopy

- Goals
  - Production of NTD-Ge thermistor
    1. neutron irradiation → doping (neutron transmutation doping, NTD)
    2. fabrication → thermistor
  - Quality & quantity check for NTD-Ge thermistor

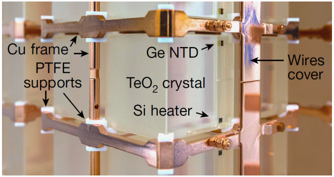
- $0\nu\beta\beta$ decay (center)



- WIMP search



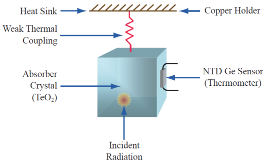
- Bolometer (CUORE)



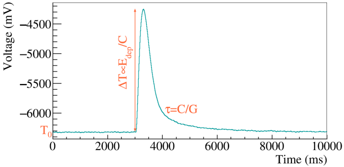
Bolometers using NTD-Ge Thermistor

- Characteristics
  - operating temperature: 10-100 mK
  - low heat capacity: $C < 10^{-13}$ J/K
  - temperature rise: $\sim$10 mK for 6 keV x-ray
  - high thermal conductivity
- Advantages
  - high detection efficiency
  - low intrinsic background
  - good energy resolution ($\sim$5 keV for 2.62 MeV γ)

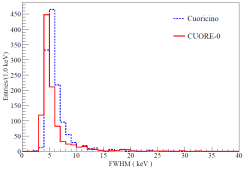
- Diagram of bolometer



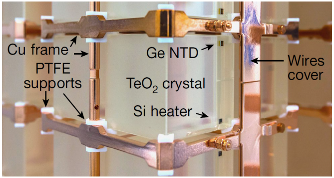
- Pulse from bolometer



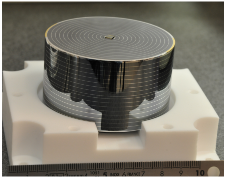
- Energy resolution



- Bolometer (CUORE)



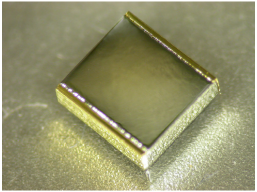
- Bolometer (EDELWEISS)



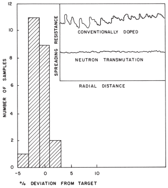
NTD-Ge Thermistor

- Doping level: 10^{17}–$10^{18}/\mathrm{cm}^2$
- Advantages
  - high sensitivity
  - low specific heat
  - fast rise time
  - good doping uniformity (random isotope distribution)
  - precise control of doping concentration
- Production
  - Neutron irradiation
  - annealing to recover the fast neutron-induced damage in the lattice structure (e.g. 600 $^\circ\mathrm{C}$, 2 hr)
  - electrical contact (e.g. 100-nm-thick Au-Ge alloy (88% Au + 12% Ge))
  - annealing (e.g. 400 $^\circ\mathrm{C}$, 2 min., Ar atmosphere)

- NTD-Ge thermistor (CUORE)



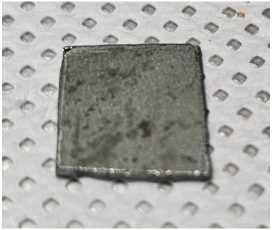
- Production homogenity & doping uniformity



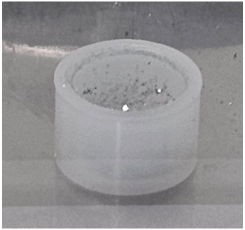
Ge Samples

- Ge samples for testing neutron irradiation using research reactor HANARO at KAERI
- Samples from HPGe crystal (n-type, $\sim 10^{13}/\mathrm{cm}^2$)
- Total 8 Ge samples (6 disks + 2 powder)
- Sample weight: 0.08 mg (powder) - 0.8 g (disk)

- Ge sample (disk)



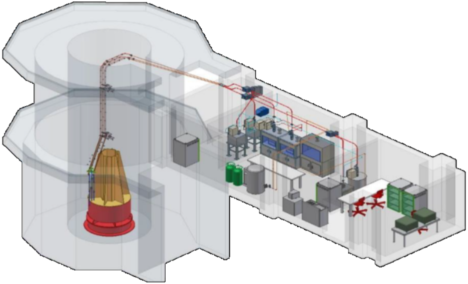
- Ge sample (powder)



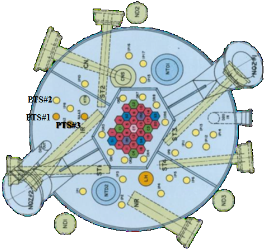
Neutron Irradiation using HANARO

- Transfer of samples between the lab and HANARO using pneumatic transfer system (PTS)
- Neutron irradiation holes in HANARO (PTS#1-3)
- The maximum irradiation time: 6 hr

- PTS facility



- Neutron irradiation holes in HANARO



- Averaged neutron fluxes for 30 MW of HANARO thermal power $[N/\mathrm{cm}^2]$

Hole	Thermal	Epithermal	Fast
PTS#1	$4.80\pm0.02\times10^{13}$	$7.80\pm0.22\times10^{11}$	$6.38\pm0.49\times10^{10}$
PTS#2	$3.30\pm0.09\times10^{13}$	$3.440\pm0.29\times10^{11}$	$3.27\pm0.47\times10^{10}$
PTS#3	$1.53\pm0.06\times10^{14}$	$1.01\pm0.07\times10^{12}$	$9.78\pm0.05\times10^{11}$

Decay Process After Neutron Irradiation

^{70}Ge (21%) + n → ^{71}Ge + γ	σ_T = (3.43±0.17) b	
	σ_E = 1.5 b	Ga (acceptor)
^{71}Ge + e^- → ^{71}Ga + ν_e	$\tau_{1/2}$ = 11.4 days	
^{74}Ge (36%) + n → ^{75}Ge + γ	σ_T = (0.51±0.08) b	
	σ_E = (1.0±0.2) b	As (donor)
^{75}Ge → ^{75}As + e^- + $\bar{\nu}_e$	$\tau_{1/2}$ = 83 minutes	
^{76}Ge (7.4%) + n → ^{77}Ge + γ	σ_T = (0.160±0.0014) b	
	σ_E = (2.00±0.35) b	Se (double donor)
^{77}Ge → ^{77}As + e^- + $\bar{\nu}_e$	$\tau_{1/2}$ = 11.33 hours	
^{77}As → ^{77}Se + e^- + $\bar{\nu}_e$	$\tau_{1/2}$ = 38.8 hours	

σ_T: thermal neutron capture cross section

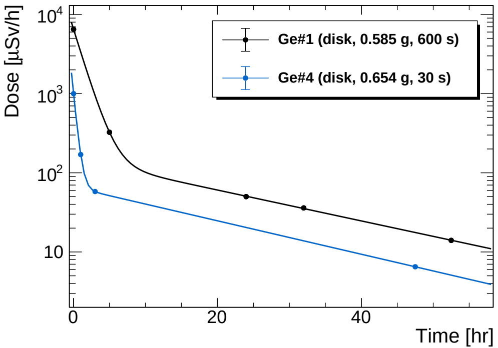
σ_E: epithermal neutron capture cross section

Ge Related Isotopes after Neutron Irradiation

- Dominant γs: ^{77}Ge and ^{75}Ge related (no γ peaks for $^{70}\text{Ge} + \text{n} \rightarrow {}^{71}\text{Ge} + \gamma$)
- ^{71}Ge: stable, electron capture $\rightarrow$ ^{71}Ga
- ^{71}Ga: stable
- ^{75}Ge: 82.8 min
- ^{75m}Ge: 48 s
- ^{75}As: stable
- ^{76}As: 26.2 hr
- ^{76}Se: stable
- ^{77}Ge: 11.2 hr
- ^{77m}Ge: 53.7 s
- ^{77}As: 38.8 hr
- ^{77}Se: stable
- ^{78}As: 90.7 min (not found in γ spectra)
- ^{78}Se: stable

Dose Rates after Neutron Irradiation

- Neutron irradiation in two different holes (PTS#1, PTS#2)
- Neutron flux: PTS#1 > PTS#2

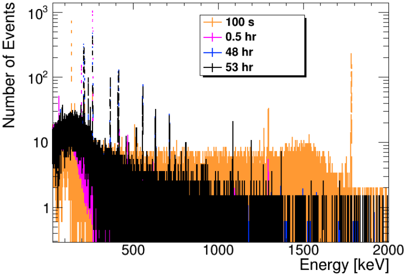


- Evaluation: neutron irradiation 1 hours, 1 g

Cooling [day]	0	1	2	3	4	5	6	7
Dose [μSv/h]	188,000	3,750	1,170	363	113	36	11	4
Dose [μSv/h]	67,200	520	177	61	21	7	3	1

Gamma Spectra after Neutron Irradiation

- Ge samples w/ different cooling time after neutron irradiation

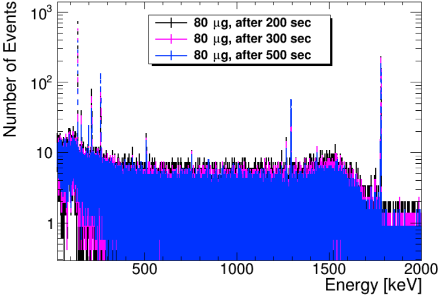


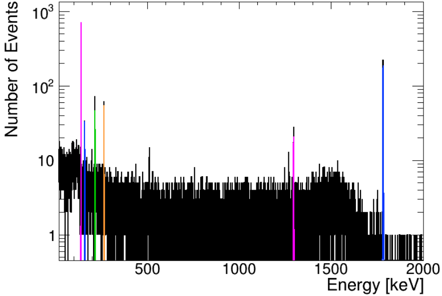
- γ peaks and related isotopes

Energy [keV]	Isotope	Energy [keV]	Isotope	Energy [keV]	Isotope
139.53	^{75m}Ge	367.37	^{77}Ge	559.08	^{76}As
159.03	^{77}Ge	413.68	^{77}Ge	613.79	^{77}Ge
198.60	^{75}Ge	419.08	^{75}Ge	634.46	^{77}Ge
211.01	^{77}Ge	419.72	^{77}Ge, ^{77m}Ge	714.33	^{77}Ge
215.48	^{77}Ge	520.24	^{77}Ge	1085.08	^{77}Ge
238.97	^{77}As	520.61	^{77}As	1296.09	^{77}Ge
249.78	^{77}As	557.75	^{77}Ge	1784.60	^{77}Ge
264.66	^{75m}Ge, ^{75}Ge, ^{75}Se	557.97	^{77}Ge		

Gamma Spectra after Neutron Irradiation: Early Time

- Tested Ge sample: powder, 0.08 mg, 5 sec



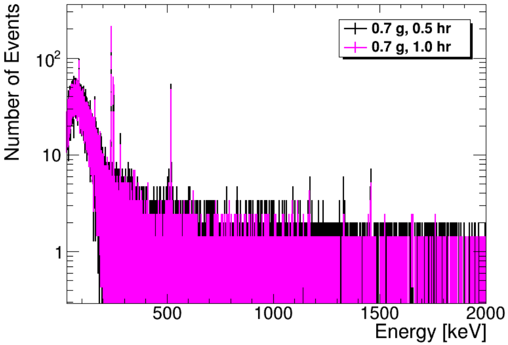


- γ peaks and related isotopes

Energy [keV]	Isotope	Energy [keV]	Isotope
139.53	^{75m}Ge	520.24	^{77}Ge, ^{77}As
159.03	^{77}Ge	1296.09	^{77}Ge
215.48	^{77m}Ge	1784.60	^{77}Ge
264.66	^{75m}Ge, ^{75}Ge, ^{75}Se		

Gamma Spectra after Neutron Irradiation: After 2 Weeks

- Tested Ge samples: (disk, 30 min, broken) and (disk, 1 hr)



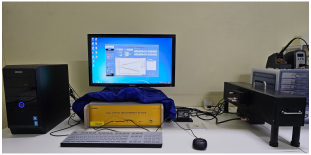
- γ peaks and related isotopes

Energy [keV]	Isotope	Energy [keV]	Isotope
159.03	^{77}Ge	279.54	^{75}Ge, ^{75}Se
238.97	^{77}As	520.24	^{77}Ge
249.78	^{77}As	520.61	^{77}As

Hall Effect Measurement Device (HEMD) at KAERI

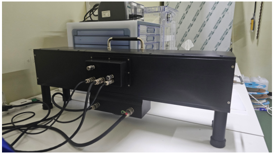
- Hall effect: current in magetic field → electric potential difference (Hall voltage) production across an electrical conductor
- Measurment parameters
  - dopant concentration
  - resistivity
  - conductivity

- HEMD

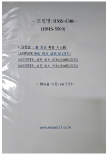


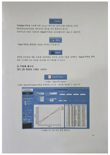
- Main device

- Measurement part

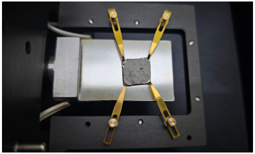


- Manual for the device





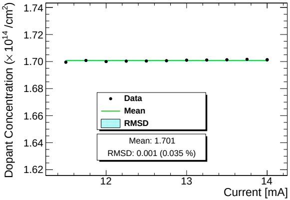
- Sample connection



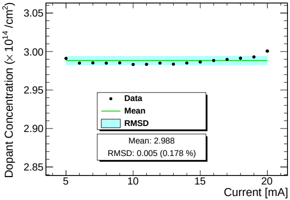
Dopant Concentrations w/ Different Irradiation Time

- Measuring dopant concentration using HEMD
- Carrying out neutron irradiation using research reactor HANARO

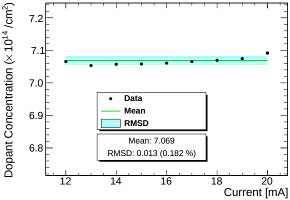
- Sample: Ge#3
- Weight: 0.693 g
- Reactor power: 27 MW
- irradiation hole: PTS#2
- irradiation time: 1 hr



- Sample: Ge#5
- Weight: 0.789 g
- Reactor power: 25 MW
- irradiation hole: PTS#2
- irradiation time: 2 hr



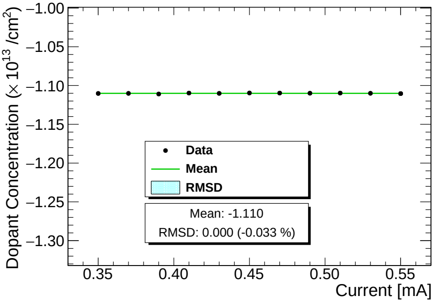
- Sample: Ge#6
- Weight: 0.762 g
- Reactor power: 25 MW
- irradiation hole: PTS#2
- irradiation time: 4 hr



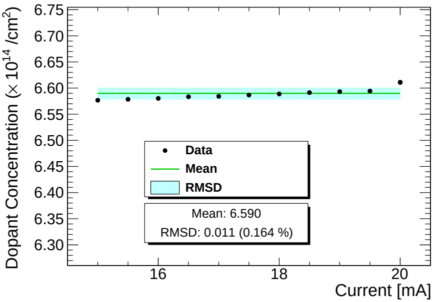
Dopant Concentration: Ge#11

- Sample: Ge#11 (disk, 0.775 g)
- Neutron irradiation
  - PTS#2, 21 MW, 6 hr (August 29, 2024)

- Before irradiation



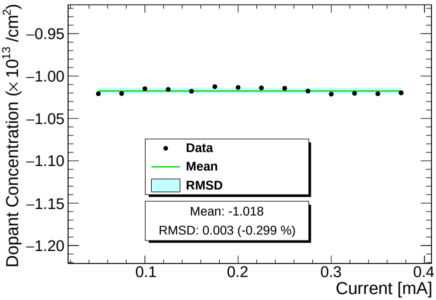
- After irradiation



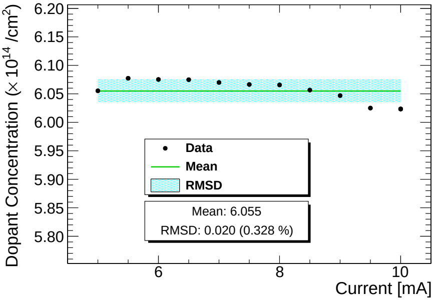
Dopant Concentration: Ge#12

- Sample: Ge#12 (disk, 0.717 g)
- Neutron irradiation
  - PTS#2, 21 MW, 6 hr (August 30, 2024)

- Before irradiation



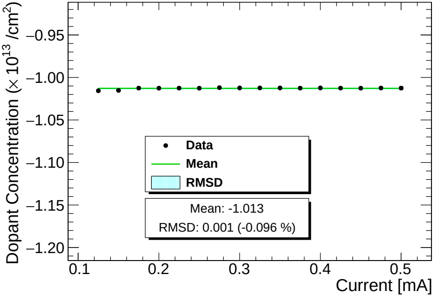
- After irradiation



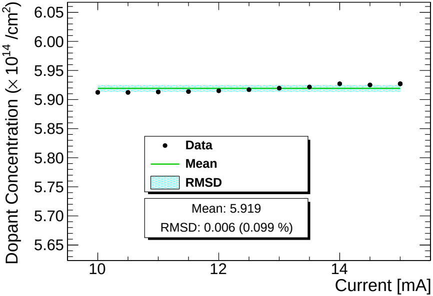
Dopant Concentration: Ge#13

- Sample: Ge#13 (disk, 0.735 g)
- Neutron irradiation
  - PTS#2, 21 MW, 6 hr (September 2, 2024)

- Before irradiation



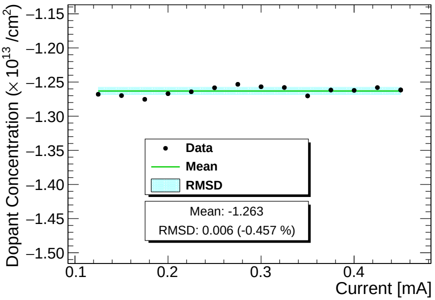
- After irradiation



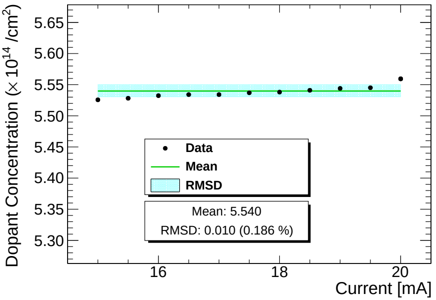
Dopant Concentration: Ge#14

- Sample: Ge#14 (disk, 0.602 g)
- Neutron irradiation
  - PTS#2, 21 MW, 6 hr (September 3, 2024)

- Before irradiation

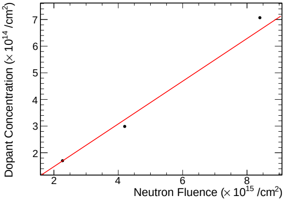


- After irradiation



Summary

- Testing time values for different neutron irradiation holes in HANARO
  - irradiation time: 5 sec - 4 hr
  - cooling time: 200 sec - 2 weeks
  - dose rates for neutron irradiated Ge samples
- Dominant isotopes after neutron irradiation
  - short cooling time ($<$ 10 min): meta state of Ge, Ge
  - long cooling time ($>$ 1 week): ^{77}Ge, ^{77}As, ^{75}Se



- Dopant concentration for 1-4 hr (25-27 MW): 1.5-5.1$\times 10^{14}/\mathrm{cm}^2$
- Dopant concentration for 6 hr, 21 MW

Sample	Ge#11	Ge#12	Ge#13	Ge#14	Average
Doping ($10^{14}/\mathrm{cm}^2$)	6.590	6.055	5.919	5.540	
Normalized for 1 g	8.503	8.445	8.053	9.203	8.551

- Plans
  - optimizing neutron irradiation configuration
  - validating dopant concentration measurements using reference material
  - measuring dopant concentration using other methods (SIMS, DLTS, etc.)
  - increasing neutron irradiation time (8 hr, 12 hr, ..., 800 hr)
    $\rightarrow$ achieving $10^{17}/\mathrm{cm}^2$ dopant concentration
  - electrical contact, temperature sensing, etc.